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Biodegradable materials in dentistry: A comprehensive review of current trends

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Abstract

The dental industry has witnessed a paradigm shift towards biodegradable materials, driven by the need for sustainable and environmentally friendly solutions. Biodegradable materials in dentistry offer a promising alternative to traditional non-degradable materials, providing many benefits for patients, clinicians, and the environment. However, challenges persist, including limited durability and standardized regulations. This review article explores the current state of biodegradable materials in dentistry, including their applications, advantages, and limitations. Further, this article discussed the use of biodegradable materials in dental implants, restoratives, and temporary devices, as well as their potential for tissue engineering and regenerative dentistry. Additionally, the discussion covered the clinical significance, emphasizing the possibility of biodegradable materials transforming dental procedures and reducing their environmental footprint. As the field continues to evolve, biodegradable materials are poised to play a vital role in shaping the future of sustainable dentistry.

Keywords: Bioceramics, Biodegradable materials, Biodegradable polymers, Durability.

1. Introduction

Biodegradation is the natural process by which microorganisms, such as bacteria and fungi, break down organic matter [1]. Unlike composting, it occurs spontaneously. Biodegradable materials have significantly impacted various fields due to their versatility. In medicine, they have enhanced patient outcomes and minimized complications. The packaging industry has adopted biodegradable materials to reduce plastic waste, while agriculture has benefited from increased crop yields and decreased waste [2]. The textiles and construction sectors have also embraced biodegradable materials for sustainable practices. Additionally, biodegradable materials have optimized drug delivery systems in pharmaceuticals and reduced packaging waste in the food industry [3]. As research progresses, the potential for biodegradable materials to revolutionize industries and promote sustainability is immense and promising.

Dentistry increasingly embraces biodegradable materials due to their numerous advantages, including reduced environmental impact, improved biocompatibility, enhanced patient comfort, fewer follow-up procedures, and decreased need for secondary surgeries [4,5]. These benefits make biodegradable materials increasingly valuable in the field of dentistry.

The biodegradation process consists of four stages: biodeterioration, biofragmentation, assimilation, and mineralization [1]. Biodegradable materials are eventually decomposed into water and carbon dioxide under aerobic conditions or methane under anaerobic conditions through hydrolysis, enzymatic degradation, and chemical catalysis [6].

2. Classification of biodegradable materials

Biodegradable materials are briefly classified as described in Figure 1.

2.1 Biodegradable polymers

Biodegradable polymers are materials that can be broken down by living organisms, primarily microorganisms, into simpler substances like water, carbon dioxide, biomass, and inorganic compounds [7]. This process is known as biodegradation. Microorganisms use enzymes to decompose the polymer structure [8]. Biodegradable polymers can be classified based on their source, the products they break down into, and their specific uses (Tables 1 and 2).

2.2 Bioceramics

Bioceramics are specialized ceramic materials developed for medical and dental use. Their unique combination of biocompatibility, bioactivity, and mechanical strength makes them ideal for various applications. Common bioceramic materials include hydroxyapatite, calcium phosphate cements, bioactive glass, zirconia, and calcium silicate-based cements like MTA.

Different areas of interest in bioceramic materials are given in Table 3.

2.3 Biodegradable composites

Biodegradable composites are materials composed of a matrix, often made from polymers, and a reinforcing agent, such as natural fibres [10]. Biodegradable composites can be used in a variety of industries, including industrial, medicinal, and energy applications. Some examples of biodegradable composites include bio-nanocomposite polymers, vegetable fibre composites and Flax fiber-reinforced composites. Table 4 outlines the various applications of biocomposites. Figure 3 illustrates the different properties of biocomposites [11]. The following fibres are reviewed as they are most used in the industry for biodegradable composites; Flax fibres, Kenaf fibres, Hemp fibres, and Jute fibres [12].

2.3.1 Materials based on extracellular matrix: These materials are widely used for tissue engineering and regenerative medicine. Nano-fibre scaffolds based on ECM for articular cartilage regeneration are one of the promising applications of this material [7].

2.3.2 Biodegradable metals: The three main types of biodegradable metals are magnesium-based alloys, iron-based alloys, and zinc-based alloys. Magnesium-based alloys have been studied the most in vitro, in vivo, and clinically, while iron-based alloys are still in animal testing [13]. They are used in dentistry for temporary support, bone growth stimulation, and reimplanted teeth. Regarding the possible uses of Zn-based alloys, recent research shows that cardiovascular applications prevail [14].

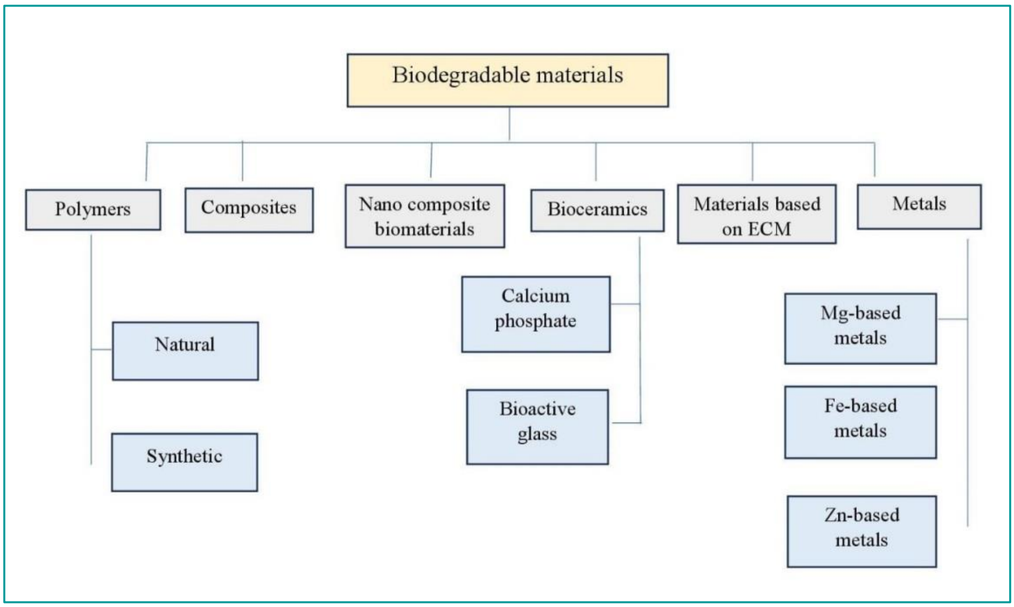

Figure 1. Classification of biodegradable materials.

Table 1.Classification of Biodegradable Polymers

Name of Polymer	Source	Mechanism of degradation	Degradation products	Uses
Polylactic acid (PLA)	Corn starch Sugarcane	Hydrolytic Degradation Microbial Degradation	Lactic acid	GTR membranes Resorbable sutures Bone screws
Poly glycolic acid (PGA)	Sugar cane sugar beet	Hydrolytic Degradation Microbial Degradation Auto catalysis	Glycolic acid	Resorbable sutures Tissue scaffolds Composite materials
Polylactic-co-Glycolic Acid (PLGA)	Unripe grapes and sugar beets.	Hydrolytic Degradation Microbial Degradation	Lactic acid and glycolic acid	Drug delivery systems and resorbable sutures
Polycaprolactone (PCL)	Ring-Opening Polymerization	Hydrolytic Degradation	Hydroxycaproic acid	Long-term drug delivery systems and tissue engineering scaffolds
Polyhydroxyalkanoates (PHA)	Bacterial Production (*Ralstoniaeutropha*, *Cupriavidusnecator)* Sugars, Vegetable oils, and waste materials	Microbial Degradation	Water and carbon dioxide	Bone grafts and as scaffolds for tissue engineering
Polydioxanone (PDO)	Ring-opening polymerization of p-dioxanone, a cyclic monomer	Hydrolytic Degradation Microbial Degradation Autocatalysis	P-dioxanone	Sutures

Table 2. Classification of Natural Polymers

Name of polymer	Source	Uses
Collagen	Animal tissues	GTR membranes, bone grafts, and as a matrix for cell growth
Chitosan	Exoskeleton of crustaceans	Wound dressings, periodontal therapy, and drug delivery systems
Alginate	Brown seaweed	Impression materials, wound dressings, and as a scaffold for tissue engineering
Hyaluronic Acid (HA)	Extracellular matrix of connective tissues	Periodontal therapy, tissue regeneration, mouthwashes and gels
Gelatin	Collagen	Drug delivery systems, scaffolds for tissue engineering, and wound dressings
Cellulose	Plant cell walls	Dental materials like fillers, adhesives, and impression materials

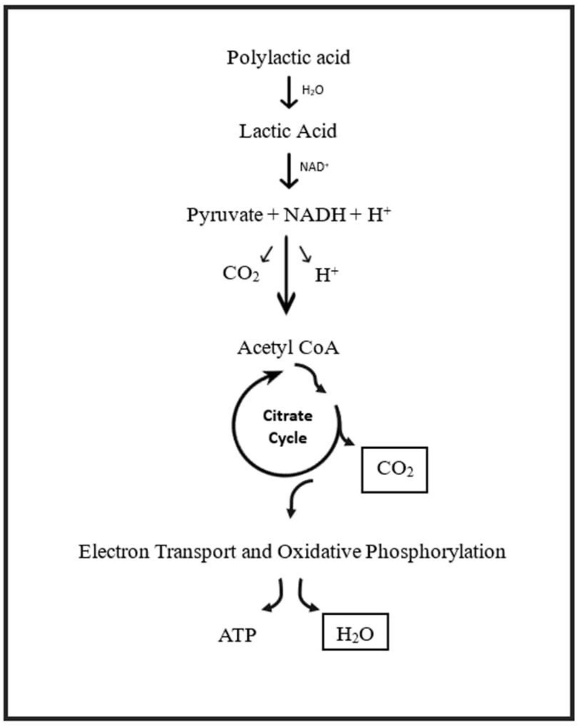

Figure 2. Mechanism of degradation of Polylactic acid

Table 3: Role of bioceramic material in different branches

Area of interest	Bioceramics role
Dental implants	Enhance osseointegration and reduce the risk of rejection
Bone grafting	Bone regeneration and tissue engineering
Dental restoratives	Crowns, bridges, and dentures
Tissue engineering	Support the growth of new tissue and promote regeneration
Orthodontic brackets	Aesthetic and biocompatible alternative to traditional metal brackets
Dental cements	Luting and restorative procedures
Tooth whitening	Whitening toothpaste and mouthwashes
Dental membranes	Guided tissue regeneration
Maxillofacial reconstruction	Reconstruct facial defects and trauma
Periodontal treatment	Periodontal regeneration and tissue repair

Figure 3. Properties of bio-composites

Table 4. Advantages of different biocomposites [10]

Material	Advantages
PLA composite materials	Moulded in any shape, 3D printing applications
Starch-based composites	Renewable, biodegradable, inexpensive, and abundantly available
Nanocomposites	Biocompatible, nontoxic, and biologically active toward microbial growth, while also providing physical protection
Polyglycolide	Can be completely degraded in the human body without the need for special enzymes

Table 5. Various manufacturers of different biodegradable materials

Biodegradable products	Companies
Sutures	Ethicon, Medtronic, Deme TECH, Hu-Friedy, B. Braun
Mini implants	Inion, Biomatlante, Polyganics, SonicWeld Rx®
Dental Teeth and Denture base Material	Evonik Industries, GC Corporation, 3M Oral Care.
Aligners	Smile Direct Club, Smilelign, Sustain Align, Biome Align.
Biocomposites	Straumann group, Dentsply sirona, Zimmer biometdental, Botiss biomaterials, Collagen matrix Inc
Miniplates	GrandFix®, SonicWeldRx®, LactoSorb®, RapidSorb®, FIXORB-MX®, SuperFIXORB MX® (OsteotransMX®)

3. Application of biodegradable materials in different fields of dentistry

3.1 Biodegradable or bioresorbable mini-implants

Magnesium, iron, zinc, and their alloys are the leading biodegradable metals for implant applications. Compared to calcium and strontium, these metals offer superior stability, lasting for 9-12 months before complete degradation without leaving harmful residues or causing significant adverse reactions [13].

Recent studies on resorbable implants demonstrate that they are frequently enveloped by bony tissue, occasionally with a thin fibrous layer. Mg-Ca alloys specifically degrade within three months following bone formation [14,15]. To mitigate magnesium alloy degradation, the application of protective coatings, such as calcium phosphate, fluorinated materials, or polymers, is a viable strategy. By adjusting the PLA/PGA ratio, the degradation rate, excretion, and biomechanical properties of the implants can be effectively modulated [16]. A comprehensive list of manufacturers specializing in mini-implants is provided in Table 5.

3.2 Biodegradable aligners

In addition to conventional BPA-free and recyclable aligner materials, innovative compostable and fully biodegradable options, such as GT FLEX, are emerging. These materials are engineered to offer superior flexibility and strength compared to traditional commercial aligners (Table 5). GT FLEX is available in three distinct formulations—Original, Pro, and Max—with thicknesses ranging from 0.6 to 1.0 millimetre [17].

3.3 Biodegradable Material for dental teeth and denture base material

Historically, PMMA has been the main material utilized for both denture bases and teeth. However, its limitations, including susceptibility to staining, noise during mastication, low impact strength, limited shelf life, and inconsistent performance, have prompted research into alternative materials [18].

Various reinforcements have been investigated to improve the mechanical characteristics and longevity of PMMA. These include glass fibres, saline glass fibres, polypropylene, and vegetable fibres [19] as shown in table 6. By incorporating these materials into the PMMA matrix and evaluating their impact on tensile strength, impact strength, compressive strength, and microhardness, researchers aim to develop denture bases that are more resilient and comfortable for patients.

3.4 Biodegradable suture

Sutures are part of the everyday practice of surgery. Biodegradable sutures are used to close wounds and can be tailored to degrade at a rate that matches the healing process of the tissue. They promote healing, deliver drugs and in treating wounds [20]. Various manufacturers and the common biodegradable sutures are described in Tables 5 and 7, respectively.

3.5 Biodegradable root filling material

Resilon, introduced in 2004 as a substitute for gutta-percha, is a root canal filling material composed of a methacrylate resin base, bioactive glass, and radiopaque fillers. This thermoplastic polymer is designed to bond with root dentin, forming a monolithic seal within the canal [21].

Research has focused on both abiotic and biotic degradation of Resilon. As a polymer blend incorporating bioactive glass and mineral fillers, it is essential to evaluate Resilon's biodegradability by microorganisms. The polycaprolactone component of Resilon is susceptible to alkaline and enzymatic hydrolysis and can be degraded by microorganisms present in dental sludge. Numerous studies have investigated the abiotic and biotic degradation of Resilon.

Table 6. Composition of different vegetable fibres

S.No.	Parameters	Unit	Potato fiber	Onion fiber	Carrot fiber	Sweet lime	Lemon
1	Cellulose	%	42.60	41.54	42.68	41.58	41.80
2	Lignin	%	44.13	43.11	44.81	38.63	43.51
3	Crude fiber	%	33.82	32	34.26	32.66	33.15
4	Total ash	%	5.34	6.5	7.61	3.70	6.23
5.	Moisture	%	4.26	4.81	5.14	6.38	7.13
6	Specific gravity		1.075	0.847	0.751	0.725	0.781
7	pH		6.9	6.6	6.82	7	6.8

Table 7. Various biodegradable sutures

Suture	Composition	Tensile strength retention-in vivo	Absorption-loss of mass
Plain gut	Collagen	Lost within 7-10 days	Enzymatic-within 70 days
Chromic gut	Collagen	Retained for 7-10 days, some retains @21 days	Enzymatic- 90+ days
Vicryl	Polyglactin	60% remains @14 days; 30% remains @21 days	Hydrolyzed; minimally until 40thday; complete between 60-90 days.
Polydioxanone Suture II	Polydioxanone	70% remains @14 days; 50% remains @28 days; 25% @ 6 weeks	Hydrolyzed; minimally until 90thday; complete within 6 months
Monocryl C	Poliglecaprone	50-60% remains @7 days; 20-30% remains @14 days; tensile strength lost by 21 days	Complete between 91-119 days

3.6 Biodegradable intra canal medicament

Calcium hydroxide ($Ca(OH)_2$) has been used in endodontics for years as an intracanal medication due to its antibacterial properties. Over time, numerous efforts have been made to address its limitations, such as reduced antibacterial effectiveness caused by dentine buffering, which decreases the drug's alkalinity [22].

The anatomical complexities of root canal systems can make it difficult for conventional intracanal medicaments to reach all areas [23]. To address this, advancements in drug delivery systems using nanotechnology have been proposed [24].

3.6.1 Hydroxide-loaded Poly (Lactic-co-glycolic Acid)biodegradable nanoparticles: $Ca(OH)_2$-loaded PLGA nanoparticles (NPs) were optimized and characterized, exhibiting a polydispersity index (PI) below 0.2, an average size under 200 nm, a high negative zeta potential (ZP), and excellent entrapment efficiency (EE). These nanoparticles demonstrated sustained drug release and enhanced penetration into dentinal tubules, making them a promising alternative for intracanal antibacterial treatment [25-26].

PLGA undergoes biodegradation through a process known as ester hydrolysis [27]. The presence of methyl side groups in PLA renders it more hydrophobic than PGA. Consequently, lactide-rich PLGA copolymers exhibit lower hydrophilicity, absorb less water, and degrade at a slower rate [28].

3.7 Bioresorbable miniplates

For complex facial fractures, rigid plates and screws are traditionally employed. However, these metal implants can interfere with imaging techniques like CT and MRI scans, and may also lead to corrosion, electrolysis, hypersensitivity, and potential carcinogenic risks. To mitigate these challenges, there is a growing interest in developing bioresorbable osteo-fixation materials [29]. Table 5 lists several manufacturers of miniplates.

The majority of bioresorbable plates currently in use are fabricated from synthetic semi-crystalline poly-4 (alpha-hydroxy acid) and its copolymers. A comprehensive review of the literature pertaining to the application of bioresorbable plates is provided, along with background information on various studies as presented in Table 8. Unlike titanium, poly-4 (alpha-hydroxy acid) possesses unique properties that make it well-suited for biodegradation (Table 9).

3.8 Biodegradable magnesium-based bio membrane

Biodegradable metals are extensively researched for tissue regeneration applications due to their biodegradability, mechanical properties, bone-forming capacity, biocompatibility, and antibacterial effects [34]. Magnesium, a vital element involved in over 300 cellular processes, supports enzymatic reactions, mitochondrial function, protein synthesis, DNA replication, and cell proliferation. Table 10 highlights the unique properties of magnesium that make it suitable for use in biomembranes.

Biomembranes incorporating magnesium-based materials could potentially combine the mechanical strength of metallic alloys with the biocompatibility and slow degradation characteristics of natural tissues [35]. Table 5 lists several manufacturers of biodegradable materials [36].

4. Disadvantages of biodegradable materials

In dentistry, biodegradable materials, while environmentally beneficial, encounter challenges such as inadequate durability for long-term applications, potentially resulting in restoration failures [37]. Their unpredictable degradation can compromise the stability of dental work, and the combination of higher costs and specialized handling further complicates their use. Table 11 outlines some of the drawbacks associated with commonly employed biodegradable materials.

Table 8. Studies on bioresorbable mini plates

Study	Applications of Bio-resorbable miniplates	Advantages of Bio-resorbable miniplates
Kulkarni *et al.* [30]	To treat the maxillofacial fractures	Do not impose an increase in clinical morbidity
Enislidis G *et al.* [31]	To treat zygomatic fractures	Simple and safe
Landes *et al.* [32]	To treat sagittal split osteotomies	function as titanium in fixation for orthognathic surgery

Table 9. Comparison of titanium and poly-4 (α-hydroxy acid) [33]

Property	Titanium	Poly-4 (α-hydroxy acid)
Nature of material	Harder	Softer and weaker
Type of pressure	Firm pressure	Finger tight
Screw placement	Tapping needed	No tapping needed
Cost	Less	High

Table 10. Properties of Magnesium used for biomembrane

Property	Function
Antibacterial properties	Reduce the risk of bacterial infection and bone resorption.
Plasticity	Good and helps in handling & adapting membranes to complex shapes of bony defect
Mechanical properties	Allow the membrane to maintain the space for osteogenesis.

Table 11. Various disadvantages of biodegradable materials [37]

Material	Disadvantages
Polymers	Rapid degradation: • Loss of mechanical strength • Undesired inflammatory response
Metals: Mg alloys	Rapid degradation: • Loss of mechanical strength. • Formation of H_2 gas bubbles delaying fracture healing.
Ceramics: Tricalcium phosphate	Brittle, and poor tensile strength.

5. Advances in biodegradable materials

To address the challenges outlined earlier, researchers are focusing on developing biodegradable materials with enhanced durability [17]. One approach involves blending biodegradable polymers with other materials to improve their mechanical properties. Additionally, surface modifications are being explored to alter the surface characteristics of these materials, thereby increasing their longevity. Another promising strategy is chemical cross-linking, which enhances mechanical strength and stability. Researchers are also investigating the development of nanostructured biodegradable materials that exhibit superior mechanical performance. Furthermore, biohybrid materials, which combine biodegradable components with biological elements such as proteins or cells, are being designed to further improve durability.

6. Conclusion

This review article provides a comprehensive overview of biodegradable materials in dentistry, highlighting their applications and potential benefits. In conclusion, biodegradable materials are poised to revolutionize dentistry by offering a sustainable alternative to traditional non-resorbable materials. However, further research is necessary to enhance their mechanical properties, degradation rates, and clinical performance.

As the field continues to evolve, biodegradable materials are expected to play a pivotal role in shaping the future of dentistry, enabling more sustainable, patient-centered, and biomimetic approaches to dental care. By leveraging the potential of biodegradable materials, we can pave the way for a new era of dental treatments that prioritize patient health and minimize environmental impact.

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