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THE EVOLUTION AND MODERN ADVANCEMENT OF DENTAL MATERIALS: FROM ANCIENT SUBSTITUTES TO MODERN BIOACTIVE SYSTEMS

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Abstract: The evolution of dental materials has progressed from early natural and metallic materials—such as gold, ivory, and bone—to modern high—performance ceramics, composites, fibre—reinforced polymers, bioactive, and smart biomaterials. This progression has been driven by the need for greater aesthetics, adhesion, biocompatibility, and durability, paralleling the rise of digital workflows such as CAD/CAM and 3D printing. In stomatology, advanced materials now support not only structural restoration but also tissue interaction, disease prevention, and regenerative functions, shifting the discipline from passive replacement to biologically active and minimally invasive care. The time evolution of materials used in dental applications has been a shift from natural and metal—based materials toward adhesive, aesthetic, and bioactive systems. The advancement of materials for stomatology has fundamentally transformed dental practice, shifting it from purely mechanical replacement of lost tooth structure toward aesthetic, biomimetic, and biologically integrated care. Modern materials—such as zirconia, hybrid ceramics, fiber—reinforced polymers, bioactive agents, and smart biomaterials—do not only improve strength and durability; they actively support tissue remineralization, antimicrobial protection, and stress distribution that better mimic natural dentition. The present comprehensive review explores the diverse materials used in dental science, emphasizing their pivotal role in dental applications.

Keywords: dental materials— zirconia, hybrid ceramics, fiber—reinforced polymers, bioactive agents, and smart biomaterials—, evolution & advancement

INTRODUCTORY NOTES

Dental materials play a role in multiple areas of dental science, such as restorative dentistry, prosthodontics, orthodontics, endodontics, and others.[1-5,17-18] Dental materials are specialized substances—metals, ceramics, polymers, and composites—used to restore, replace, or treat tooth structures. Key types include composite resin (tooth—coloured fillings), amalgam (durable silver—coloured metal), porcelain/ceramics (natural—looking crowns), and titanium (dental implants).[1-5] These materials are selected due to their particular attributes and uses, their selection being influenced by aspects such as the particular dental treatment, the requirements of the patient, the dentist's inclinations regarding appearance or durability, and the advancements in dental materials.

Dental science progresses continuously, and innovative materials are created to enhance patient results and contentment. [6-11,17-30] In this context, the evolution of materials science is an extensive and intricate process that stretches over thousands of years.[6-11] It has transformed from basic understanding of materials needed for survival and housing into a highly advanced discipline with major technological and scientific consequences. [17-30]

The domain of dentistry has experienced a significant transformation in the materials employed for dental treatment, following a journey from the basic options of earlier times to the advanced materials utilized now.[6-11] Historically, dental materials were frequently restricted to naturally sourced or easily made substances, such as different metals for fillings and basic ceramics for prosthetics.[11-16] Throughout the years, these substances have transformed notably, influenced by progress in chemistry, materials science, and healthcare technology. Currently, the variety of materials utilized in dentistry encompasses intricate composites, biocompatible polymers, ceramics improved at the molecular level, and nanomaterials engineered for durability and appearance. Contemporary dentistry provides sophisticated choices regarding the various types of dental implant materials.[17-30] Titanium, zirconia, titanium alloys, ceramic composites, polymer—based implants, and hydroxyapatite—coated implants all fulfill distinct functions in the success of implants.[31-46]

The evolution of dental materials has moved from simple, natural elements to sophisticated biomaterials designed to mimic, protect, and even regenerate oral tissues. In ancient times, gold, ivory, bone, and shells were used to replace or

stabilize teeth, prioritizing durability and appearance over biological compatibility.[10,12-14,26] By the 18th and 19th centuries, porcelain teeth, amalgam, and vulcanite rubber laid the foundation for standardized restorative and prosthetic dentistry.[11,17-20]

Figure 1. Materials used in dentistry (for natural—looking crowns)

Figure 2. Materials used in dentistry (for dental implants)

In the 20th century, the arrival of composites, glass ionomers, and early ceramics introduced aesthetic, adhesive, and preventive–oriented materials, gradually shifting dentistry away from metal–dominated solutions. The late 20th and early 21st centuries brought zirconia, hybrid ceramics, fibre–reinforced polymers, and CAD/CAM technologies, enabling strong, metal–free, and digitally fabricated restorations.[16,29,33-35,38,41] Today, bioactive and smart biomaterials complete this evolution by interacting with the oral environment–releasing ions, inhibiting bacteria, and supporting tissue repair–so that modern stomatology is no longer based merely on replacement, but on functionally integrated and biologically responsive care.[7,25,38,42,45,46]

Therefore, each era added a key technical leap–porcelain and amalgam, polymers and composites, zirconia and ceramics, bioactive and smart systems–so that modern stomatology now uses materials that are stronger, aesthetic, adhesive, bioactive, and digitally compatible, turning dental treatment from simple replacement into a precision, biologically tuned discipline. Earliest prosthetic and restorative solutions was based on availability and craftsmanship rather than scientific material design. Main innovations makes that stomatology moves from passive replacement to biologically active, digitally integrated, and regenerative–oriented care, with materials that support not only structure but also prevention and repair.[25,27,37,39,42,45]

Biocompatibility in dentistry has evolved from the relatively passive, inert compatibility of ancient gold to the active, tissue–supporting behaviour of modern bioactive and smart materials.[9,13,14,45] The shift is not only about tolerating the material in the mouth, but about how the material interacts with the tooth, pulp, bone, and oral environment. The evolution of biocompatibility has moved from passive non–toxicity (gold and early metals), through tolerance with some irritation (amalgam, early resins), to active support of tissue metabolism and regeneration (bioactive cements, smart materials). In practical terms, modern bioactive materials no longer just sit in the mouth; they participate in the biological environment by helping to seal and protect the tooth and surrounding tissues, which is a much higher level of biocompatibility than what simple gold–based systems could ever provide.

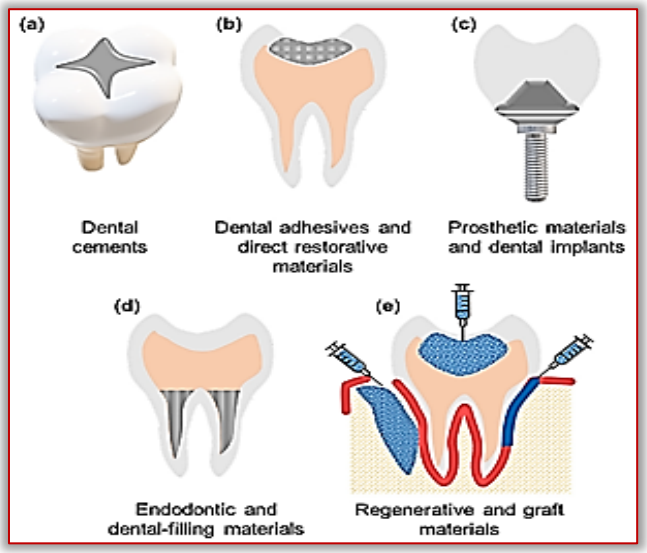

Figure 3. Biocompatibility in dentistry

Economic factors have strongly shaped the evolution of dental materials, determining which materials are developed, adopted, and scaled in clinical practice. Overall, the trajectory has moved from luxury, artisan–grade materials toward more cost–effective, industrially produced systems, yet advanced materials remain constrained by price, regulation, and market demand. Early gold–based restorations were limited to wealthier patients because of high material and labour costs while the adoption of amalgam and basic composites was

driven partly by their lower cost compared with gold, allowing wider access to restorative care. Today, zirconia, hybrid ceramics, and CAD/CAM materials are often more expensive than traditional materials, so practices adjust by reserving them for selected cases where aesthetics or durability justify the price.[26,36,40,42] The rise of mass—produced amalgam, acrylic resins, glass ionomers, and composites reduced unit cost and made them standard in general practice. In practice, economic factors mean that not all theoretically superior materials reach every patient. Gold—quality biocompatibility and zirconia—level longevity are often reserved for cases where cost is secondary to function and aesthetics.[1-5,11,19] Conversely, lower—cost but still clinically adequate materials remain dominant in public—health and budget—conscious settings.

The realm of dental materials has significantly evolved due to the emergence of advanced substances such as smart dental composites and materials enhanced with nanotechnology.[29,33] These developments have greatly expanded the range and effectiveness of dental care, offering both dentists and patient's choices that were not accessible before.[37,43] In fact, the evolution of dental materials is not just a technological story but an economic one: materials advance fastest when they balance performance, biocompatibility, manufacturability, and profitability in a global market increasingly shaped by private—health demand, digital workflows, and tightening regulation. Shortly, from gold and ivory to amalgam and acrylics, followed to composites and ceramics, and today, to zirconia, hybrid systems, and bioactive materials, with economy, biocompatibility, digital workflows, and patient demand all driving each step.

HISTORICAL PROGRESSION

Ancient and early dentistry relied on whatever materials were locally available, especially gold, ivory, bone, shells, jade, and other stones. These materials were used for tooth replacement, stabilization, fillings, and decorative or symbolic restorations rather than the highly engineered materials used today. In that sense, ancient dentistry laid the foundation for later developments in restorative and prosthetic materials.[7,11,16,20,28,34,38,40] Ancient and early dentistry relied on simple restorative materials such as ivory, animal teeth, seashells, metals, and later gold foil. Therefore, the main materials used are:

- Gold was the most important early dental material because it was malleable, durable, and corrosion—resistant, making it suitable for crowns, wires, and bridges. Gold wire was used to stabilize loose teeth and secure replacement teeth, an early form of dental splinting or bridgework.
- Ivory and bone were used to fabricate artificial teeth and replacements, especially in ancient Italy and the Mediterranean world.
- Shells and stones such as jade or turquoise were used in some ancient civilizations, including Mayan dentistry, for inlays and aesthetic restorations.
- Beeswax appears in very early evidence of dental filling, showing that even prehistoric people experimented with simple restorative materials.

Figure 4. Gold – the most important early dental material

Figure 5. Ivory and bone as artificial teeth

Early dental materials were chosen mainly for availability, workability, and symbolic value, not for the biological or mechanical precision expected today. Gold stood out because it could be shaped easily and lasted well in the mouth, while bone, ivory, and shells were useful because they could be carved into tooth—like forms. Egyptians used gold wires and ivory to stabilize loose teeth, the Mayans implanted carved seashells into jawbones while Romans experimented with iron and bronze dental replacements. These early attempts were crude and often failed due to infection or rejection, but they laid the foundation for future innovations. These early practices are important because they show the first attempts to combine function, replacement, and appearance in dentistry.

Experimentation continues in the Middle Ages & Renaissance. During this period, tooth replacement methods remained primitive, often placed these

replacements without proper sterilization, leading to complications.

In the 18th and 19th centuries, dental materials shifted from mainly handmade natural materials to more standardized restorative and prosthetic materials. This period is important because it laid the groundwork for modern restorative dentistry, when porcelain teeth, vulcanite denture bases, and early metallic restorations became common, improving function and manufacturability.[20,27] Gold was widely used in the 18th Century for fillings, wires, and denture bases because it was durable and malleable while Porcelain teeth began to appear at the end of the century, offering a more natural appearance than bone or ivory. Ivory, bone, and human or animal teeth were still used for dentures and artificial teeth.[1-3,7,41] Dentistry at this stage was still highly artisanal, with materials shaped individually by hand. In the 19th century Porcelain teeth became more common and commercially produced while Gold foil remained an important filling material because of its long service life and adaptability. In this period the Amalgam emerged in the early 1800s and became popular because it was cheaper and easier to place than gold. Therefore, the 18th century was dominated by gold, porcelain beginnings, ivory, and bone, while the 19th Century brought porcelain expansion, amalgam, and vulcanite. This evolution marks the transition from elite, custom—made dental substitutes to more practical and widely available restorative materials.[1-3,7,20,27,41]

Figure 6. Dental substitutes for restorative materials

In the late 19th and early 20th centuries, dental materials were transitioning from handcrafted, partly improvised solutions to more standardized clinical and industrial materials. This era is especially important because it introduced the first truly modern restorative and prosthetic materials that shaped 20th—century dentistry. In this period, amalgam became the dominant posterior restorative material because it was cheaper and easier to use than gold, making restorative treatment more accessible while Gold remained a premium restorative material for fillings and crowns because it was durable, workable, and well tolerated in the mouth. Also, porcelain was used more widely for artificial teeth and denture work, especially in combination with gold or metal bases. This period saw the shift from highly artisanal dentistry to more reproducible restorative care. Fillings were no longer dominated only by gold foil, and denture materials became more practical, cheaper, and easier to fabricate on a larger scale. The early 20th century also began to see the first implant materials and more experimental use of metals in oral rehabilitation. The key change was from craft—based materials to industrial and clinically scalable materials.

The mid—20th century was a turning point in dental materials because dentistry moved from mostly metallic and handmade solutions toward modern restorative systems.[29,31,33,36] The biggest changes were the widespread use of amalgam, the introduction of acrylic resins, the first composite resins, and the rise of elastomeric impression materials.[22,32,35,41] The mid—20th century introduced acrylic resins, stainless steel, casting alloys, and impression materials that expanded prosthodontic and restorative options. Dental amalgam became the standard filling material in the 1950s because it was strong, durable, and inexpensive while Acrylic resins expanded denture and appliance fabrication, making prostheses more natural—looking and easier to process. The biggest breakthrough came when is accidentally discovered the osseointegration—the process where bone fuses with titanium, when titanium implants became the standard due to their durability and biocompatibility.

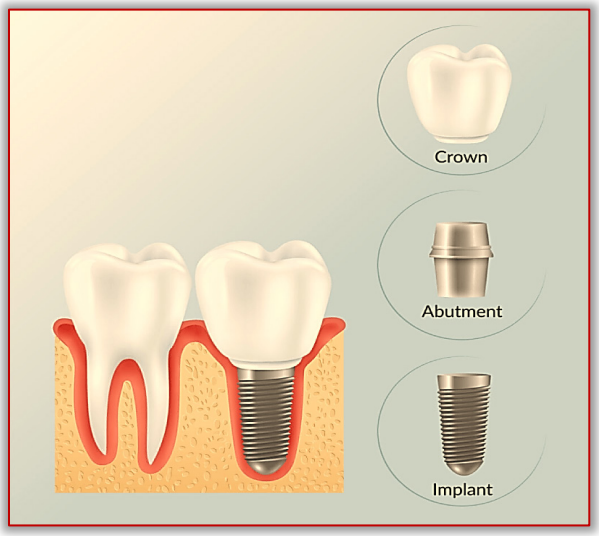

Figure 7. Titanium implants – the standard for implantology

From the 1960s onward, resin composites, acid etching, and glass ionomer cements changed dentistry by enabling adhesive, tooth—coloured restorations. Composite resins appeared in the 1960s, opening the door to tooth—coloured restorative dentistry. This era marks the shift from

materials chosen mainly for durability and simplicity to materials designed for function, aesthetics, and clinical precision. Amalgam still dominated posterior restorations, but composites introduced the concept of direct tooth—coloured fillings. Impression materials also improved the fit of crowns, bridges, and dentures by capturing more accurate details. The mid—20th century laid the foundation for today's restorative dentistry because it introduced the material families that later evolved into modern composites, hybrid ceramics, and adhesive systems. In practical terms, this was the period when dentistry began to look less like repair with simple substitutes and more like biomimetic reconstruction.

The modern phase of dental materials is defined by a shift toward high—performance, aesthetic, and biologically active systems that work better with digital dentistry. In practice, this means stronger ceramics, smarter composites, improved polymers, and materials designed for CAD/CAM and 3D workflows. The past few decades have focused on replacing metal with tooth—coloured materials, especially composites and reinforced ceramics.

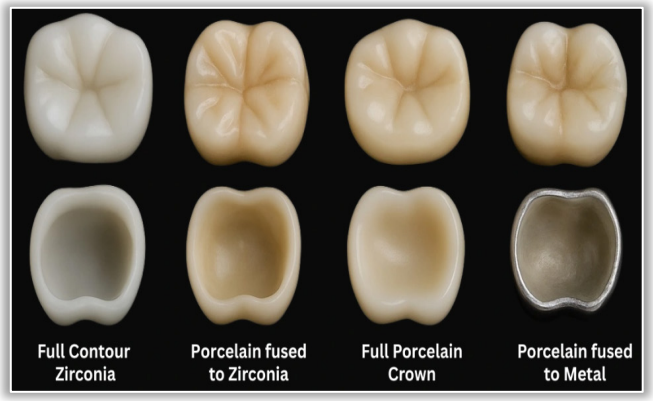

Figure 8. The four primary types of long—term dental crowns

Zirconia and other advanced ceramics now dominate many indirect restorations because they combine high strength with improved aesthetics. Zirconia became a modern benchmark for crowns, bridges, and implant restorations because newer generations combine high strength with better translucency and biocompatibility while Hybrid ceramics and resin—matrix ceramics grew because they are easier to mill, faster to process, and more forgiving in conservative restorations. Fibre—reinforced polymers expanded into long—term provisional and implant—adjacent applications thanks to better stability and stress distribution while bioactive and smart materials introduced functions like ion release, antibacterial activity, self—healing, and tissue support.[16,29,44] Digital dentistry has also accelerated the use of CAD/CAM ceramics, hybrid ceramics, and 3D—printable materials.[9,15,22,26,39,43,45]

CURRENT RESEARCH

Current research is moving toward smart biomaterials that can release ions, resist bacteria, or actively support healing. The biggest long—term trend is that dental materials have evolved from being chosen mainly for availability and durability to being selected for a balance of strength, aesthetics, adhesion, and biocompatibility. More recently, the field has moved beyond passive materials toward bioactive and digitally manufactured systems. Future dental materials beyond the 2020s are expected to become more bioactive, more digitally manufacturable, and more adaptive to the oral environment.

The future is not just about stronger materials, but about materials that do more than replace lost tissue: they may prevent infection, promote healing, or repair minor damage themselves. Digital workflows will also shape the market, so material choice will increasingly depend on compatibility with CAD/CAM and additive manufacturing rather than only on classical mechanical properties. In practical terms, dentistry is moving toward a mix of:

- high—strength ceramics for load—bearing restorations,
- hybrid/resin—based materials for speed and flexibility,
- bioactive systems for biological performance, and
- smart nanostructured materials for long—term function.

Advancement in materials for stomatology is moving toward smarter, stronger, and more bioactive systems that improve durability, aesthetics, and clinical performance. The main trends now are advanced zirconia, hybrid ceramics, fiber—reinforced polymers, smart/antibacterial biomaterials, and 3D—printable materials for faster digital workflows. Main material trends are:

- ZIRCONIA has become more translucent while keeping high strength, so it is used more widely for crowns and restorations that need both appearance and toughness. Advanced zirconia will likely remain important, but with better translucency, multilayer shading, and improved machinability for highly aesthetic restorations.
- HYBRID CERAMICS and RESIN—CERAMIC MATERIALS are growing in chair side dentistry because they are easier and faster to mill and do not require sintering. Hybrid ceramics and high—performance polymers will continue growing for chair side and implant—adjacent applications because they balance aesthetics, resilience, and processing speed.
- FIBER—REINFORCED POLYMERS are gaining importance for long—term provisional and implant—adjacent applications because they combine stability with lighter weight.
- NANOMATERIALS will be used more often to reinforce composites, improve wear resistance,

and add antibacterial or remineralizing functions.

- BIOACTIVE MATERIALS such as ion—releasing glasses and ceramics are being designed to support tissue integration and sometimes provide antibacterial effects, which is especially useful in restorative and implant dentistry.
- SMART BIOMATERIALS are a newer direction, including self—healing composites, antibacterial nanoparticles, and shape—memory or responsive materials that can improve longevity and reduce failures. Smart biomaterials will expand, including self—healing composites, antimicrobial surfaces, and materials that respond to pH, moisture, or bacterial activity.
- SUSTAINABLE MATERIALS will gain attention, with more interest in recyclable, lower—waste, and eco—friendlier dental products.

What this means clinically? These advances are making restorations more personalized and more durable, while also reducing treatment time through CAD/CAM and 3D printing workflows. In practice, that means a dentist can increasingly choose materials based on the balance of strength, esthetics, and biological interaction rather than relying only on traditional metal, acrylic, or conventional ceramic systems. As example, a modern crown might now be made from high—translucency zirconia for posterior strength, or from a hybrid ceramic for a faster chair side restoration, depending on the clinical case. For implant surfaces or endodontic sealers, researchers are also adding bioactive or antimicrobial components to improve healing and reduce bacterial colonization.

The next step in stomatology materials is likely the combination of digital manufacturing and functional biology, meaning materials that are not only printable or millable, but also actively help prevent infection, promote osseointegration, or repair minor damage themselves. That is where the field is moving now, especially in restorative dentistry, endodontic, and implantology. 3D printing and hybrid manufacturing will become more central, especially for provisional restorations, guides, splints, and increasingly some definitive applications.

EXPANDING THE TECHNICAL AND BIOLOGICAL POSSIBILITIES IN STOMATOLOGY

From gold—wire bridges and ivory teeth to zirconia crowns and bioactive/smart materials, the evolution of dental materials has continuously expanded the technical and biological possibilities in stomatology. Each material wave has enabled new types of conservative, aesthetic, implant—based, and regenerative treatments, turning modern dentistry into a field where materials actively participate in health rather than just passively replacing lost tissue.

- ZIRCONIA's time evolution in dentistry is a move from a framework ceramic to a versatile, high—performance restorative material used in crowns, bridges, implant parts, and monolithic restorations.

Zirconia became successful because it offered something dentistry needed for decades: metal—like strength without a metal framework. Its transformation toughening mechanism gave it crack resistance, and its biocompatibility made it suitable for oral use. As esthetic demand increased, newer translucent grades made it useful not only in posterior teeth but also in visible anterior restorations.

Zirconia was first explored scientifically in the late 1960s and early 1970s, when researchers identified its stabilized crystal behavior and transformation toughening potential. Early dental use focused on zirconia—containing systems such as In—Ceram Zirconia, where it served mainly as a strong substructure material for posterior restorations. In the 1990s and early 2000s, zirconia entered dentistry more broadly as researchers and clinicians recognized its combination of strength, toughness, and biocompatibility.

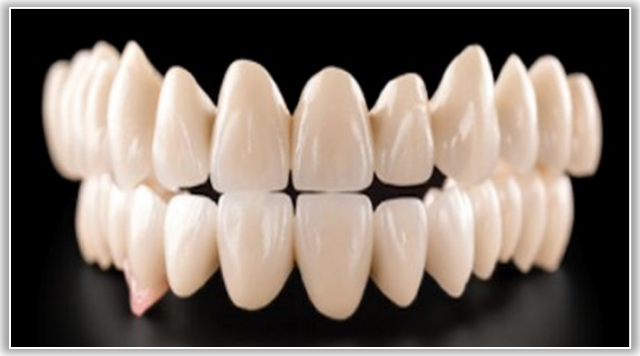

Figure 9. Dental zirconia

CAD/CAM technology then accelerated its adoption by making it possible to mill precise custom restorations. The first generations were mainly opaque and used with veneering porcelain, but chipping problems pushed the development of more translucent and multilayer shading, monolithic zirconias. Modern zirconia have higher optical quality, broader clinical use.[17,18,21,22,37]

Today zirconia is one of the most important materials in restorative and prosthetic dentistry, especially for single crowns, bridges, implant abutments, and increasingly monolithic restorations. The trend has moved from "strong but opaque" to "strong, more translucent, and digitally manufacturable". That is why zirconia is often seen as one of the clearest examples of the evolution of modern dental materials.

- HYBRID CERAMICS and RESIN—CERAMIC MATERIALS are a relatively new branch of dental materials that emerged to bridge the gap between brittle ceramics and more flexible resin—based systems.

Their evolution has been driven by the need for restorations that are easier to mill, less brittle, and more biomimetic in elastic behavior. The time evolution can be synthetized as follow:

- Early ceramic era: Dentistry first relied on feldspathic and glass ceramics for aesthetics, but these materials were brittle and required careful case selection.
- Shift toward reinforced ceramics: Stronger ceramics such as lithium disilicate improved fracture resistance, but they still remained ceramics at core, with limited shock absorption.
- Hybrid concept appears: Hybrid ceramics and resin–matrix ceramics were developed by combining a ceramic network with a polymer phase, or by embedding nano–ceramic fillers in a resin matrix.
- CAD/CAM adoption: Their biggest clinical growth came with digital dentistry, because they can be milled efficiently, often without sintering or crystallization firing, which shortens workflow.
- Current phase: Newer resin–ceramic systems are now being designed for better wear resistance, better marginal sealing, easier repair, and improved compatibility with minimally invasive restorations.

Early use was mostly for conservative indirect restorations such as inlays, onlays, veneers, and single crowns, especially where thin restorations were desirable. As material processing improved, their indications expanded into implant–supported crowns, provisional–to–permanent workflows, and more esthetic CAD/CAM restorations. Current research is focused on making them stronger, more wear resistant, and more biologically active, including potential antimicrobial or remineralizing functions.[7,10,12,25,27,30,42]

Figure 10. Hybrid ceramics and resin—ceramic materials

Hybrid ceramics were introduced to solve three common problems in restorative dentistry: ceramic brittleness, the need for large tooth reduction, and long manufacturing times. Their elastic modulus is closer to dentin, so they can distribute occlusal stress more evenly and may reduce crack formation at margins. They also tend to be gentler to opposing dentition and easier to repair intraorally than many pure ceramics.

The overall evolution is from ceramic–dominant brittleness toward hybrid materials that better imitate tooth behaviour. In practical terms, hybrid ceramics and resin–ceramics have become important because they combine aesthetics, speed, and easier repair with enough strength for many everyday restorative cases.[15,19,29,36,38]

- FIBER–REINFORCED POLYMERS in dentistry have evolved from experimental reinforcement materials into practical options for prosthodontics, restorative dentistry, endodontics, orthodontics, and denture repair.

Fiber reinforcement was introduced to solve a key problem in dentistry: polymer materials were easy to process and esthetic, but often too weak or fracture–prone on their own. Fibers help by stopping crack growth, spreading stress, and improving flexural performance when they are well bonded to the resin matrix. Time evolution can be described as follow:

- In the 1960s, early dental research used glass fibers to reinforce PMMA denture bases and reduce fracture risk.
- In the 1970s, carbon and graphite fibers were tried in acrylic resins and composite systems, but their dark color limited esthetic use.
- In the 1980s and early 1990s, aramid and then silane–treated glass fibers improved strength and made esthetic clinical use more realistic.
- By the 2000s, fiber–reinforced composites became established in removable prosthodontics, fixed partial restorations, root canal posts, splints, and repairs.
- In the 2010s to now, CAD/CAM and prefabricated FRC systems expanded their clinical predictability, while research moved toward nanofibers and improved fiber–matrix design.

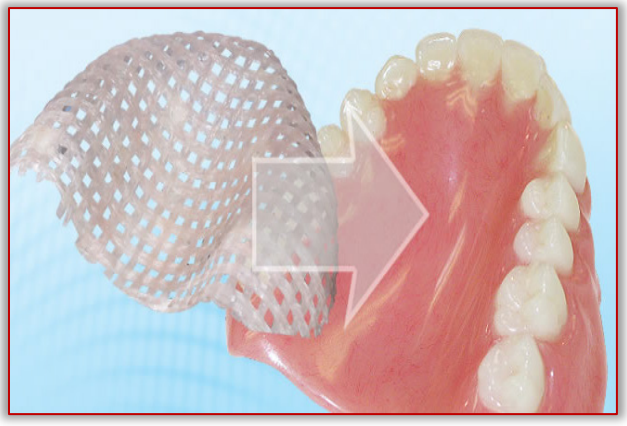

Figure 11. Fiber—reinforced polymers in dentistry

Modern fiber–reinforced polymers are being optimized by changing fiber type, loading, aspect ratio, and interfacial bonding so they can approach

the mechanical behavior needed for more demanding dental applications. The trend is toward lighter, more esthetic, repairable, metal–free systems that still offer useful toughness and fatigue resistance.

The evolution of fiber–reinforced polymers in dentistry has been from simple denture reinforcement to highly engineered composite systems used across several branches of dentistry. Their main value today is combining polymer processing advantages with improved mechanical performance, especially where metal–free design is desirable.

- BIOACTIVE MATERIALS in dentistry have evolved from simple protective or sealing agents into materials that actively interact with tooth and tissue biology.

Their development marks a shift from passive restoration to functional restoration, with emphasis on remineralization, antibacterial action, and tissue repair.[10,24,25,30] Time evolution can be described as follow:

— The earliest bioactive behavior in dentistry can be traced to calcium hydroxide, introduced in the 1920s for pulp capping and dentin bridge formation.
— In the early 1990s, mineral trioxide aggregate (MTA) became a major step forward in endodontics and repair dentistry because of its sealing ability and biologic response.
— Later, bioactive glass–ionomer and calcium silicate–based materials expanded the concept into restorative dentistry, where ion release could support remineralization and reduce secondary caries.
— In the 2010s and 2020s, nanotechnology and hybrid formulations improved antimicrobial activity, mechanical performance, and handling.
— Current research focuses on materials that not only release ions but also respond to the oral environment and support regeneration more predictably.

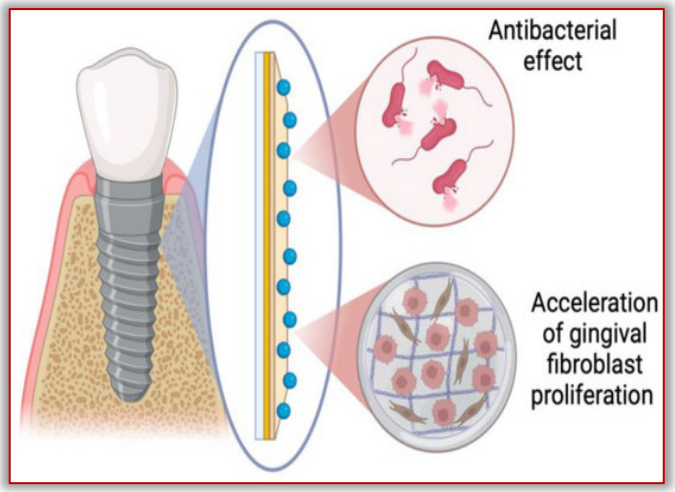

Figure 12. Bioactive materials in dentistry

Bioactive materials first became important in endodontics and pulp therapy, then moved into liners, bases, and restorative materials. Today they are also used in preventive and regenerative dentistry because they can interact with the tooth structure instead of remaining inert. This makes them especially valuable in minimally invasive dentistry, where preserving and strengthening remaining tooth tissue is the goal.

As overall trend, the evolution of bioactive dental materials is really a move from sealing and replacing toward repairing and stimulating biology. The next generation is likely to combine ion release, antibacterial function, and better mechanical properties in one material.

- SMART BIOMATERIALS in dentistry have evolved from early responsive materials into sophisticated systems that can sense and react to the oral environment.

The trend is moving from passive restoration toward materials that adapt, protect, and sometimes even help regenerate tissues. Intelligent biomaterials in restorative dentistry are designed to sense and react to various physiological and environmental triggers, such as mechanical pressure, pH variations, and temperature alterations. In contrast to traditional inert restorative materials, these advanced systems combine diagnostic and therapeutic roles within clinical practice.[26,28,40]

Time evolution can be structured as follow:

— In the 1980s, smart materials began entering dentistry through shape–memory alloys, especially nickel–titanium alloys, which changed orthodontics and endodontics.
— In the 1990s and 2000s, glass ionomer–based systems and resin–modified formulations became important because they could interact more favourably with tooth structure.
— In the 2010s, researchers expanded smart concepts into self–healing composites, smart ceramics, and implant coatings with antibacterial or osseointegration–promoting behaviour.
— In the 2020s, the field shifted toward multi–stimulus systems that respond to pH, stress, temperature, light, or magnetic/electrical cues. The newest direction is integration with 4D printing, where the material changes over time after placement.

Smart biomaterials are valuable because they do more than fill space; they can improve longevity, reduce failure, and support minimally invasive dentistry. In restorative dentistry, they are being developed to detect acid attack, release protective agents, and resist bacterial colonization. In orthodontics and endodontics, shape–memory and stress–responsive behavior can make treatment more efficient and predictable.

The latest research is focused on combining several smart functions in one material, such as antibacterial activity plus remineralization plus stress response. Another major trend is pairing smart biomaterials with digital workflows, especially 3D and 4D printing, to create restorations that are more customized and time–responsive. This suggests future dental materials will be increasingly adaptive, not just durable.

CLINICAL CHALLENGES AND FAILURE RATES OF ADVANCED DENTAL MATERIALS

Advanced dental materials have improved a lot, but their failures are still driven by a mix of material limits, technique sensitivity, and oral environment. Advanced dental materials (zirconia, hybrid ceramics, fibre–reinforced polymers, bioactive and smart materials) have greatly improved aesthetics, strength, and biological performance, but they still fail in predictable ways because clinical conditions, technique, and design do not fully match laboratory expectations. Why failures happen? Clinical failure is rarely caused by one factor alone. The oral environment is harsh, with moisture, temperature changes, acid attacks, chewing forces, and biofilm all acting together. Material performance also depends on how well laboratory properties translate to real clinical conditions, and that link is still imperfect for many new products.

The most common problems are secondary caries, fracture, wear, debonding, and marginal breakdown, and these issues remain important across composites, ceramics, and other modern restorative systems. Therefore, the main clinical challenges can be enounced as follow:

- Secondary caries and marginal breakdown remains one of the most frequent reasons restorations are replaced, especially for resin–based materials that are more prone to biofilm accumulation at margins. Even with advanced composites and ceramics, poor isolation, contamination, or inadequate bonding lead to microleakage and recurrent decay, especially around fillings and crown margins.
- Fracture and chipping are major concerns for brittle materials such as ceramics, because clinical forces, flaws created during fabrication, and mouth conditions can initiate cracks. Brittle materials like zirconia and some ceramics, or thin hybrid–ceramic restorations, can fail under high stress, poor design, or fabrication flaws
- Wear and degradation affect composites, hybrid ceramics, and polymer–based materials over time, reducing anatomy, surface quality, and fit. Resin–based materials, hybrid ceramics, and polymers lose anatomy and surface quality over time, especially under heavy occlusion or corrosive oral conditions.
- Bonding failures happen when adhesion is compromised by contamination, poor isolation, curing problems, or unfavourable tooth/ restoration geometry. Many advanced restorations rely on strong adhesion; if bonding technique is suboptimal, margins open and the restoration fails.
- Technique sensitivity is still a major issue for many advanced materials; even good materials can fail if placement, light curing, or finishing is suboptimal.

Newer materials have reduced some classic problems seen in early generations, especially with composites and ceramics. Better filler systems, improved ceramic processing, more reliable bonding protocols, and smarter digital workflows have all helped lower failure risk. Even so, the field still needs more long–term data that connects laboratory testing with real clinical survival. Advanced dental materials are more capable than older materials, but they are also often more demanding clinically. Their success depends not only on the material itself, but on case selection, isolation, bonding, preparation design, and maintenance over time. In practice, the best material is usually the one whose properties match the clinical situation and whose failure risks are easiest to control.

Failures of advanced materials rarely stem from the material alone; they usually result from mismatch between material properties and clinical conditions, plus limitations in technique or design. The key is to select materials whose strengths match the case (occlusion, span, thickness, and biofilm risk) and to respect the technical requirements (bonding, preparation, curing, and maintenance) rather than treating them as “magic” solutions.

CONCLUSIONS

Overall, the advancement of materials for stomatology has moved from passive, durable, but biologically limited materials toward aesthetic, adhesive, bioactive, and digitally manufacturable systems. The major direction is no longer just replacement of lost tooth structure, but restoration that better matches tooth biology, function, and long–term patient needs.

These material advances directly drive innovation in dental applications because they enable:

- More conservative and minimally invasive techniques (less aggressive tooth preparation, inlay–onlay and ultra–thin crowns),
- Wider use of adhesive dentistry, thanks to improved resins, cements, and bioactive interfaces,
- Digital and CAD/CAM–driven workflows, since materials like zirconia, hybrid ceramics, and resin–ceramics are designed for milling and 3D printing,

— Regenerative and preventive strategies, where materials can release ions, resist caries, and support pulp/dentin responses instead of only passively shielding the tissue.

In essence, the evolution of materials is not an isolated "lab" topic; it is the material basis for almost all modern innovations in restorative dentistry, prosthetics, implantology, and endodontic. Better materials allow clinicians to treat more complex cases predictably, reduce invasiveness, and extend the service life of restorations, turning stomatology into a more patient–centred, biologically aware, and digitally enabled discipline. As general remarks, we can conclude that:

— Early dental materials were chosen mainly for availability and strength, such as amalgam, gold, and simple ceramics. Earlier eras focused mainly on durability and replacement, but the modern phase adds precision, aesthetics, and biological interaction.

— The modern phase of dental materials is not just about making restorations last longer. It is about creating materials that are stronger, easier to process, more natural–looking, and increasingly able to interact positively with oral tissues. Modern materials increasingly combine strength with aesthetics, with composites, zirconia, hybrid ceramics, and fibre–reinforced polymers now widely used in restorative and prosthetic dentistry.

— Bioactive and smart materials represent the next stage because they can interact with the oral environment, release ions, resist bacteria, and sometimes respond to stimuli.

— Digital manufacturing has also changed how these materials are used, since CAD/CAM and 3D printing now shape both the material choice and the restoration design. This has made dentistry more conservative, faster, and more personalized. Digital dentistry and nanotechnology have accelerated this progress by improving precision, processing speed, and material performance.

What this means clinically? The practical result is that clinicians now have more material choices for each case, allowing treatment to be tailored to load, aesthetics, adhesion, biocompatibility, and reparability. Zirconia has become a benchmark for strength, hybrid ceramics offer a balance of flexibility and aesthetics, fibre–reinforced polymers provide stress distribution and repair advantages, and bioactive/smart materials add a biological dimension that older materials lacked. The modern phase of dental materials is not just about making restorations last longer. It is about creating materials that are stronger, easier to process, more natural–looking, and increasingly able to interact positively with oral tissues. Today, the strongest long–term trend is the movement toward personalized, minimally invasive, and regenerative dentistry rather than simple substitution of missing tissue.

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