processes

Review

Advanced Biomedical Applications of Multifunctional Natural and Synthetic Biomaterials

Mariana Chelu and Adina Magdalena Musuc *

"Ilie Murgulescu" Institute of Physical Chemistry, Romanian Academy, 202 Spl. Independentei, 060021 Bucharest, Romania; mchelu@icf.ro
* Correspondence: amusuc@icf.ro

Abstract: Biomaterials are mostly any natural and synthetic materials which are compatible from a biological point of view with the human body. Biomaterials are widely used to sustain, increase, reestablish or substitute the biological function of any injured tissue and organ from the human body. Additionally, biomaterials are uninterruptedly in contact with the human body, i.e., tissue, blood and biological fluids. For this reason, an essential feature of biomaterials is their biocompatibility. Consequently, this review summarizes the classification of different types of biomaterials based on their origin, as natural and synthetic ones. Moreover, the advanced applications in pharmaceutical and medical domains are highlighted based on the specific mechanical and physical properties of biomaterials, concerning their use. The high-priority challenges in the field of biomaterials are also discussed, especially those regarding the transfer and implementation of valuable scientific results in medical practice.

Keywords: biomaterials; biocompatibility; biomedical; biodegradability; tissue engineering; biopolymers; bioceramics

check for updates

Citation: Chelu, M.; Musuc, A.M. Advanced Biomedical Applications of Multifunctional Natural and Synthetic Biomaterials. *Processes* **2023**, *11*, 2696. https://doi.org/10.3390/pr11092696

Academic Editors: Maurizio Ventre and Selestina Gorgieva

Received: 15 August 2023
Revised: 5 September 2023
Accepted: 7 September 2023
Published: 8 September 2023

1. Introduction

Maintaining the quality of life through good health is required, and it is absolutely necessary worldwide. Currently, the permanent and growing interest in the study and advanced development of biomaterials is focused on medical or healthcare applications due to the requirements in the domain of drug administration, tissue engineering, medical device industry, permanent or temporary implants. As the need for high-accuracy and individualized treatments continues to grow, research pursues both the improvement of biomaterials in classic applications and the obtaining of new effective bioactive materials for multiple advanced applications, regenerative medicine or other health dysfunctions, including theranostic biomaterials (diagnosis, monitoring capabilities and combined therapy) [1–9].

In current medicine, biomaterials have an important role, both in stimulating healing and for regeneration of the initial biological or functional activity. Biomaterials can exist in natural or synthetic form. They are exploited in multiple applications in the medical field due to their biocompatibility. In this regard, biocompatibility can be defined as "the study and the knowledge of interactions between living and non-living materials" [10] and biomaterials as "any materials projected to interface with biological systems from the human body to evaluate, support, treat, enhance, augment, restore or replace any damaged tissue, organ, or function of the body" (definition proposed by the European Society for Biomaterials Consensus Conference II) [11]. Because of the fact that biomaterials are in direct contact with the human body fluids and tissues, they must accomplish several features such as stability, biocompatibility and safety.

Historical sources indicate the first use of biomaterials in antiquity [12]. In ancient Egypt, it was practiced since 3000 BC by using animal tendons as sutures, coconut shells to repair injured skulls, wood and ivory as false teeth [13]. Likewise, in Greece and India since the 1st century BC, doctors performed plastic surgeries on wounded soldiers practicing the use of biomaterials [14]. The first more elaborate applications of natural biomaterials are dated in the modern period, with the first surgical operation used to replace the hip with ivory performed in Germany, in 1891 [15].

Starting with the 19th century, bone plates began to be integrated into successful operations, with the role to stabilize bone fractures and to speed up their healing. In 1951, the first allograft taken from a deceased person was successfully implanted, and in 1954, a synthetic arterial substitute was used for the first time to treat 10 patients. In 1958, the Dacron vascular prosthesis was obtained as a viable alternative to harvested human grafts, which presented certain complications after implantation [16,17].

The first artificial heart valves start from the early 1950s, when a methacrylate ball was implanted in the descending aorta by Charles Hufnagel. In 1960, the mitral valves were replaced using a flexible polyurethane mitral prosthesis with a Teflon chorda tendineae attachment, by Nina Braunwald. The last step in valves' evolution is represented by the progress in advanced valve alternatives called regenerative or tissue-engineered valves [18].

The history of biomaterial applications is presented in Figure 1 (adapted from reference [19]).

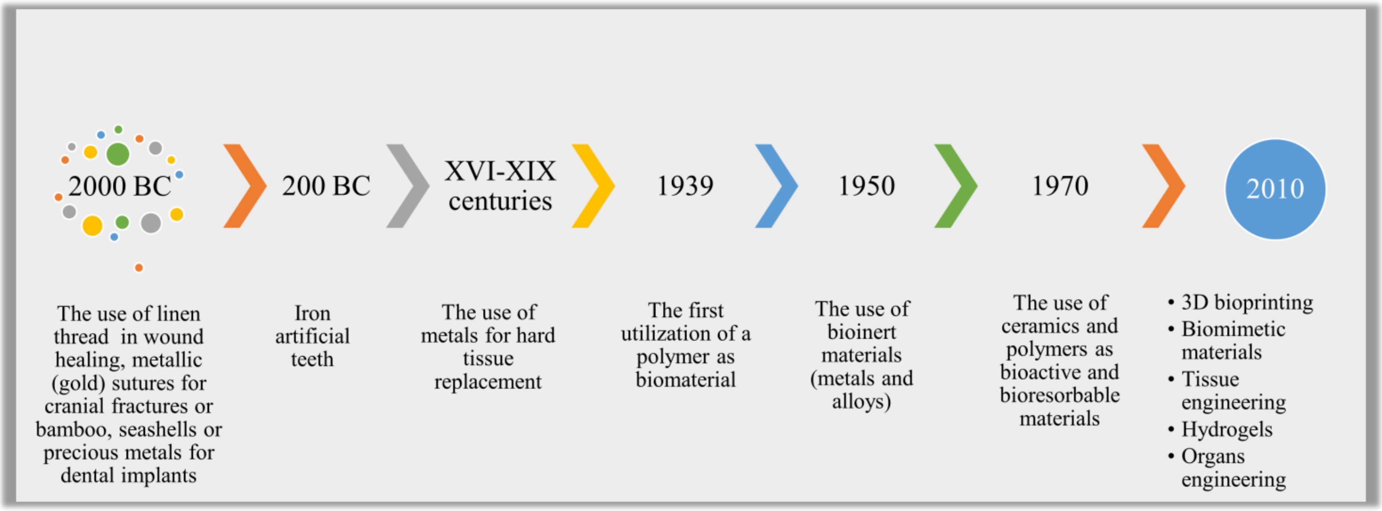

Figure 1. The evolution of materials as biomaterials from prehistory to recent time (adapted from reference [19]).

To exemplify the continuous growth in the publications on and the increasing research attention to this topic, a graphical representation showing the annual number of publications on biomaterials used for biomedical applications from 2003 to 2023 (Figure 2a) is included, which was obtained using the Scopus database [20]. The diagram highlights a significant growth in the publication numbers in the analysed 20 years. The search was performed using "biomaterials for biomedical" in all fields, "biomedical" in keywords and limited only to articles and reviews. In addition, a representation regarding the publications evaluated by subject area is shown in Figure 2b.

In this context, the present review aims to scrutinize the most recent technologies related to advanced biomedical applications of multifunctional natural and synthetic biomaterials and their classification based on their source. The purpose and the objective of the present work is to emphasize the design and functions of a new generation of biomaterials inspired by natural ones and capable of being critical mechanisms in various sides of modern civilization.

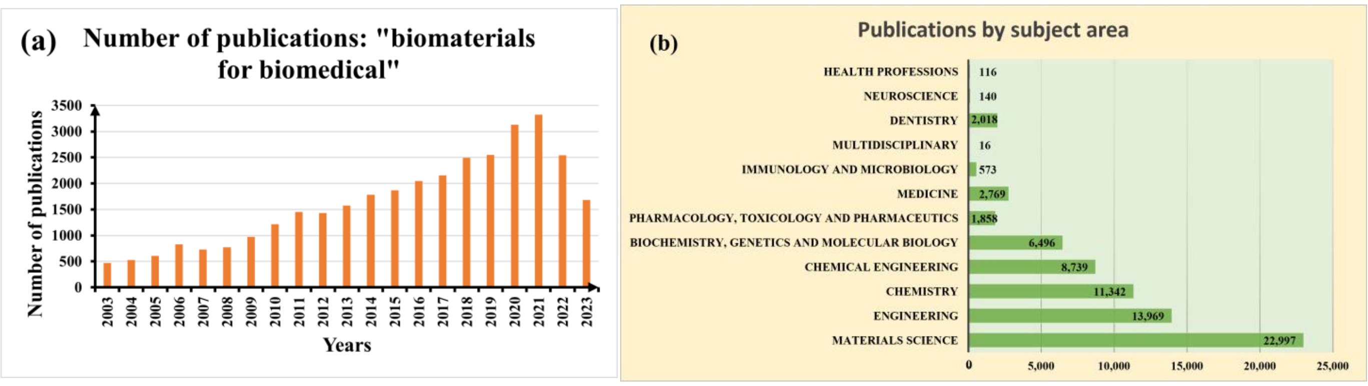

Figure 2. (**a**) Evolution of the number of scientific papers related to the search of "biomaterials for biomedical applications" phrase published between 2003 and 2023. (**b**) Evolution of publications by subject area. Source: Scopus (accessed on 12 August 2023) [20].

2. Biomaterials from Natural Sources

Presently, an increased interest has been focused on the development of biomaterials obtained from natural sources due to their several advantages such as biocompatibility, ease of production, renewability, low cost, availability, nonimmunogenicity [21]. Biomaterials derived from natural sources can be grouped in four main categories: protein-based materials, polysaccharide-based materials, glycosaminoglycan-based materials and extracellular matrix materials (Figure 3).

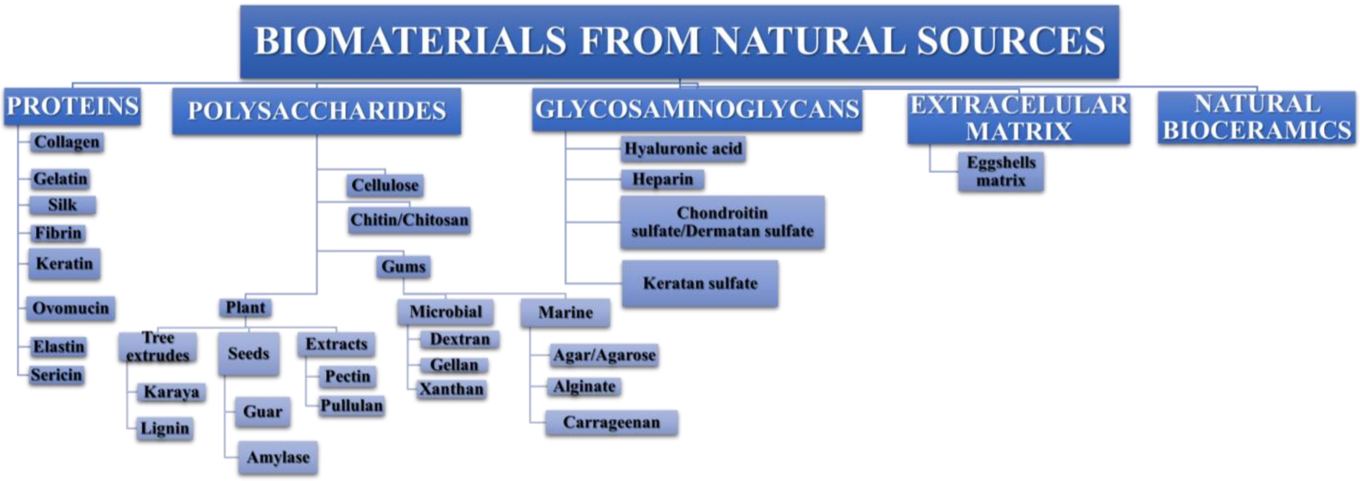

Figure 3. Classification of biomaterials obtained from natural sources.

Generally, biomaterials derived from natural sources are used (i) to restore or to replace a damaged tissue or organ, (ii) to promote the tissue regeneration, (iii) as a drug delivery system, (iv) to develop bone scaffolds.

2.1. Protein-Based Materials

Recently, a growing interest has been observed in the development of protein-based biomaterials due to the limited fossil source and also to their versatile characteristics such as high mechanical performance, biocompatibility and biodegradability [22–24].

2.1.1. Collagen

Collagen is the main protein from the whole animal body protein content (25–35%), with a significant role in providing support for tissues and cells and in sustaining structural and biological integrity of the extracellular matrix. Collagen is found in the skin, tendons, ligaments, cartilage, bones, corneas, blood vessels, intervertebral discs, gut and teeth [25].

Well-suited to build structures for tissue engineering, collagen is a biomaterial often used in biomedical applications based on its biocompatible, biodegradable and noncytotoxic properties [26,27]. Collagen can be processed and used in a variety of forms: (i) collagen-based films or membranes (2D) which are used especially for healing skin wounds and tissue regeneration (cornea, bones) due to good biocompatibility and biodegradability [28]; (ii) in different forms of scaffolds (3D), as pure collagen structures [29,30] or with synthetic polymers [31]. A schematic representation of collagen at different length scales and of different structures is shown in Figure 4 [32].

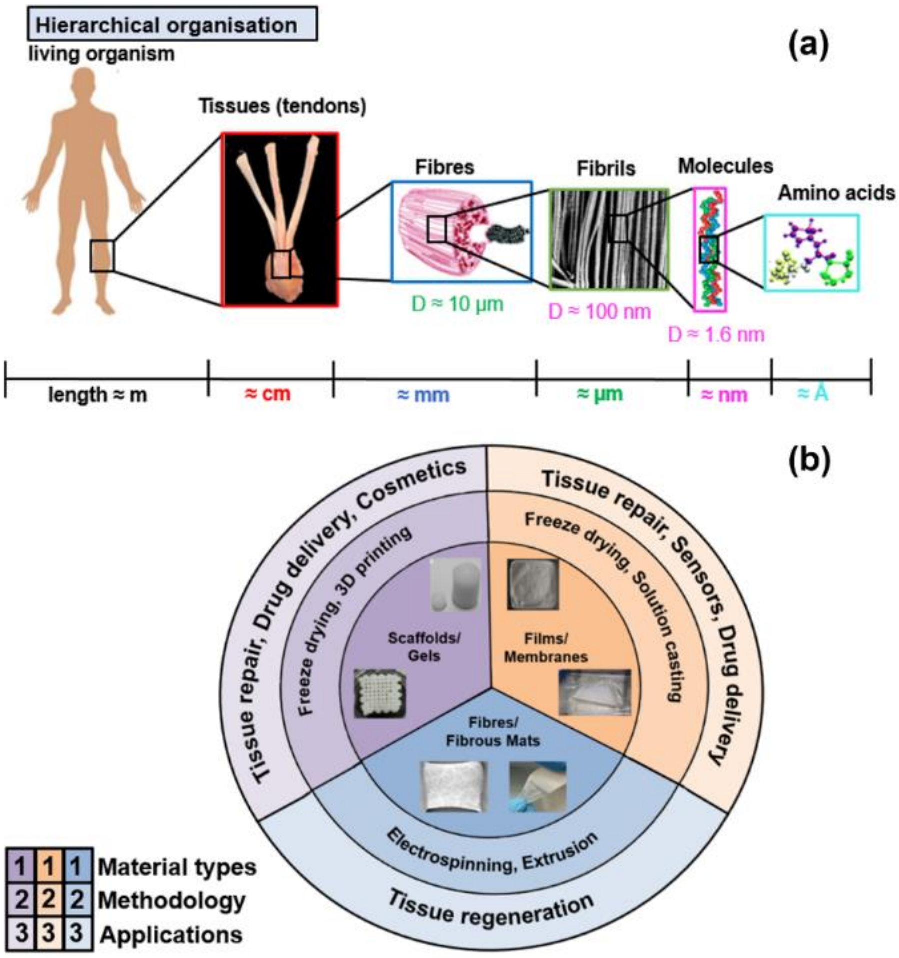

Figure 4. (**a**) Hierarchical assembly of collagen at different length scales; (**b**) various collagen structures with the corresponding processing techniques and related biomedical applications. (reprinted from reference [32]).

Collagen-based sponges are used in intraoperative surgery (in neurology) [33] as scaffolds in bone tissue engineering [34], as haemostatic dressings [35] or as an alternative biomaterial for the healing of cutaneous wounds with antibacterial properties [36]. Collagen blended with other biomaterials is used in reconstructive surgery [37] and as a haemostatic dressing for fast blood absorption [38].

2.1.2. Gelatine

Gelatine is a natural polymer derived from the hydrolysis of collagen, being a biocompatible, biodegradable, elastic and nontoxic material. In the field of tissue engineering, gelatine is often used in several systems, such as drug delivery systems, injectable hydrogels, scaffolds or wound dressing films. A mixture of demineralized bone matrix and gelatine together with absorbable gelatine sponges has been tested in bone tissue engineering to maintain haemostasis in multiple surgeries [39]. Gelatine has a disadvantage in terms of thermostability. Depending on the temperature, it can pass relatively easily from the solid state to the gel [40]. At the same time, one of its advantages is the ability to absorb water, useful in tissue regeneration, as in the case of formulations such as nanocomposite hydrogels for treating wounds [41] or injectable hydrogels to favour bone regeneration [42].

2.1.3. Silk

Silk, a fibrous biomaterial obtained from protein fibroin from silkworm cocoons or spider silk blends, is a biocompatible and biodegradable natural polymer frequently used for applications in regenerative medicine and tissue engineering [43]. The mixture with different natural or synthetic polymers or fibrous materials is used to improve its biodegradability, biocompatibility and to adjust the mechanical properties, by obtaining functional biomaterials in the form of hydrogels [44], thin films or coatings [45], nanoparticles [46], fibres, 3D printed structures [47] or in the form of composite scaffolds [48] for the medical field.

2.1.4. Fibrin

Recently, biomaterials or their composites were often used for tissue engineering, due to their bioavailability and low price. Fibrin is one of the most promising natural biomaterials for articular cartilage repair [49]. Fibrin polymers and composites are often used as transport vehicles for bioactive molecules to induce regeneration and promote wound healing or as delivery carriers for multiple cell lines (Figure 5) [50].

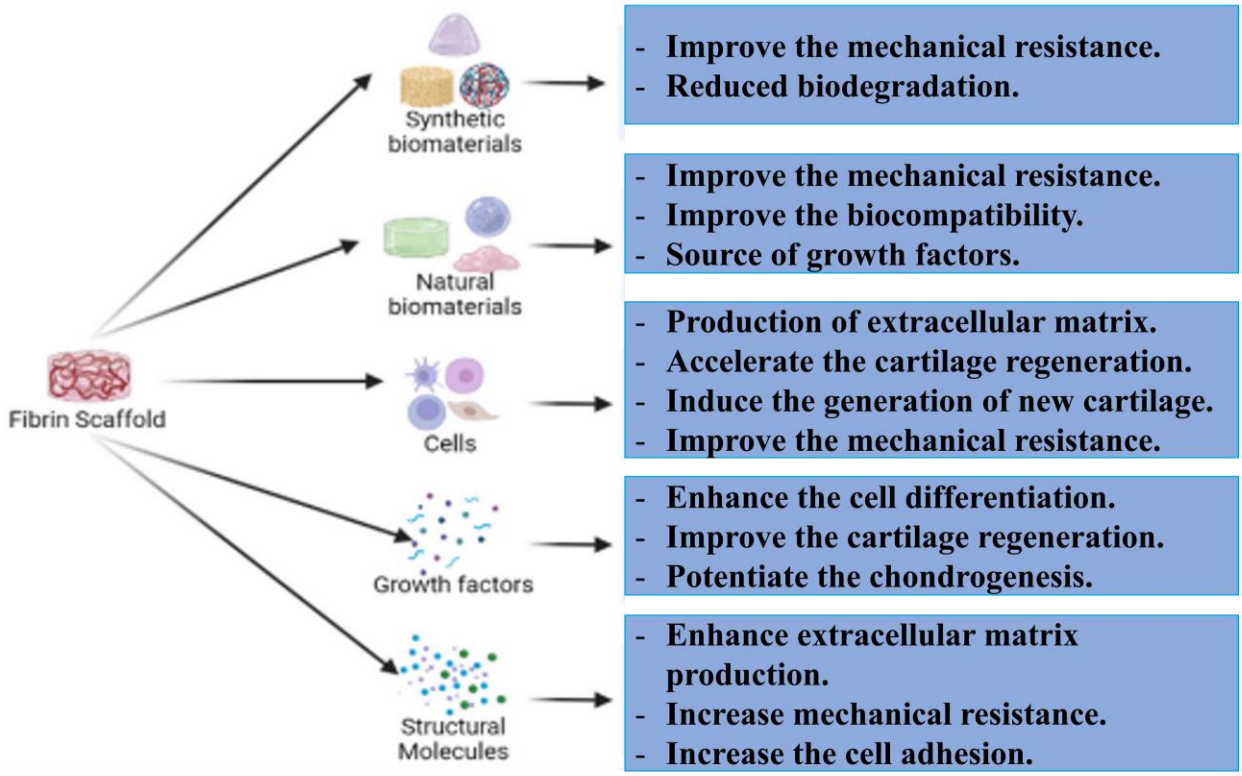

Figure 5. The advantages of the use of fibrin as a scaffold in order to promote the repair of chondral tissue (adapted from reference [50]).

2.1.5. Keratin

Due to their intrinsic biological properties and excellent biocompatibility, keratin-based biomaterials have shown increased interest recently and are widely used for biomedical applications such as tissue engineering, drug delivery, wound healing [51]. The main sources of keratin extractives are wool, horns, hair, nails and feathers. Keratin is a structured protein with a high cysteine content (7–15%). The main methods used to extract and solubilize keratin are reduction, oxidation, alkaline extraction, microwave irradiation, steam explosion and by means of ionic liquids [52]. Keratin-based formulations are used as (i) hydrogels for diabetic wound dressing material, regeneration of pupal tissue, in substrates for cellular attachment and proliferation; as (ii) films for reconstruction of ocular surface, drug delivery and as (iii) fibres for tissue engineering [51].

2.1.6. Ovomucin

Ovomucin is a glycoprotein carbohydrate (representing between 2 and 4% of total egg albumin) with high molecular weight, composed of a carbohydrate-rich β-subunit (50–57%, a molecular weight of about 400 kDa) and a carbohydrate-poor α-subunit with approximately 11–15% of carbohydrates [53]. Ovomucin possesses antibacterial, antitumor, antiviral, antioxidant activities and immune properties with multiple applications in intestinal injury treatment of gastrointestinal tract after dietary intake or as biocompatible porous hydrogel for additional development as an implant material for bone or tissue engineering [54,55].

2.1.7. Elastin

Obtained by extraction from different biological sources, elastin, a hydrophobic amino acid with a high degree of intermolecular cross-linking, is used as a dressing to speed up the healing of chronic wounds or for large surfaces [56]. Elastin, an extracellular matrix protein, is recognized for providing elasticity to organs and/or tissues. Consequently, elastin is present in human organs with elastic properties such as blood vessels, elastic ligaments, in lung and in skin. Elastin-based biomaterials are used in a wide range of applications such as tissue engineering, skin substitutes, vascular grafts, heart valves and elastic cartilage [57].

2.1.8. Lactoferrin

Lactoferrin is a mammalian iron-binding glycoprotein which belongs to the transferrin class. Recently, lactoferrin has gained potential as a therapeutic agent and as a pharmacological compound. Lactoferrin possesses immunomodulatory, anti-inflammatory, antioxidant, antiviral, antimicrobial and anticancerogenic activities. Lately, various technologies have been developed to advance the lactoferrin's role in the ocular drug bioavailability (Figure 6) [58].

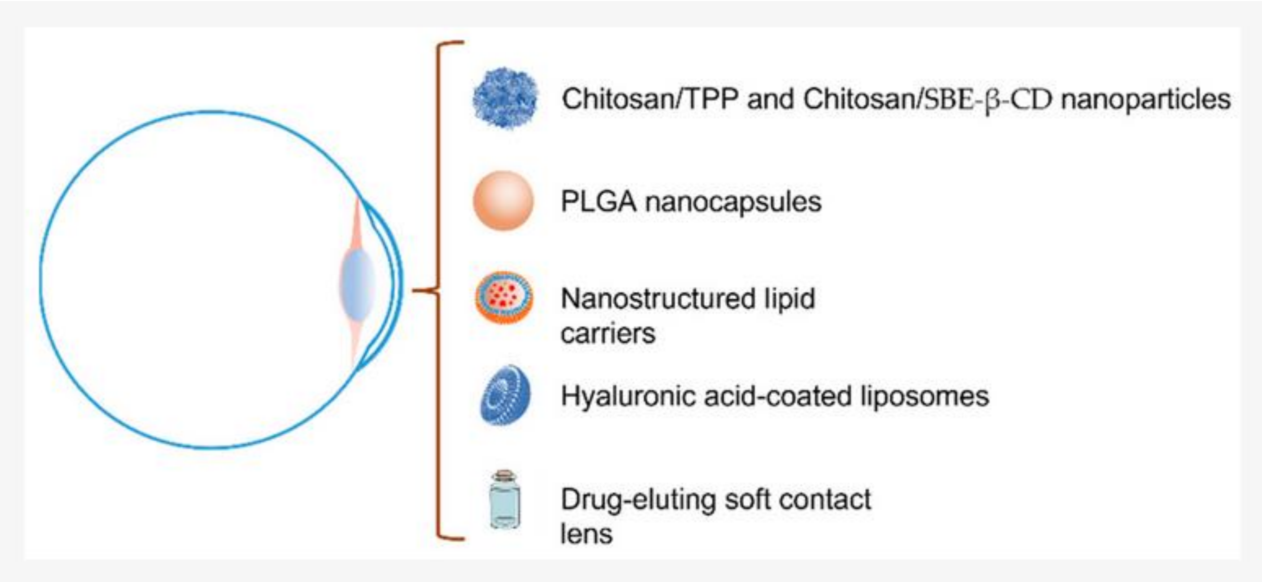

Figure 6. The improvement methodologies of lactoferrin ocular drug bioavailability. (reprinted from reference [58]).

2.1.9. Sericin

Sericin, a component of silk known as silk sericin, has grown consideration in recent years in sericin-based biomaterials. Due to its role in the sustenance of cell proliferation and attachment and stimulation of cell differentiation, sericin has been used in tissue engineering and cell culture [59–71]. A summary of sericin-based biomaterials for biomedical applications is presented in Figure 7.

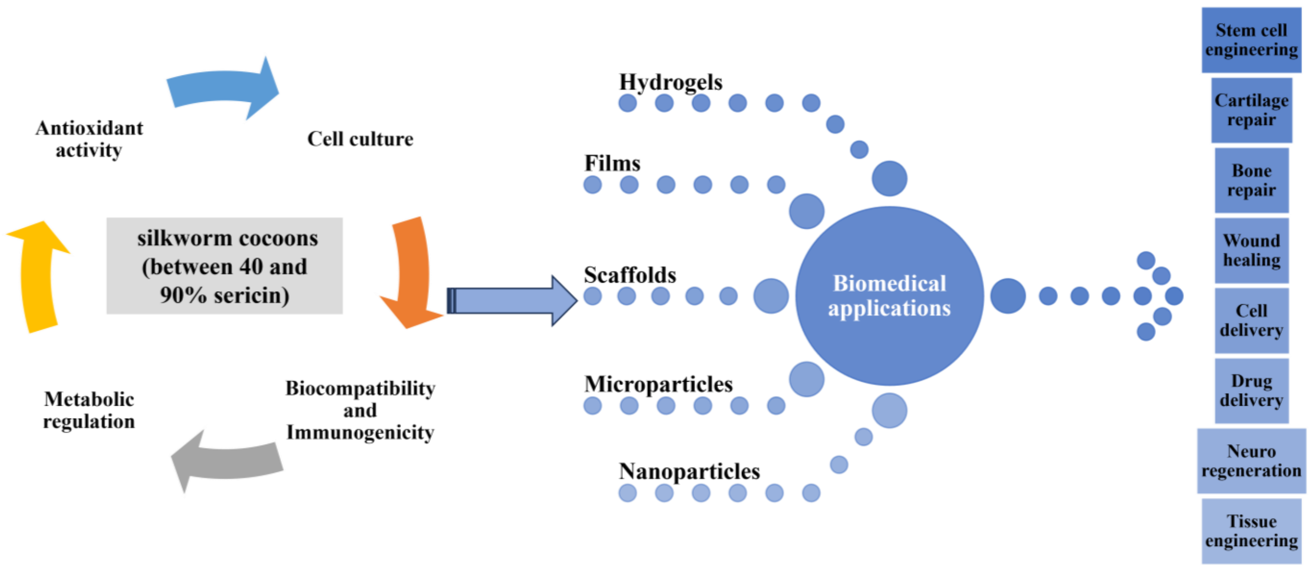

Figure 7. Examples of sericin-based biomaterials, their properties and biomedical applications.

2.2. Polysaccharides

2.2.1. Cellulose

The main sources of cellulose in nature are plants (wood and secondary products from agriculture), algae, bacteria and marine animals, being practically an abundantly available biomaterial [72]. Cellulose can be found in three forms, namely cellulose nanocrystals, cellulose nanofibers and bacterial or microbial nanocellulose. Cellulose nanocrystals demonstrate unique characteristics, such as large surface area, good crystallinity, as well as excellent mechanical strength. [73]. Cellulose-based materials can be used as antibacterial agents, for tissue engineering, for wound dressing, for artificial blood vessels and for drug delivery in the form of aerogels, hydrogels, three dimensional scaffolds and membranes [74].

2.2.2. Chitin/Chitosan

Chitosan and its precursor chitin are bioavailable polymers that come from the shells or skeletons of marine and nonmarine organisms [75]. They have been studied and used in a very large range of biomedical and nanobiotechnology applications because they have advantageous properties, such as nontoxicity, biocompatibility, biodegradability. Because chitosan is water-soluble and easily forms ionic and hydrogen bonds with drug structures, it can be widely used in drug delivery systems, cancer therapy, wound healing and tissue engineering [76]. To maximize the therapeutic potential and bioavailability of drugs in a controlled and continuous manner [77], various micro- and nanoparticles have been developed as their active carriers [78,79], hydrogels [80–83] scaffolds [84–87] and organic or inorganic matrices based on chitosan or chitin [88].

2.2.3. Gums

Natural gum-based polysaccharides and their derivatives are biodegradable polymeric materials which present advantages over synthetic polymers, mainly since they are nontoxic, bioavailable and inexpensive [89]. Natural gums can be divided based on their sources and chemical structures as follows: (i) of plant origin (tree exudates, seed gums and extracts), (ii) of microbial origin and of (iii) marine origin. Gums are principally synthesized from the following three categories: (a) tree or shrub exudates, (b) plant exudate gums and (c) the endosperm of some seeds [90]. A graphic illustration of the natural gum sources, gum-based materials and their possible biomedical applications is shown in Figure 8.

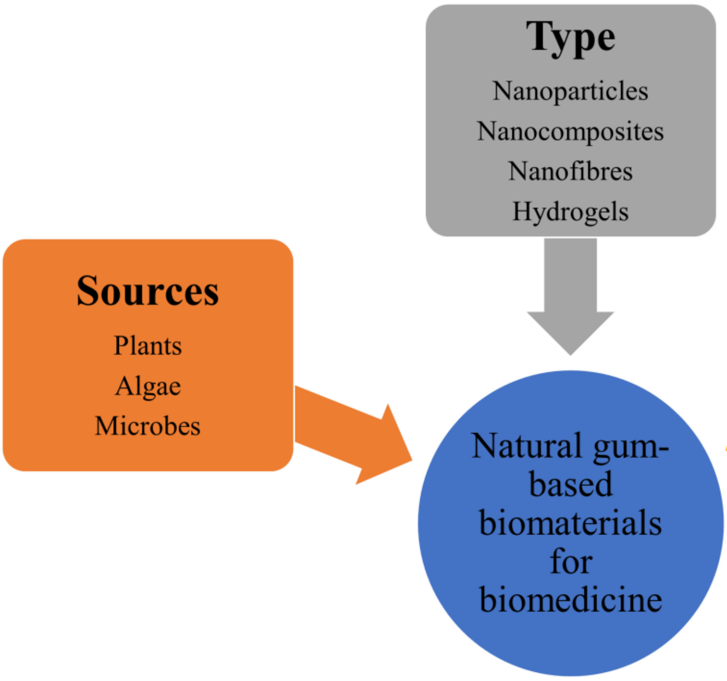

Figure 8. Diagram of sources of natural gums and their advanced biomedical applications (adapted from reference [90]).

The significant characteristics of natural gums are (i) the ability to form viscous solutions by attracting and binding water molecules, (ii) the ability to act as fibres and (iii) the ability to form films. Besides their origin, natural gums are also grouped and classified into the following categories:

(a) Anionic, cationic and nonionic, based on the surface charges;
(b) Linear and branched chains, based on their structure [91].

Plant Gum-Based Biomaterials

(i) Tree extrudes

Gum arabic, a natural polysaccharide obtained from *Acacia nilotica*, is part of the Leguminosae family. It is composed of different compounds: galactose (39–42%), arabinose (24–27%), glucuronic acid (15–16%), rhamnose (12–16%), protein (1.5–2.6%), nitrogen (0.22–0.39%) and moisture (12.5–16%). Its main application is in the food industry, pharmaceuticals and cosmetics. Recently, gum arabic has been extensively used for drug delivery and in a biomedical domain, as nanoscaffolds [92–95].

Gum karaya is produced from Sterculia species trees. Gum karaya is an exceptional natural vegetable bioproduct, with good biocompatible, biodegradable, renewable properties, it is easy to handle and store, has a low cost and is frequently used in food, pharmaceutical, denture-fixation, wound-dressing, nanoencapsulation and other industrial applications (cosmetics, textile and paper industry) [96–99].

Lignin is the main component of plant cell walls, which protects the plant from different stress factors and provides mechanical support. The chemical structure of lignin is complex, being composed of methoxy, phenolic and aliphatic hydroxyl groups. Lignin has satisfactory biocompatibility. Its cytotoxicity depends on the process of chemical extraction, as well as antioxidant and antimicrobial properties. The application of lignin in the biomedical domain can be summarized as follows: for wound healing as hydrogel-based materials, in tissue engineering as hydrogels and nanofibers, in drug delivery due to its ability to encapsulate hydrophobic/lipophilic drugs for oncological therapy [100–105].

Gum tragacanth, an acidic and anionic polysaccharide having a high molecular weight and durability, is produced from various species of Astragalus. This gum possesses good stability and biodegradability, is available in nature and is nontoxic [106]. Gum tragacanth is used in many biomedical applications for wound healing, prevention of growing of cancer cells, tissue engineering and as a gelling agent in pharmacy [107–109].

(ii) Seed gums

Guar gum, a natural hydrophilic polysaccharide derived from the endosperm of *Cyamopsis tetragonolobus* or *Cyamopsis psoraloides* seed, is formed by linear 1,4 linkages of β−D−mannopyranose, and the branch contains 1,6 linkages of α−D−galactopyranose. Guar gum is highly soluble in water, is nontoxic over a wide range of pH; its hydrogels are biodegradable in nature, have higher flexibility and are biocompatible. Based on these properties, guar gum has been widely applied in the biomedical domain for targeted drug delivery and in tablets [110–113].

(iii) Extracts

Pectin extracted from biomass, using different treatment conditions, can be used in biomedical applications. Several applications of pectin can be mentioned in 3D printable inks as scaffolds with chitosan [114], in drug delivery applications [115], as a hydrogel for cancer-targeted drug delivery [116], in tissue engineering [117] and for wound healing [118].

Pullulan, a fungal exopolysaccharide which is produced by *Aureobasidium pullulans* and *Aureobasidium melanogenum* under aerobic conditions, has several properties that make it highly soluble in water, tasteless, edible, odourless, nontoxic and biodegradable [119]. Among biomedical applications of pullulan that can be mentioned are for bone formation and/or repair [120], wound healing [121], tissue regeneration [122] and drug delivery [123,124].

Microbial Gum-Based Biomaterials

Dextran is a nontoxic, hydrophilic, biodegradable and biocompatible homopolysaccharide derived from bacterial attack of sucrose with dextransucrase or maltodextrins with dextrinase [125]. This biocompatible homopolysaccharide has been broadly applied in pharmaceutical and biomedical applications to stimulate wound healing and rehabilitation of skin and to decrease the inflammatory response [126–129].

Over the past few years, gellan gum, a high-molecular-weight linear anionic exopolysaccharide, formed by microbial fermentation of *Sphingomonas paucimobilis*, has been paid attention and considerably used in some areas such as clinical and biomedical applications [130]. Due to its adaptable characteristics such as tuneable mechanical properties, biocompatibility, biodegradability, easy functionalization and fabrication, gellan gum has attracted the researchers as a promising biomaterial in regenerative medicine (cartilage and intervertebral disc repair), drug delivery and tissue engineering [131–133]. Generally, gellan gum is used in composite biomaterials by blending it with additional biopolymers or nanomaterials in order to improve the poor mechanical strength and lower stability [134–136].

Xanthan gum, an anionic polysaccharide is produced by a Gram-negative bacteria named *Xanthomonas* bacteria. Xanthan gum due to its biodegradability and biocompatibility has been used in numerous biomedical applications alone or in combination with other natural and/or synthetic polymers in tissue regeneration [137,138], wound healing [139–141] and the controlled release of drugs [142].

Marine Gum-Based Biomaterials

Agar, a hydrophilic polysaccharide, is extracted from red seaweed with a composition containing 30% agaropectin and 70% agarose (the main component responsible for the gelation process). Its usage as hydrogels or air-dried films was reported in wound dressing and wound healing [143,144].

Alginate is an anionic biopolysaccharide formed by units of mannuronic acid and glucuronic acid, randomly arranged [145]. Alginate has been extensively used in tissue engineering, cancer therapy, wound care, controlled drug delivery and nanomedicines due to its biocompatibility [146–152].

Carrageenan is a naturally occurring, linear sulphated polysaccharide extracted from red seaweeds. It is composed of the disaccharide units alternating 4-linked α-D-galactopyranose (the B unit) and 3-linked β-D-galactopyranose (the A unit) residues. Carrageenans hold several advantages such as abundant availability, biocompatibility and biodegradability, antiviral activity, antimicrobial properties, sustainability permitting their usage as remarkable functional biomaterials for advanced biomedical applications [153–159].

2.3. Glycosaminoglycans

Both fibrous proteins and distinct polysaccharides named glycosaminoglycans are present in the composition of the extracellular matrix. Glycosaminoglycans are formed by a linear chain represented by repeated disaccharide units [160,161].

2.3.1. Hyaluronic Acid

Hyaluronic acid, a linear anionic polysaccharide, is a major macromolecular component of the extracellular matrix in the most connective tissues. Due to its biocompatible, biodegradable and bioresorbable nature, limited immunogenicity, recognized by cell surface receptors, its flexible and unique viscoelasticity properties, hyaluronic acid has been extensively studied in recent years for biomedical applications [162–164]. This biopolymer is useful in medicine for the treatment of diverse pathological situations such as arthritis but is also used in drug delivery and tissue engineering [165,166].

2.3.2. Heparin

Heparin is an acidic sulphated polysaccharide belonging to the glycosaminoglycan family which is isolated by extraction from animal tissues such as porcine intestine. Heparin is formed by repeating disaccharide units of $1 \rightarrow 4$-linked hexuronic acid and glucosamine saccharide residues. Heparin is used in the manufacture of membranes [167] or in the novel polyelectrolyte-scavenging method for biomedical applications [168]. This glycosaminoglycan has been proposed for the cystic fibrosis treatment, for neurodegenerative diseases, as an antimicrobial agent, and in the pancreatitis treatment [169].

2.3.3. Chondroitin Sulphate/Dermatan Sulphate

Studies initiated in the 1950s on bovine material and developed later, led to a better understanding of the biosynthesis and homeostatic roles of chondroitin sulphate/dermatan sulfate, especially in the control of bone development and in the regulation of the assembly of collagen fibrils as well as cytokines. These findings were followed by highly significant correlations between CS/DS synthesis and certain genetic abnormalities in humans [170].

2.3.4. Keratan Sulphate

Keratan sulphate (KS) is the newest glycosaminoglycan, an elaborated molecule with a distinctive structure, whose function is still to be revealed; cornea, cartilage and brain being the main tissue sources of KS in the human body. It has an important role in the regulation of cells in epithelial and mesenchymal tissues, as well as in bones [171].

2.4. Extracellular Matrix

The role of the extracellular matrix and vascular basement membranes and their influence in the regulation of angiogenesis and the progression of some tumours has been studied and highlighted [172]. Various biomaterials of synthetic and natural origin have been investigated as new scaffolds for heart valve tissue engineering, especially for paediatric patients. Among them, glycosaminoglycans such as chondroitin sulfate and hyaluronic acid are the main components of cardiac cushions, as important parts that regulate the functionality of the complex system of heart valves [173].

Eggshells Matrix

By recycling biological waste such as eggshells and using different natural extracts or other compounds, materials similar to natural bone minerals have been obtained for orthopaedic and dental applications [174], such as hydrogels with super absorbent properties for drug delivery systems [175] or composite materials in electrochemical sensors for the determination of ascorbic acid, dopamine and uric acid in human urine and blood serum [176].

2.5. Bioceramics

Based on their origin, bioceramics can be classified as follows:

(i) Natural. Natural bioceramics occur naturally in natural corals, algae, natural pearls, shells, eggshell matrix, teeth and bones.
(ii) Synthetic. Synthetic bioceramics are produced artificially and include hydroxyapatite, calcium phosphate-based materials, bioglass, alumina, zirconia, silicon nitride.

In Figure 9, a schematic representation of the main natural and synthetic bioceramic materials is shown.

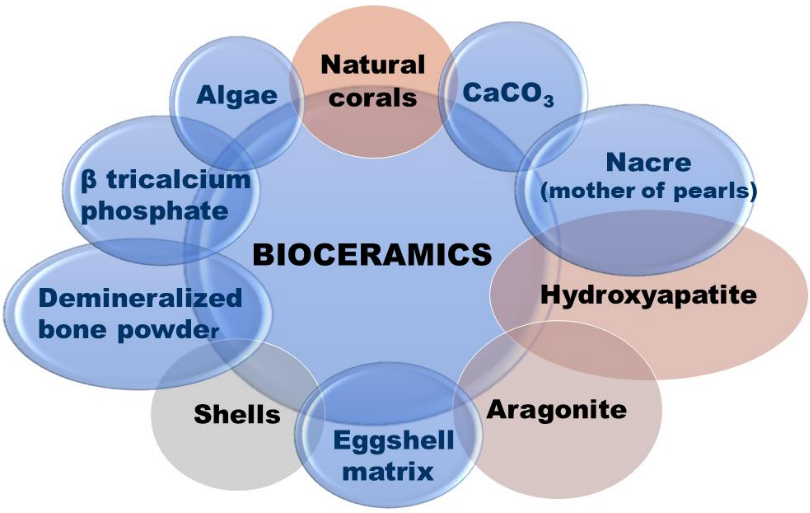

Figure 9. Classification of main bioceramics-based biomaterials from natural and synthetic sources.

Bioceramics are classified based on tissues response into the main three classes as follows:

(i) Bioactive ceramics represented by hydroxyapatites, fluorapatite-based composites, bioactive glasses and bioactive glass ceramics;
(ii) Biodegradable/bioresorbable ceramics with the presence of calcium phosphate, tricalcium phosphate, aluminium–calcium phosphate, zinc–calcium phosphorous oxides, zinc–sulphate–calcium phosphates, ferric–calcium phosphorous oxides, coralline, calcium aluminates;
(iii) Bioinert/nonresorbable ceramics which includes alumina, zirconia, carbons and silicon nitride.

Table 1 summarizes the most recent applications of natural and synthetic bioceramics in the biomedical area.

Table 1. Bioceramics used in biomedical applications.

Bioceramics	Examples	Applications	References
Bioactive ceramics	hydroxyapatites	coatings on metallic implants	[177–179]
	fluorapatite-based composites	bone applications	[180]
	bioactive glasses	bone substitute and drug carrier	[181]
	bioactive glass ceramics	chemo hyperthermia	[182]
Biodegradable (bioresorbable)ceramics	aluminium–calcium phosphate	biomedical application	[183]
	zinc–calcium phosphorous oxides	postoperative tumour treatment	[184]
	zinc–sulfate–calcium phosphates	tissue engineering	[185]
	ferric–calcium phosphorous oxides	scaffolding for cell and drug delivery	[186]
	coralline	drugs	[187]
	calcium aluminates	bioactive dental materials	[188]
Bioinert (nonresorbable) ceramics	alumina	drug delivery	[189]
	zirconia	biomedical applications	[190]
	carbons	biomedical applications for tissue engineering	[191]
	silicon nitride	biomedical applications in medical implants	[192]

3. Biomaterials from Synthetic Sources

The classification of biomaterials obtained from synthetic sources is presented in Figure 10.

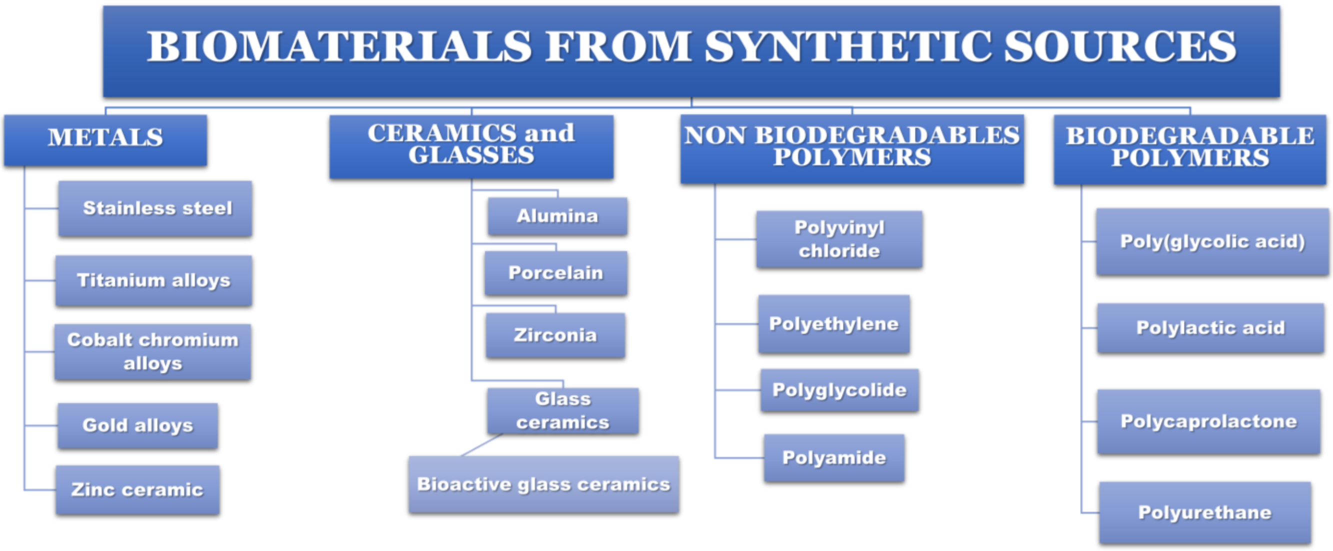

Figure 10. Classification of biomaterials obtained from synthetic sources.

Table 2 lists the main advantages and disadvantages of biomaterials obtained from synthetic sources and their most relevant biomedical applications (adapted from reference [19]).

Table 2. Advantages and disadvantages of biomaterials obtained from synthetic sources and their most relevant biomedical applications.

Category	Advantages	Disadvantages	Applications	References
Metals	high mechanical properties; low friction; high fatigue resistance; ductility; low cost	poor biocompatibility; stiffness; high specific weight; low resistance to corrosion	orthopaedic, orthodontic, cardiovascular, joint prostheses	[193–196]
Ceramics	good biocompatibility; chemical inertness; high compressive strength; low thermal and electrical conductivity; corrosion resistance	low impulsive tensile strength; high specific weight; brittleness; reproducibility; not easy to process	orthopaedic, orthodontic, cardiovascular; coatings; bone tissue regeneration; surgical implants	[197–199]
Nonbiodegradable and biodegradable polymers	toughness; low specific weight; low frictional properties; good processability	low mechanical strength; degradability over time; deformability over time	orthopaedic, orthodontic, cardiovascular, breast implants, scaffolding for soft tissues; eye lenses, artificial tendons	[200–204]
Biologically-derived materials (porcine/bovine pericardium)	superior biocompatibility	poor reliability; difficult handling and storage	bioprosthetic heart valves, total artificial heart	[205,206]

3.1. Metals

Metallic biomaterials are predominantly used to replace damaged hard tissues. Various types of high-strength alloys containing nontoxic elements are used for various biomedical applications. Functional devices based on NiTi (Nitinol) alloys have been developed due to their exceptional shape memory and super elastic properties. The alloy is used for the manufacture of self-expandable stents for cardiovascular surgery as well as super elastic bone staples for orthopaedics or super elastic orthodontic wires for dentistry [207]. Patient-specific medical implants such as bone plates, screws, cranial or dental devices are manufactured with the necessary biocompatibility, bioactivity, surface integrity and wear resistance [208].

Table 3 summarizes recently developed metal-based biomaterials for the use in the biomedical domain.

Table 3. Metal biomaterials used in biomedical applications.

Metals	Characteristics	Applications	References
Titanium alloys	biocompatibility, corrosion resistance, high mechanical properties, high fatigue resistance, ductility	orthopaedic implant materials, bone plates, dental implants, spinal internal fixation devices, orthodontic wires, intramedullary nails	[209]
Mg alloys	nontoxicity, biocompatibility	bioresorbable orthopaedic materials	[210,211]
Conventional stainless steel	corrosion resistance	metal implants	[212,213]
Platinum	systemic treatment	chemotherapy	[214]
Nickel	therapeutic activity	antibacterial agent	[215]
CoCr alloys	mechanical properties	dental prosthesis; dental restorations	[216]
Nitinol	super-elasticity, shape memory	endovascular stents	[217]

3.2. Ceramics and Glasses

Among the materials commonly used for clinical applications, the biocompatible characteristic of ceramics makes it suitable for implants, tissue regeneration and engineering applications. The demand for high-quality devices is determined by global health care problems of the increasingly numerous populations, such as defects or dysfunctions of the bone skeleton, osteoarthritis or those in the field of dentistry. Ceramics find numerous applications in biomedicine due to their excellent biocompatibility in the dental field, from dental restoration to implants, for joints or bone substitutes, bone fillings and scaffolds for tissue engineering. Some ceramic implants can be used as porous substrates to help the ingrowth of new bone tissue and can be resorbed after tissue regeneration.

A porous nanocomposite material in the form of hematite nanoparticles covered by amorphous alumina was produced by sol–gel combustion synthesis. Porous nanocomposite particles have proven capable of inducing special magnetic properties, making them suitable as contrast agents for imaging applications, namely in ultra-high field MRI [218]. Alumina and zirconia have been used as ceramic fillers for many types of polymer–ceramic composites developed as biomaterials in dental prosthetics [219]. Biofunctional materials, such as silicate glass ceramics, are studied and applied for the regeneration and healing of bone tissue [220], in cancer treatment by hyperthermia [221], in implants [222] or for total replacement in articulating surfaces to promote osseointegration [223]. Larry Hench is one of the pioneers of studies regarding the influence of the chemical structure of bioactive glasses and glass ceramics in general, on the interaction with the physiological system, as well as the connection between the glass surface and the living tissue [224]. Beginning in 1969, Hench developed for the first time a bioactive and biocompatible melt-derived glass material called bioglass, with the potential to form bonds with mineralized bone tissue even in the body's physiological environment [225]. The main purpose of his study was to replace inert implants made of other materials (for example plastic or metal) that were not well supported by the human body. Most bioglasses contain Na_2O, CaO, P_2O_5 and SiO_2 in their formula. The latter was added in a weight percentage <55%, because a larger amount of SiO_2 could lead to the loss of bioactivities. In 1969, studies were successfully carried out on rats, on the adhesion of a bioglass to bone and muscle 6 weeks after implantation. This material had a composition of $45SiO_2$–$24.5Na_2O$–24.5CaO–$6P_2O_5$ by weight (%) and was named 45S5 Bioglass® [226]. Later, in 1991, Hench proposed the development of bioactive gel-derived glasses [227]. These studies marked a shift in interest from bioinert materials to bioactive materials. Bioactive glass has multiple uses: (i) in solid form, as different prostheses, in dentistry, bone regeneration medicine or in tissue engineering; (ii) in the form of powders for covering biomedical devices; (iii) in the form of composites, as different filling materials and (iv) as a drug delivery system [228–235].

In their work, M Montazerian and ED Zanotto presented an interesting review of the history of bioactive glass ceramics, highlighting their biochemical and mechanical properties, as well as trends in the manufacture of commercial bioglass products for various biomedical applications [236].

Glass-ceramic materials can be made from glasses through a suitable heat treatment, resulting in nucleation phases and the growth of specific crystalline phases inside the remanent vitreous matrix. It has a very fine microstructure with a small number of or no residual pores. These characteristics improve the mechanical qualities of the final product. A favourable microstructure can be achieved both through appropriate heat treatments and through the use of additives that can act as nucleating agents [237]. The main methods of obtaining bioactive glasses and glass ceramics are the traditional melting techniques [238], the sol–gel method [239–241], the synthesis assisted by ultrasound [242], microwaves [243] or the hydrothermal synthesis [244].

3.3. Nonbiodegradable Polymers

Nondegradable polymers are used in biomedicine, being resistant substrates over time and proving a good performance throughout the life of the patients. They are easily processed in different shapes and can be bio-integrated together with other materials into larger or smaller surfaces, in various thicknesses. They are robust and present excellent mechanical properties [245]. In the medical field, nondegradable polymers are used for the manufacture of tissue engineering scaffolds, orthopaedic implants, heart valves, bone and cartilage substitutes, vascular grafts, artificial hips, eye lenses, fillings and other components in the dental field, bone cements. Many nondegradable polymers such as poly(ethylene), poly(propylene), poly(tetrafluoroethylene), poly(methyl methacrylate), polyurethanes, poly(dimethylsiloxane), poly(ethylene terphthlate), poly(sulfone), poly(ethyleneoxide) are processed under trade names by different companies as parts or medical devices for diverse medical dysfunctions. The most important parameters of long-term implantable nondegradable materials are their biocompatibility, biostability and mechanical resistance to wear [246].

3.4. Biodegradable Polymers

Synthetic biodegradable polymers can be tailored to have an improved and stable range of mechanical and chemical properties compared to natural polymers. They do not present the risk of causing an immune reaction or transmitting microbes or viruses, but the issue of biocompatibility and possible long-term effects such as the appearance of scars or inflammations arises. Among the most commonly employed biodegradable synthetic polymers for biomedical applications are saturated aliphatic polyesters, polyanhydrides and polyurethanes.

Poly(glycolic acid) (PGA), polylactic acid (PLA) and the copolymer poly(lactic-co-glycolic acid) (PLGA) are saturated aliphatic polyesters frequently used for the manufacture of 3D scaffolds applied in tissue engineering, due to their biocompatibility and biodegradability [247]. PLA is a material used extensively in biomedical applications and very suitable especially for cardiac, dental or orthopaedic fixation devices, because it is biocompatible. However, it is biodegradable over a long period of time and also can be used for other implantable devices, especially in paediatric patients [248]. It is used in regenerative medicine due to its ability to stimulate hard tissue regeneration in bone grafting procedures, having an extraordinary capacity for bioresorption. Many studies have been reported on PLA-HA [249] or PLA-polycaprolactone-hydroxyapatite composite materials that have highlighted their promising preliminary results for biomedical applications [250]. As a hydrophilic and highly crystalline polymer, with a relatively fast degradation rate in aqueous solutions or in vivo, PGA can be used in drug delivery [251], biological adhesives/glues [252], oral surgical treatments and injectable microspheres [253].

Poly(ε-caprolactone) (PCL) is a useful biodegradable biomaterial that can slowly degrade (in few years) under physiological conditions and is therefore used for long-term implants (in the treatment of bone defects), drug delivery systems [254] and as delivery platforms for various extracellular matrix proteins [255] or 3D scaffolds [256]. Polyanhydrides are hydrophobic polymers whose degradation occurs more through surface erosion than volume. This feature is very practical in the case of the release of certain drugs and especially important in the case of extremely strong drugs. Because water does not penetrate before the polymer is eroded, the implanted drugs are kept safe [257]. The PCL is conventionally used as a local (targeted) delivery vehicle especially for the controlled release of chemotherapeutic agents [258].

Polyurethanes are biocompatible, biodegradable polymers with excellent flexibility, durability and resistance. Due to their biostability, they are favourable inert materials for development of medical devices [259], vascular grafts [260], prostheses [261], heart valves [262,263], catheters [264], drug delivery and as porous scaffolds for tissue regeneration [265].

Table 4 summarizes the recent developments of polymer-based biomaterials in the biomedical domain.

Table 4. Polymeric materials used in biomedical applications.

Polymers	Characteristics	Applications	References
Polyesters	degradability, bioresorbability (new polymer classes)	tissue engineering, nanoscaled drug delivery systems	[266]
Polyurethane	easily malleable and flexible, biocompatibility, prominent mechanical properties (high tensile strength, toughness and resistance to degradation)	biomedical devices (cardiovascular surgery, orthopaedic surgery and traumatology, reconstructive surgery, gynaecology and obstetrics, gene therapy, implantable vascular grafts)	[267,268]
Polyamides	biocompatibility, controlled porosity, high processability, excellent stress crack resistance, biocompatibility, good mechanical strength and good stability in human body fluid	antimicrobial wound dressings, wound healing applications	[269,270]
Polysiloxanes	extensible elastomer, low tensile strength and tensile modulus	implantable devices (vascular prostheses), magneto-responsive 4D-printed bioproducts	[271,272]
Acrylics	good mechanical strength, resistant to a wide range of chemicals, excellent UV-light transmittance, good scratch resistance, biocompatibility	odontological applications including artificial teeth, dentures and denture bases, obturators, provisional or permanent crown, biomedical applications	[273,274]
Polymeric composites	biocompatibility, high corrosion resistance, very high compressive yield strength, bioresorbable implant material, antimicrobial properties	orthopaedic applications, tissue engineering, flexible antibacterial surfaces, antiadhesive surface biomaterials, acrylic bone cements, dental adhesives, antiadhesive surfaces for biomedicine, medical sutures	[275–277]

4. Composite Biomaterials

Composites are materials based on two or more different compounds in order to improve the individual properties of materials such as surface characteristics, mechanical strength and biocompatibility in order to be easy for manufacturing. Polymer-based composites have shown an increased interest in biomedicine applications for drug release, tissue engineering, regenerative medicine, wound dressings, surgical operations, medical imaging in cancer detection and dental resin composites [278,279].

The recently developed biomaterials for their applications in the biomedical area are shown in Table 5.

Table 5. Composite biomaterials for biomedical applications.

Material	Characteristics	Applications	References
Smart elastomer composites	rapid light-responsive self-healing ability and shape memory	surgical sutures to promote wound healing (as spiral-like stand)	[280]
HNT-PVA-ALG-Hap composite on alkali-treated Ti–6Al–4V alloy substrate	biocompatible with the human tissues	biomedical applications (bone regeneration)	[281]

Table 5. *Cont.*

Material	Characteristics	Applications	References
Polydopamine (PDA)-coated hydroxyapatite (HA)-reinforced polyvinyl alcohol (PVA) films	higher mechanical properties, homogeneous mineral distributions, high antibacterial capacities against Acinetobacter *Baumannii* (*A. Baumannii*), *Staphylococcus aureus* (*S. aureus*) and *Streptococcus mutans* (*S. mutans*), good biocompatibility with fibroblast (L929) cells and MCS cells	biomedical fields (tooth-bone treatments for coating, filling or occlusion purposes)	[282]
Electrospun graphene oxide/calcium hydroxyapatite/ polycaprolactone composites	biocompatibility, antimicrobial activity	excellent biological compatibility for prospective application in medicine and clinical dentistry biologically (compatible matrix for potential bone tissue regeneration with antimicrobial effect)	[283]
Ternary nanocomposites, including graphene oxide (GO), hydroxyapatite (HAP) and cadmium selenite (CdSe) encapsulated into nanofibrous scaffolds of polylactic acid	good wettability and mechanical properties, cell viability and cell growth in vitro	advanced bioactive material for effective and fast wound healing, for tissue engineering application	[284]
Dual mineral-substituted hydroxyapatite (DM-HAP) combined with biodegradable polymer alginate–chitosan (ALG-CS) and graphene oxide	improved antibacterial activity performance and bioactivity	tissue engineering applications (orthopaedic applications as soft bone tissue replacements)	[285]
$NiFe_2O_4$/NG/cellulose composites	antibacterial activity against *Escherichia coli* (Gram-negative bacteria) and *Bacillus subtilis* (Gram-positive bacteria)	biomedical applications (as antibacterial material)	[286]
Biocomposite based on alginate/gelatine crosslinked with genipin	thermal stabilization	bioengineering (support for β-galactosidase enzyme immobilization)	[287]
Chitosan/poly(vinyl alcohol)/graphene oxide (CS/PVA/GO) nanocomposites	biodegradable films with good mechanical, chemical and biological properties	tissue engineering and cell regeneration	[288]
CNF-NCG reinforced drug-loaded PVA/MC/PEG glutaraldehyde cross-linked novel electrospun nanofibrous bio-nanocomposites (BNCs)	biocompatibility, biodegradability	transdermal drug delivery systems	[289]
Biowaste-derived nanophase yttrium-substituted hydroxyapatite/citrate cellulose/opuntia mucilage (Y-nHAP/CC/OM) biocomposites	potential bacterial resistance against both Gram-positive and Gram-negative strains, in vitro cytocompatibility, considerable mechanical, antibacterial and biological properties, valorisation of biowaste material	biomedical applications	[290]
Hydroxyapatite (HA)/nanostructured monticellite ceramic composites	good in vitro bioactivity biocompatibility and antibacterial properties, ceramic composites could induce apatite formation in SBF	biomaterial for clinical applications such as orthopaedic and dentistry	[291]

Summarizing, the main properties of biomaterials required for their applications in the biomedical domain are presented in Figure 11, and the strategy for synthesis and processing technologies applied in order to develop biomaterials for the use in biomedical fields is presented in Figure 12.

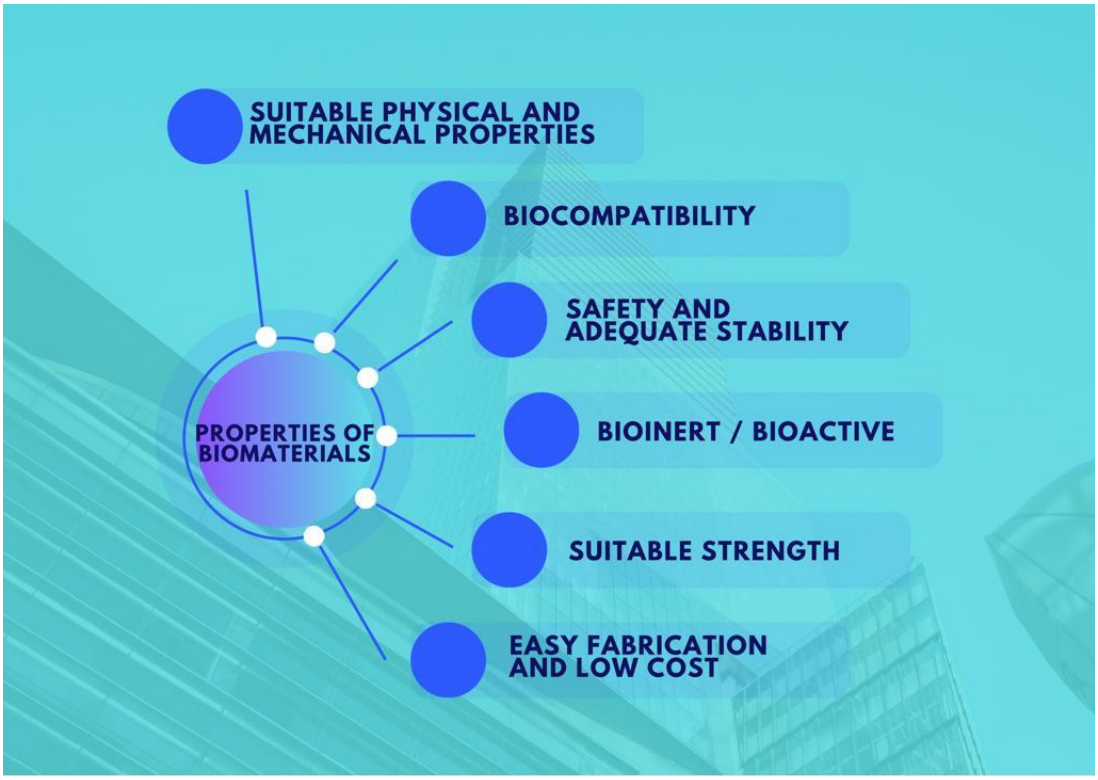

Figure 11. Required properties of biomaterials to be use in biomedical applications.

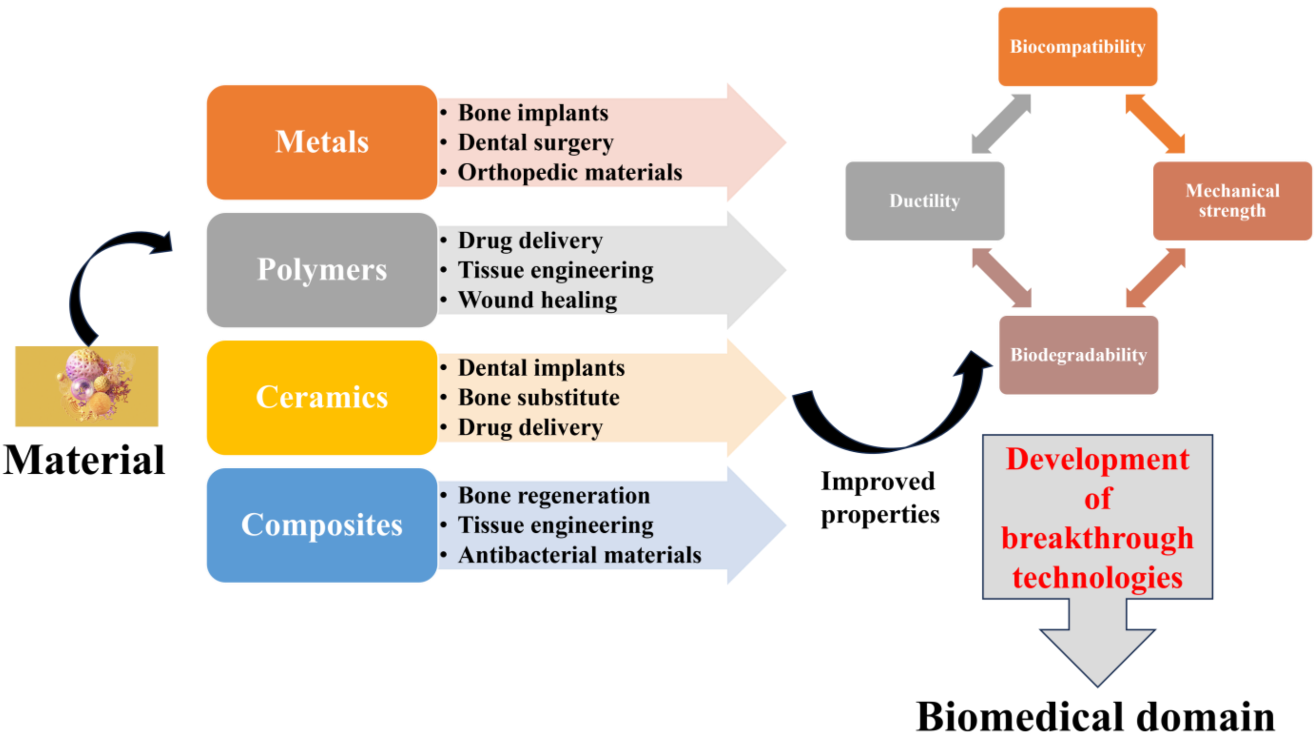

Figure 12. Biomedical applications of biomaterials.

5. Conclusions and Future Perspectives

Progress in biomaterials will comprise the advance of supplementary functional medical biomaterials and the extended usage of biomaterials in the novel areas of their application. Nevertheless, the future may also suggest a prospect for researchers in the field to reconsider essentially the method in which motivation is drawn from natural science. Consideration of the natural mechanisms of complex dynamic performances of materials in their medium may lead to the design/synthesis of innovative materials that replicates the nature by reproducing the functional comportment of these biomaterials in order to acquire new properties that are presently unreachable. The future research will be focused on a new generation of bioinspired "smart", multifunctional biomaterials for monitoring health and for preventing biological crises. A serious rational stage in biomaterial design and synthesis will be their recognition as models or templates of biopolymers and organisms for multifunctional, active devices. The economic and social impact will be diminished by reducing the costs related to the manufacturing process of existing chemicals and drugs. This will need the progress and application of new methods from different areas such as engineering, biology and the physical and chemical sciences.

Author Contributions: Conceptualization, M.C. and A.M.M.; methodology, A.M.M.; validation, A.M.M.; resources, A.M.M.; data curation, M.C. and A.M.M.; writing—original draft preparation, M.C. and A.M.M.; writing—review and editing, A.M.M.; visualization, A.M.M.; supervision, A.M.M.; project administration, A.M.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

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

References

1. Ackun-Farmmer, M.A.; Overby, C.T.; Haws, B.E.; Choe, R.; Benoit, D.S.W. Biomaterials for Orthopaedic Diagnostics and Theranostics. *Curr. Opin. Biomed. Eng.* **2021**, *19*, 100308. [CrossRef] [PubMed]
2. Kharbikar, B.N.; Zhong, J.X.; Cuylear, D.L.; Perez, C.A.; Desai, T.A. Theranostic biomaterials for tissue engineering. *Curr. Opin. Biomed. Eng.* **2021**, *19*, 100299. [CrossRef]
3. Li, J.; Zhang, H.; Han, Y.; Hu, Y.; Geng, Z.; Su, J. Targeted and responsive biomaterials in osteoarthritis. *Theranostics* **2023**, *13*, 931–954. [CrossRef]
4. Ersanli, C.; Tzora, A.; Skoufos, I.; Voidarou, C.; Zeugolis, D.I. Recent Advances in Collagen Antimicrobial Biomaterials for Tissue Engineering Applications: A Review. *Int. J. Mol. Sci.* **2023**, *24*, 7808. [CrossRef]
5. Gu, Z.; Wang, J.; Fu, Y.; Pan, H.; He, H.; Gan, Q.; Liu, C. Smart biomaterials for articular cartilage repair and regeneration. *Adv. Funct. Mater.* **2023**, *33*, 2212561. [CrossRef]
6. Gao, N.; Zeng, X.; Chen, H.; Pan, G.; Chen, G.; Xie, Z. Responsive Biomaterials for Controlled Release and Cancer Theranostics. *Front. Bioeng. Biotechnol.* **2023**, *11*, 1255293. [CrossRef] [PubMed]
7. Nehru, S.; Rajavel, T.; Misra, R. Smart Theranostic Biomaterials for Advanced Healthcare Application. In *Functional Biomaterials: Drug Delivery and Biomedical Applications*; Springer: Singapore, 2022; pp. 187–201.
8. Khatun, S.; Bonala, S.; Pogu, S.V.; Rengan, A.K. Functional Biomaterials: Drug Delivery and Biomedical Applications Polymeric Micelle in Drug Delivery Applications. In *Functional Biomaterials*; Jana, S., Ed.; Springer: Singapore, 2022. [CrossRef]
9. Sam, S.; Joseph, B.; Thomas, S. Exploring the antimicrobial features of biomaterials for biomedical applications. *Results Eng.* **2023**, *17*, 100979. [CrossRef]
10. Assad, M.; Jackson, N. Biocompatibility evaluation of orthopedic biomaterials and medical devices: A review of safety and efficacy models. In *Encyclopedia of Biomedical Engineering*, 1st ed.; Narayan, R.J., Ed.; Elsevier: Amsterdam, The Netherlands, 2019; Volume 2, pp. 281–309.
11. Doherty, P.J.; Williams, R.L.; Williams, D.F.; Lee, J.C. (Eds.) *Biomaterial-Tissue Interfaces, Advances in Biomaterials*; Elsevier: Amsterdam, The Netherlands, 1992; Volume 10.
12. Huebsch, N.; Mooney, D.J. Inspiration and application in the evolution of biomaterials. *Nature* **2009**, *462*, 426–432. [CrossRef] [PubMed]
13. Heness, G.; Ben-Nissan, B. Innovative bioceramics. *Mater. Forum* **2004**, *27*, 104–114.
14. Zimmerman, L.M.; Veith, I. *Great Ideas in the History of Surgery*, 1st ed.; Norman Publishers: New York, NY, USA, 1993.
15. A Brief History of Biomedical Materials [PDF] DSM. 2009, pp. 1–2. Available online: https://www.dsm.com/content/dam/dsm/cworld/en_US/documents/brief-history-biomedical-materials-en.pdf (accessed on 1 August 2023).

16. Hu, K.; Li, Y.; Ke, Z.; Yang, H.; Lu, C.; Li, Y.; Guo, Y.; Wang, W. History, progress and future challenges of artificial blood vessels: A narrative review. *Biomater. Transl.* **2022**, *3*, 81–98. [CrossRef]
17. Moritz, W.R.; Raman, S.; Pessin, S.; Martin, C.; Li, X.; Westman, A.; Sacks, J.M. The History and Innovations of Blood Vessel Anastomosis. *Bioengineering* **2022**, *9*, 75. [CrossRef] [PubMed]
18. Russo, M.; Taramasso, M.; Guidotti, A.; Pozzoli, A.; Nietilspach, F.; von Segesser, L.K.; Maisano, F. The evolution of surgical valves. *Cardiovasc. Med.* **2017**, *20*, 285–292. [CrossRef]
19. Todros, S.; Todesco, M.; Bagno, A. Biomaterials and Their Biomedical Applications: From Replacement to Regeneration. *Processes* **2021**, *9*, 1949. [CrossRef]
20. Available online: https://www.scopus.com (accessed on 12 August 2023).
21. Insuasti-Cruz, E.; Suarez-Jaramillo, V.; Mena Urresta, K.A.; Pila-Varela, K.O.; Fiallos-Ayala, X.; Dahoumane, S.A.; Alexis, F. Natural Biomaterials from Biodiversity for Healthcare Applications. *Adv. Healthc. Mater.* **2022**, *11*, 2101389. [CrossRef]
22. Sun, J.; Han, J.; Wang, F.; Liu, K.; Zhang, H. Bioengineered Protein-based Adhesives for Biomedical Applications. *Chemistry* **2022**, *28*, e202102902. [CrossRef] [PubMed]
23. Roberts, A.D.; Finnigan, W.; Kelly, P.P.; Faulkner, M.; Breitling, R.; Takano, E.; Scrutton, N.S.; Blaker, J.J.; Hay, S. Non-covalent protein-based adhesives for transparent substrates—Bovine serum albumin vs. recombinant spider silk. *Mater. Today Bio* **2020**, *7*, 100068. [CrossRef]
24. Fan, J.; Abedi-Dorcheh, K.; Sadat Vaziri, A.; Kazemi-Aghdam, F.; Rafieyan, S.; Sohrabinejad, M.; Ghorbani, M.; Rastegar Adib, F.; Ghasemi, Z.; Klavins, K.; et al. A Review of Recent Advances in Natural Polymer-Based Scaffolds for Musculoskeletal Tissue Engineering. *Polymers* **2022**, *14*, 2097. [CrossRef]
25. Brovold, M.; Almeida, J.I.; Pla-Palacín, I.; Sainz-Arnal, P.; Sánchez-Romero, N.; Rivas, J.J.; Almeida, H.; Dachary, P.R.; Serrano-Aulló, T.; Soker, S.; et al. Naturally-Derived Biomaterials for Tissue Engineering Applications. *Adv. Exp. Med. Biol.* **2018**, *1077*, 421–449. [CrossRef]
26. Li, Y.; Liu, Y.; Li, R.; Bai, H.; Zhu, Z.; Zhu, L.; Zhu, C.; Che, Z.; Liu, H.; Wang, J.; et al. Collagen-based biomaterials for bone tissue engineering. *Mater. Des.* **2021**, *210*, 110049. [CrossRef]
27. Habermehl, J.; Skopinska, J.; Boccafoschi, F.; Sionkowska, A.; Kaczmarek, H.; Laroche, G.; Mantovani, D. Preparation of ready-to-use, stockable and reconstituted collagen. *Macromol. Biosci.* **2005**, *5*, 821–828. [CrossRef]
28. Bose, S.; Li, S.; Mele, E.; Williams, C.J.; Silberschmidt, V.V. Stability and mechanical performance of collagen films under different environmental conditions. *Polym. Degrad. Stab.* **2022**, *197*, 109853. [CrossRef]
29. Sionkowska, A. Collagen blended with natural polymers: Recent advances and trends. *Prog. Polym. Sci.* **2021**, *122*, 101452. [CrossRef]
30. Ferreira, A.C.; Bomfim, M.R.Q.; da Costa Sobrinho, C.H.B.; Boaz, D.T.L.; Da Silva Lira, R.; Fontes, V.C.; Arruda, M.O.; Zago, P.M.W.; Filho, C.A.A.; Dias, C.J.M.; et al. Characterization, antimicrobial and cytotoxic activity of polymer blends based on chitosan and fish collagen. *AMB Express* **2022**, *12*, 102. [CrossRef]
31. Xie, Y.; Kawazoe, N.; Yang, Y.; Chen, G. Preparation of mesh-like collagen scaffolds for tissue engineering, *Mater. Adv.* **2022**, *3*, 1556–1564. [CrossRef]
32. Bose, S.; Li, S.; Mele, E.; Silberschmidt, V.V. Exploring the Mechanical Properties and Performance of Type-I Collagen at Various Length Scales: A Progress Report. *Materials* **2022**, *15*, 2753. [CrossRef]
33. Shen, M.; Qiao, N.; Shou, X.; Chen, Z.; He, W.; Ma, Z.; Ye, Z.; Zhang, Y.; Zhang, Q.; Zhou, X.; et al. Collagen sponge is as effective as autologous fat for grade 1 intraoperative cerebral spinal fluid leakage repair during transsphenoidal surgery. *Clin. Neurol. Neurosurg.* **2022**, *214*, 107131. [CrossRef]
34. Santhakumar, S.; Oyane, A.; Nakamura, M.; Koga, K.; Miyata, S.; Muratsubaki, K.; Miyaji, H. In situ precipitation of amorphous calcium phosphate nanoparticles within 3D porous collagen sponges for bone tissue engineering. *Mater. Sci. Eng. C* **2020**, *116*, 111194. [CrossRef]
35. Sun, L.; Li, B.; Song, W.; Zhang, K.; Fan, Y.; Hou, H. Comprehensive assessment of Nile tilapia skin collagen sponges as hemostatic dressings. *Mater. Sci. Eng. C* **2020**, *109*, 110532. [CrossRef]
36. Valenzuela-Rojo, R.D.; López-Cervantes, J.; Sánchez-Machado, D.I.; Escárcega-Galaz, A.A.; del Rosario Martínez-Macias, M. Antibacterial, mechanical and physical properties of collagen—Chitosan sponges from aquatic source. *Sustain. Chem. Pharm.* **2020**, *15*, 100218. [CrossRef]
37. Matsumine, H.; Fujimaki, H.; Takagi, M.; Mori, S.; Iwata, T.; Shimizu, M.; Takeuchi, M. Full-thickness skin reconstruction with basic fibroblast growth factor-impregnated collagen-gelatin sponge. *Regen. Ther.* **2019**, *11*, 81–87. [CrossRef] [PubMed]
38. Yang, Y.; Zhang, Y.; Min, Y.; Chen, J. Preparation of methacrylated hyaluronate/methacrylated collagen sponges with rapid shape recovery and orderly channel for fast blood absorption as hemostatic dressing. *Int. J. Biol. Macromol.* **2022**, *222*, 30–40. [CrossRef] [PubMed]
39. El-Fattah, A.M.A.; Ebada, H.A.; Tawfik, A. Surgiflo® may have a potential impact on the healing process in cricotracheal resection anastomosis. *Clin. Otolaryngol.* **2020**, *45*, 870–876. [CrossRef]
40. Zheng, F.; Yang, X.; Li, J.; Tian, Z.; Xiao, B.; Yi, S.; Duan, L. Coordination with zirconium: A facile approach to improve the mechanical properties and thermostability of gelatin hydrogel. *Int. J. Biol. Macromol.* **2022**, *205*, 595–603. [CrossRef]

41. Alsakhawy, S.A.; Baghdadi, H.H.; El-Shenawy, M.A.; Sabra, S.A.; El-Hosseiny, L.S. Encapsulation of thymus vulgaris essential oil in caseinate/gelatin nanocomposite hydrogel: In vitro antibacterial activity and in vivo wound healing potential. *Int. J. Pharm.* **2022**, *628*, 122280. [CrossRef]
42. Mohseni, M.; Shokrollahi, P.; Shokrolahi, F.; Hosseini, S.; Taghiyar, L.; Kamali, A. Dexamethasone loaded injectable, self-healing hydrogel microspheresbased on UPy-functionalized Gelatin/ZnHAp physical network promotes bone regeneration. *Int. J. Pharm.* **2022**, *626*, 122196. [CrossRef]
43. Johari, N.; Khodaei, A.; Samadikuchaksaraei, A.; Reis, R.L.; Kundu, S.C.; Moroni, L. Ancient fibrous biomaterials from silkworm protein fibroin and spider silk blends: Biomechanical patterns. *Acta Biomater.* **2022**, *153*, 38–67. [CrossRef]
44. Zhang, S.; Atta-ul-Mubeen Shah, S.; Basharat, K.; Qamar, S.A.; Raza, A.; Mohamed, A.; Bilal, M.; Iqbal, H.M.N. Silk-based nano-hydrogels for futuristic biomedical applications. *J. Drug Deliv. Sci. Technol.* **2022**, *72*, 103385. [CrossRef]
45. Chen, Z.K.; Chen, M.; Lu, S.; Zhang, F.; Zhu, T. Anisotropic silk film inspired by reed leaves for biomedical application. *Mater. Lett.* **2022**, *313*, 131754. [CrossRef]
46. Eivazzadeh-Keihan, R.; Pourakbari, B.; Jahani, Z.; Aliabadi, H.A.M.; Kashtiaray, A.; Rahmati, S.; Pouri, S.; Ghafuri, H.; Maleki, A.; Mahdavi, M. Biological investigation of a novel nanocomposite based on functionalized graphene oxide nanosheets with pectin, silk fibroin and zinc chromite nanoparticles. *J. Biotechnol.* **2022**, *358*, 55–63. [CrossRef] [PubMed]
47. Casanova-Batlle, E.; Guerra, A.J.; Ciurana, J. A novel direct ink writing manufacturing system to 3D print highly concentrated silk fibroin. *Procedia CIRP* **2022**, *110*, 231–235. [CrossRef]
48. Zhao, W.; Cao, S.; Cai, H.; Wu, Y.; Pan, Q.; Lin, H.; Fang, J.; He, Y.; Deng, H.; Liu, Z. Chitosan/silk fibroin biomimic scaffolds reinforced by cellulose acetate nanofibers for smooth muscle tissue engineering. *Carbohydr. Polym.* **2022**, *298*, 120056. [CrossRef]
49. Radeloff, K.; Weiss, D.; Hagen, R.; Kleinsasser, N.; Radeloff, A. Differentiation Behaviour of Adipose-Derived Stromal Cells (ASCs) Seeded on Polyurethane-Fibrin Scaffolds In Vitro and In Vivo. *Biomedicines* **2021**, *9*, 982. [CrossRef]
50. Rojas-Murillo, J.A.; Simental-Mendía, M.A.; Moncada-Saucedo, N.K.; Delgado-Gonzalez, P.; Islas, J.F.; Roacho-Pérez, J.A.; Garza-Treviño, E.N. Physical, Mechanical, and Biological Properties of Fibrin Scaffolds for Cartilage Repair. *Int. J. Mol. Sci.* **2022**, *23*, 9879. [CrossRef] [PubMed]
51. Sharma, S.; Rostamabadi, H.; Gupta, S.; Kumar Nadda, A.; Saeed Kharazmi, M.; Mahdi Jafari, S. Nano/micro-formulations of keratin in biocomposites, wound healing and drug delivery systems; recent advances in biomedical applications. *Eur. Polym. J.* **2022**, *180*, 111614. [CrossRef]
52. Feroz, S.; Muhammad, N.; Ratnayake, J.; Dias, G. Keratin-Based materials for biomedical applications. *Bioact. Mater.* **2020**, *5*, 496–509. [CrossRef] [PubMed]
53. Itoh, T.; Miyazaki, J.; Sugawara, H.; Adachi, S. Studies on the characterization of ovomucin and chalaza of the hen's egg. *J. Food Sci.* **1987**, *52*, 1518–1521. [CrossRef]
54. Vivinus-Nébot, M.; Frin-Mathy, G.; Bzioueche, H.; Dainese, R.; Bernard, G.; Anty, R.; Filippi, J.; Saint-Paul, M.C.; Tulic, M.K.; Verhasselt, V.; et al. Functional Bowel Symptoms in Quiescent Inflammatory Bowel Diseases: Role of Epithelial Barrier Disruption and Low-Grade Inflammation. *Gut* **2014**, *63*, 744–752. [CrossRef]
55. Akbari, A.; Wu, J. Ovomucin nanoparticles: Promising carriers for mucosal delivery of drugs and bioactive compounds. *Drug Deliv. Transl. Res.* **2017**, *7*, 598–607. [CrossRef]
56. Engl, P.; Hedtke, T.; Götze, M.; Martins de Souza e Silva, J.; Hillrichs, G.; Schmelzer, C.E.H. Laser microstructuring of elastin-gelatin-based biomedical materials. *Procedia CIRP* **2022**, *111*, 638–642. [CrossRef]
57. Daamen, W.F.; Veerkamp, J.H.; van Hest, J.C.M.; van Kuppevelt, T.H. Elastin as a biomaterial for tissue engineering. *Biomaterials* **2007**, *28*, 4378–4398. [CrossRef] [PubMed]
58. Regueiro, U.; López-López, M.; Varela-Fernández, R.; Otero-Espinar, F.J.; Lema, I. Biomedical Applications of Lactoferrin on the Ocular Surface. *Pharmaceutics* **2023**, *15*, 865. [CrossRef] [PubMed]
59. Liu, J.; Shi, L.; Deng, Y.; Zou, M.; Cai, B.; Song, Y.; Wang, Z.; Wang, L. Silk sericin-based materials for biomedical applications. *Biomaterials* **2022**, *287*, 121638. [CrossRef]
60. Wang, Z.; Wang, J.; Jin, Y.; Luo, Z.; Yang, W.; Xie, H.; Huang, K.; Wang, L. A neuroprotective sericin hydrogel as an effective neuronal cell carrier for the repair of ischemic stroke. *ACS Appl. Mater. Interfaces* **2015**, *7*, 24629–24640. [CrossRef]
61. Qi, C.; Liu, J.; Jin, Y.; Xu, L.; Wang, G.; Wang, Z.; Wang, L. Photo-crosslinkable, injectable sericin hydrogel as 3D biomimetic extracellular matrix for minimally invasive repairing cartilage. *Biomaterials* **2018**, *163*, 89–104. [CrossRef] [PubMed]
62. Tyeb, S.; Kumar, N.; Kumar, A.; Verma, V. Flexible agar-sericin hydrogel film dressing for chronic wounds. *Carbohydr. Polym.* **2018**, *200*, 572–582. [CrossRef]
63. Ai, L.; Wang, Y.; Tao, G.; Zhao, P.; Umar, A.; Wang, P.; He, H. Polydopamine-based surface modification of ZnO nanoparticles on sericin/polyvinyl alcohol composite film for antibacterial application. *Molecules* **2019**, *24*, 503. [CrossRef]
64. Xie, H.; Yang, W.; Chen, J.J.; Zhang, X.; Lu, X.; Zhao, K.; Huang, H.; Li, P.; Chang, Z.; Wang, L.; et al. silk sericin/silicone nerve guidance conduit promotes regeneration of a transected sciatic nerve. *Adv. Healthc. Mater.* **2015**, *4*, 2195–2205. [CrossRef] [PubMed]
65. Rao, J.; Cheng, Y.; Liu, Y.; Ye, Z.; Zhan, B.; Quan, D.; Xu, Y. A multi-walled silk fibroin/silk sericin nerve conduit coated with poly(lactic-co-glycolic acid) sheath for peripheral nerve regeneration. *Mater. Sci. Eng. C* **2017**, *73*, 319–332. [CrossRef] [PubMed]

66. Zhang, L.; Yang, W.; Xie, H.; Wang, H.; Wang, J.; Su, Q.; Li, X.; Song, Y.; Wang, G.; Wang, L.; et al. Sericin nerve guidance conduit delivering therapeutically repurposed clobetasol for functional and structural regeneration of transected peripheral nerves. *ACS Biomater. Sci. Eng.* **2019**, *5*, 1426–1439. [CrossRef]
67. Li, X.; Yang, W.; Xie, H.; Wang, J.; Zhang, L.; Wang, Z.; Wang, L. CNT/Sericin conductive nerve guidance conduit promotes functional recovery of transected peripheral nerve injury in a rat model. *ACS Appl. Mater. Interfaces* **2020**, *12*, 36860–36872. [CrossRef] [PubMed]
68. Karahaliloglu, Z.; Kilicay, E.; Denkbas, E.B. Antibacterial chitosan/silk sericin 3D porous scaffolds as a wound dressing material. *Artif. Cells Nanomed. Biotechnol.* **2017**, *45*, 1–14. [CrossRef]
69. Zhang, L.; Yang, W.; Tao, K.; Song, Y.; Xie, H.; Wang, J.; Li, X.; Shuai, X.; Gao, J.; Chang, P.; et al. Sustained local release of NGF from a chitosan-sericin composite scaffold for treating chronic nerve compression. *ACS Appl. Mater. Interfaces* **2017**, *9*, 3432–3444. [CrossRef] [PubMed]
70. Lamboni, L.; Xu, C.; Clasohm, J.; Yang, J.; Saumer, M.; Schafer, K.H.; Yang, G. Silk sericin-enhanced microstructured bacterial cellulose as tissue engineering scaffold towards prospective gut repair. *Mater. Sci. Eng. C* **2019**, *102*, 502–510. [CrossRef]
71. Das, G.; Shin, H.S.; Campos, E.V.R.; Fraceto, L.F.; Del Pilar Rodriguez-Torres, M.; Mariano, K.C.F.; de Araujo, D.R.; Fernandez-Luqueno, F.; Grillo, R.; Patra, J.K. Sericin based nanoformulations: A comprehensive review on molecular mechanisms of interaction with organisms to biological applications. *J. Nanobiotechnol.* **2021**, *19*, 30. [CrossRef]
72. Surendran, G.; Sherje, A.P. Cellulose nanofibers and composites: An insight into basics and biomedical applications. *J. Drug Deliv. Sci. Technol.* **2022**, *75*, 103601. [CrossRef]
73. Almeida, A.P.C.; Saraiva, J.N.; Cavaco, G.; Portela, R.P.; Leal, C.R.; Sobral, R.G.; Almeida, P.L. Crosslinked bacterial cellulose hydrogels for biomedical applications. *Eur. Polym. J.* **2022**, *177*, 111438. [CrossRef]
74. Abdelhamid, H.N.; Mathew, A.P. Cellulose-Based Nanomaterials Advance Biomedicine: A Review. *Int. J. Mol. Sci.* **2022**, *23*, 5405. [CrossRef]
75. Chelu, M.; Popa, M.; Calderon Moreno, J.; Leonties, A.R.; Ozon, E.A.; Pandele Cusu, J.; Surdu, V.A.; Aricov, L.; Musuc, A.M. Green Synthesis of Hydrogel-Based Adsorbent Material for the Effective Removal of Diclofenac Sodium from Wastewater. *Gels* **2023**, *9*, 454. [CrossRef]
76. Baharlouei, P.; Rahman, A. Chitin and Chitosan: Prospective Biomedical Applications in Drug Delivery, Cancer Treatment, and Wound Healing. *Mar. Drugs* **2022**, *20*, 460. [CrossRef]
77. Joseph, S.M.; Krishnamoorthy, S.; Paranthaman, R.; Moses, J.A.; Anandharamakrishnan, C. A review on source-specific chemistry, functionality, and applications of chitin and chitosan. *Carbohydr. Polym. Technol. Appl.* **2021**, *2*, 100036. [CrossRef]
78. Islam, N.; Dmour, I.; Taha, M.O. Degradability of chitosan micro/nanoparticles for pulmonary drug delivery. *Heliyon* **2019**, *5*, e01684. [CrossRef] [PubMed]
79. Cai, Y.; Lapitsky, Y. Biomolecular uptake effects on chitosan/tripolyphosphate micro- and nanoparticle stability. *Colloids Surf. B Biointerfaces* **2020**, *193*, 111081. [CrossRef]
80. Araújo, D.; Rodrigues, T.; Alves, V.D.; Freitas, F. Chitin-Glucan Complex Hydrogels: Optimization of Gel Formation and Demonstration of Drug Loading and Release Ability. *Polymers* **2022**, *14*, 785. [CrossRef]
81. Montroni, D.; Kobayashi, T.; Hao, T.; Lublin, D.; Yoshino, T.; Kisailus, D. Direct Ink Write Printing of Chitin-Based Gel Fibers with Customizable Fibril Alignment, Porosity, and Mechanical Properties for Biomedical Applications. *J. Funct. Biomater.* **2022**, *13*, 83. [CrossRef]
82. Dang, P.A.; Palomino-Durand, C.; Elsafi Mabrouk, M.; Marquaille, P.; Odier, C.; Norvez, S.; Pauthe, E.; Corté, L. Rational formulation design of injectable thermosensitive chitosan-based hydrogels for cell encapsulation and delivery. *Carbohydr. Polym.* **2022**, *277*, 118836. [CrossRef]
83. Chelu, M.; Calderon Moreno, J.; Atkinson, I.; Pandele Cusu, J.; Rusu, A.; Bratan, V.; Aricov, L.; Anastasescu, M.; Seciu-Grama, A.-M.; Musuc, A.M. Green synthesis of bioinspired chitosan-ZnO-based polysaccharide gums hydrogels with propolis extract as novel functional natural biomaterials. *Int. J. Biol. Macromol.* **2022**, *211*, 410–424. [CrossRef]
84. Medeiros Borsagli, F.G.L.; Rodrigues, J.S.; Aguiar, R.A.; Paiva, A.E.; Vasquez, J.F.B.; Ramos, W.T.D.S.; Allibrandini, P.; Rocha, E.P.A.; Gonçalves, M.P.; de Souza, F.E. Low-cost luminescent scaffolds-based on thiol chitosans by microwave radiation for vertebral disc repair/theragnostic. *Int. J. Biol. Macromol.* **2022**, *209 Pt B*, 2109–2118. [CrossRef]
85. Caballero-Flores, H.; Nabeshima, C.K.; Sarra, G.; Moreira, M.S.; Arana-Chavez, V.E.; Marques, M.M.; Machado, M.E.L. Development and characterization of a new chitosan-based scaffold associated with gelatin, microparticulate dentin and genipin for endodontic regeneration. *Dent. Mater.* **2021**, *37*, e414–e425. [CrossRef] [PubMed]
86. Grabska-Zielińska, S.; Sionkowska, A.; Coelho, C.C.; Monteiro, F.J. Silk Fibroin/Collagen/Chitosan Scaffolds Cross-Linked by a Glyoxal Solution as Biomaterials toward Bone Tissue Regeneration. *Materials* **2020**, *13*, 3433. [CrossRef]
87. Leite, Y.K.; Oliveira, A.C.; Quelemes, P.V.; Neto, N.M.; Carvalho, C.E.; Soares Rodrigues, H.W.; Alves, M.M.; Carvalho, F.A.; Arcanjo, D.D.; Silva-Filho, E.C.; et al. Novel Scaffold Based on Chitosan Hydrogels/Phthalated Cashew Gum for Supporting Human Dental Pulp Stem Cells. *Pharmaceuticals* **2023**, *16*, 266. [CrossRef] [PubMed]
88. Souza, A.P.C.; Neves, J.G.; Navarro da Rocha, D.; Lopes, C.C.; Moraes, Â.M.; Correr-Sobrinho, L.; Correr, A.B. Chitosan/Xanthan membrane containing hydroxyapatite/Graphene oxide nanocomposite for guided bone regeneration. *J. Mech. Behav. Biomed. Mater.* **2022**, *136*, 105464. [CrossRef]

89. Henrique Marcondes, S.M.; Mota Ferreira, L.; Cruz, L. The use of natural gums to produce nano-based hydrogels and films for topical application. *Int. J. Pharm.* **2022**, *626*, 122166. [CrossRef] [PubMed]
90. Mohammadinejad, R.; Kumar, A.; Ranjbar-Mohammadi, M.; Ashrafizadeh, M.; Han, S.S.; Khang, G.; Roveimiab, Z. Recent Advances in Natural Gum-Based Biomaterials for Tissue Engineering and Regenerative Medicine: A Review. *Polymers* **2020**, *12*, 176. [CrossRef]
91. Choudhary, P.D.; Pawar, H.A. Recently investigated natural gums and mucilages as pharmaceutical excipients: An overview. *J. Pharm.* **2014**, *2014*, 204849. [CrossRef]
92. De, A.; Nayak, A.K.; Kundu, A.; Das, B.; Samanta, A. Chapter 7—Gum arabic-based nanomaterials in drug delivery and biomedical applications. In *Biopolymer-Based Nanomaterials in Drug Delivery and Biomedical Applications*; Bera, H., Hossain, C.M., Saha, S., Eds.; Academic Press: Cambridge, MA, USA, 2021; pp. 165–182. [CrossRef]
93. Alghuthaymi, M.A. Antibacterial action of insect chitosan/gum Arabic nanocomposites encapsulating eugenol and selenium nanoparticles. *J. King Saud Univ. Sci.* **2022**, *34*, 102219. [CrossRef]
94. Venkatesan, J.; Hur, W.; Gupta, P.K.; Son, S.E.; Lee, H.B.; Lee, S.J.; Ha, C.H.; Cheon, S.H.; Kim, D.H.; Seong, G.H. Gum Arabic-mediated liquid exfoliation of transition metal dichalcogenides as photothermic anti-breast cancer candidates. *Int. J. Biol. Macromol.* **2023**, *244*, 124982. [CrossRef] [PubMed]
95. Guru, P.R.; Kar, R.K.; Nayak, A.K.; Mohapatra, S. A comprehensive review on pharmaceutical uses of plant-derived biopolysaccharides. *Int. J. Biol. Macromol.* **2023**, *233*, 123454. [CrossRef]
96. Prasad, N.; Thombare, N.; Sharma, S.C.; Kumar, S. Recent development in the medical and industrial applications of gum karaya: A review. *Polym. Bull.* **2023**, *80*, 3425–3447. [CrossRef]
97. Krishnappa, P.B.; Kodoth, A.K.; Kulal, P.; Badalamoole, V. Effective removal of ionic dyes from aqueous media using modified karaya gum–PVA semi-interpenetrating network system. *Polym. Bull.* **2023**, *80*, 2553–2584. [CrossRef]
98. Laha, B.; Goswami, R.; Maiti, S.; Sen, K.K. Smart karaya-locust bean gum hydrogel particles for the treatment of hypertension: Optimization by factorial design and pre-clinical evaluation. *Carbohydr. Polym.* **2019**, *210*, 274–288. [CrossRef] [PubMed]
99. Sethi, S.; Medha; Thakur, S.; Kaith, B.S. Preliminary in vitro hemocompatibility assessment of biopolymeric hydrogels for versatile biomedical applications. *Polym. Bull.* **2023**. [CrossRef]
100. Ribeiro, A.M.; Santos, A.I.; Veiga, F.; Figueiras, A. 3—Lignin nanoparticle–based nanocomposite hydrogels for biomedical applications. In *Nanotechnology in Biomedicine, Functional Nanocomposite Hydrogels*; Kumar, A., Thakur, V.K., Eds.; Elsevier: Amsterdam, The Netherlands, 2023; pp. 69–90. [CrossRef]
101. Bonifacio, M.A.; Cometa, S.; Cochis, A.; Scalzone, A.; Gentile, P.; Scalia, A.C.; Rimondini, L.; Mastrorilli, P.; De Giglio, E. A bioprintable gellan gum/lignin hydrogel: A smart and sustainable route for cartilage regeneration. *Int. J. Biol. Macromol.* **2022**, *216*, 336–346. [CrossRef]
102. Mukheja, Y.; Kaur, J.; Pathania, K.; Sah, S.P.; Salunke, D.B.; Sangamwar, A.T.; Pawar, S.V. Recent advances in pharmaceutical and biotechnological applications of lignin-based materials. *Int. J. Biol. Macromol.* **2023**, *241*, 124601. [CrossRef] [PubMed]
103. Mondal, A.K.; Uddin, M.T.; Sujan, S.M.A.; Tang, Z.; Alemu, D.; Begum, H.A.; Li, J.; Huang, F.; Ni, Y. Preparation of lignin-based hydrogels, their properties and applications. *Int. J. Biol. Macromol.* **2023**, *245*, 125580. [CrossRef]
104. Jegan, A.; Periasamy, V.S.; Alshatwi, A.A. Assessment of Osteogenic Differentiation Potential of Cytocompatible Rice Husk-Derived Lignin/Silica Nanohybrids for Bone Tissue Engineering. *Silicon* **2023**, 1–11.
105. Gaspar, R.; Fardim, P. Lignin-based materials for emerging advanced applications. *Curr. Opin. Green Sustain. Chem.* **2023**, *41*, 100834. [CrossRef]
106. Li, W.-J.; Mauck, R.L.; Tuan, R.S. Electrospun nanofibrous scaffolds: Production, characterization, and applications for tissue engineering and drug delivery. *J. Biomed. Nanotechnol.* **2005**, *1*, 259–275. [CrossRef]
107. Shabani, I.; Haddadi-Asl, V.; Soleimani, M.; Seyedjafari, E.; Babaeijandaghi, F.; Ahmadbeigi, N. Enhanced infiltration and biomineralization of stem cells on collagen-grafted three-dimensional nanofibers. *Tissue Eng. A.* **2011**, *17*, 1209–1218. [CrossRef]
108. Fayazzadeh, E.; Rahimpour, S.; Ahmadi, S.M.; Farzampour, S.; Anvari, M.S.; Boroumand, M.A.; Ahmadi, S.H. Acceleration of skin wound healing with tragacanth (Astragalus) preparation: An experimental pilot study in rats. *Acta Med. Iran.* **2014**, *52*, 3–8. [PubMed]
109. Polez, R.T.; Morits, M.; Jonkergouw, C.; Phiri, J.; Valle-Delgado, J.J.; Linder, M.B.; Maloney, T.; Rojas, O.J.; Österberg, M. Biological activity of multicomponent bio-hydrogels loaded with tragacanth gum. *Int. J. Biol. Macromol.* **2022**, *215*, 691–704. [CrossRef]
110. Madni, A.; Ayub, H.; Khalid, A.; Khan, T.; Wahid, F. Chapter 2—Applications of guar gum composites. In *Green Sustainable Process for Chemical and Environmental Engineering and Science*; Inamuddin, Altalhi, T., Alrooqi, A., Eds.; Elsevier: Amsterdam, The Netherlands, 2023; pp. 27–46. [CrossRef]
111. Sharma, G.; Sharma, S.; Kumar, A.; Al-Muhtaseb, A.H.; Naushad, M.; Ghfar, A.A.; Tessema Mola, G.; Stadler, F.J. Guar gum and its composites as potential materials for diverse applications: A review. *Carbohydr. Polym.* **2018**, *199*, 534–545. [CrossRef] [PubMed]
112. Caldera-Villalobos, M.; Cabrera-Munguía, D.A.; Becerra-Rodríguez, J.J.; Claudio-Rizo, J.A. Tailoring biocompatibility of composite scaffolds of collagen/guar gum with metal-organic frameworks. *RSC Adv.* **2022**, *12*, 3672–3686. [CrossRef] [PubMed]
113. Le, T.-A.; Guo, Y.; Zhou, J.-N.; Yan, J.; Zhang, H.; Huynh, T.-P. Synthesis, characterization and biocompatibility of guar gum-benzoic acid. *Int. J. Biol. Macromol.* **2022**, *194*, 110–116. [CrossRef]

114. Michailidou, G.; Terzopoulou, Z.; Kehagia, A.; Michopoulou, A.; Bikiaris, D.N. Preliminary Evaluation of 3D Printed Chitosan/Pectin Constructs for Biomedical Applications. *Mar. Drugs* **2021**, *19*, 36. [CrossRef]
115. Eivazzadeh-Keihan, R.; Bahojb Noruzi, E.; Aliabadi, H.A.M.; Sheikhaleslami, S.; Akbarzadeh, A.R.; Masoud Hashemi, S.; Ghafori Gorab, M.; Maleki, A.; Ahangari Cohan, R.; Mahdavi, M.; et al. Recent advances on biomedical applications of pectin-containing biomaterials. *Int. J. Biol. Macromol.* **2022**, *217*, 1–18. [CrossRef]
116. Ebenezer Leonard, T.; Filbert Liko, A.; Gustiananda, M.; Budiawan Naro Putra, A.; Betha Juanssilfero, A.; Hartrianti, P. Thiolated pectin-chitosan composites: Potential mucoadhesive drug delivery system with selective cytotoxicity towards colorectal cancer. *Int. J. Biol. Macromol.* **2023**, *225*, 1–12. [CrossRef]
117. Teoh, M.W.; Ng, C.K.; Lee, S.K.Y.; Ramesh, S.; Ting, C.H.; Chuah, Y.D.; Lim, I.Y.; Tan, C.Y.; Sutharsini, U. Densification behaviors of hydroxyapatite/pectin bio-ceramics. *Mater. Today Proc.* **2023**. [CrossRef]
118. Nguyen, T.T.T.; Tran, N.T.K.; Le, T.Q.; Nguyen, T.T.A.; Nguyen, L.T.M.; Tran, T.V. Passion fruit peel pectin/chitosan based antibacterial films incorporated with biosynthesized silver nanoparticles for wound healing application. *Alex. Eng. J.* **2023**, *69*, 419–430. [CrossRef]
119. de Souza, C.K.; Ghosh, T.; Lukhmana, N.; Tahiliani, S.; Priyadarshi, R.; Hoffmann, T.G.; Purohit, S.D.; Han, S.S. Pullulan as a sustainable biopolymer for versatile applications: A review. *Mater. Today Commun.* **2023**, *36*, 106477. [CrossRef]
120. Chauhan, N.; Gupta, P.; Arora, L.; Pal, D.; Singh, Y. Dexamethasone-loaded, injectable pullulan-poly(ethylene glycol) hydrogels for bone tissue regeneration in chronic inflammatory conditions. *Mater. Sci. Eng. C* **2021**, *130*, 112463. [CrossRef] [PubMed]
121. Younas, A.; Dong, Z.; Hou, Z.; Asad, M.; Li, M.; Zhang, N. A chitosan/fucoidan nanoparticle-loaded pullulan microneedle patch for differential drug release to promote wound healing. *Carbohydr. Polym.* **2023**, *306*, 120593. [CrossRef]
122. Aydogdu, H.; Keskin, D.; Turker Baran, E.; Tezcaner, A. Pullulan microcarriers for bone tissue regeneration. *Mater. Sci. Eng. C* **2016**, *63*, 439–449. [CrossRef] [PubMed]
123. Li, H.-Y.; Xu, E.-Y. Dual functional pullulan-based spray-dried microparticles for controlled pulmonary drug delivery. *Int. J. Pharm.* **2023**, *641*, 123057. [CrossRef] [PubMed]
124. Hatami Fard, G.; Moinipoor, Z.; Anastasova-Ivanova, S.; Iqbal, H.M.N.; Dwek, M.V.; Getting, S.J.; Keshavarz, T. Development of chitosan, pullulan, and alginate-based drug-loaded nano-emulsions as a potential malignant melanoma delivery platform. *Carbohydr. Polym. Technol. Appl.* **2022**, *4*, 100250. [CrossRef]
125. Sun, G.; Mao, J.J. Engineering dextran-based scaffolds for drug delivery and tissue repair. *Nanomedicine* **2012**, *7*, 1771–1784. [CrossRef]
126. Patil, S.B.; Inamdar, S.Z.; Reddy, K.R.; Raghu, A.V.; Soni, S.K.; Kulkarni, R.V. Novel biocompatible poly(acrylamide)-grafted-dextran hydrogels: Synthesis, characterization and biomedical applications. *J. Microbiol. Methods* **2019**, *159*, 200–210. [CrossRef]
127. Omidian, H.; Dey Chowdhury, S.; Babanejad, N. Cryogels: Advancing Biomaterials for Transformative Biomedical Applications. *Pharmaceutics* **2023**, *15*, 1836. [CrossRef] [PubMed]
128. Bauleth-Ramos, T.; Shih, T.Y.; Shahbazi, M.A.; Najibi, A.J.; Mao, A.S.; Liu, D.F.; Granja, P.; Santos, H.A.; Sarmento, B.; Mooney, D.J. Acetalated Dextran Nanoparticles Loaded into an Injectable Alginate Cryogel for Combined Chemotherapy and Cancer Vaccination. *Adv. Funct. Mater.* **2019**, *29*, 1903686. [CrossRef]
129. Pacelli, S.; Di Muzio, L.; Paolicelli, P.; Fortunati, V.; Petralito, S.; Trilli, J.; Casadei, M.A. Dextran-polyethylene glycol cryogels as spongy scaffolds for drug delivery. *Int. J. Biol. Macromol.* **2021**, *166*, 1292–1300. [CrossRef]
130. Maji, K.; Dasgupta, S.; Pramanik, K.; Bissoyi, A. Preparation and Evaluation of Gelatin-Chitosan-Nanobioglass 3D Porous Scaffold for Bone Tissue Engineering. *Int. J. Biomater.* **2016**, *14*, 9825659. [CrossRef]
131. van Uden, S.; Silva-Correia, J.; Oliveira, J.M.; Reis, R.L. Current strategies for treatment of intervertebral disc degeneration: Substitution and regeneration possibilities. *Biomater. Res.* **2017**, *21*, 22. [CrossRef]
132. Pereira, D.R.; Silva-Correia, J.; Oliveira, J.M.; Reis, R.L.; Pandit, A.; Biggs, M.J. Nanocellulose reinforced gellan-gum hydrogels as potential biological substitutes for annulus fibrosus tissue regeneration. *Nanomedicine* **2018**, *14*, 897–908. [CrossRef] [PubMed]
133. Manda, M.G.; da Silva, L.P.; Cerqueira, M.T.; Pereira, D.R.; Oliveira, M.B.; Mano, J.F.; Marques, A.P.; Oliveira, J.M.; Correlo, V.M.; Reis, R.L. Gellan gum-hydroxyapatite composite spongy-like hydrogels for bone tissue engineering. *J. Biomed. Mater. Res.* **2018**, *106*, 479–490. [CrossRef]
134. Nieto, C.; Vega, M.A.; Rodríguez, V.; Pérez-Esteban, P.; Martín Del Valle, E.M. Biodegradable gellan gum hydrogels loaded with paclitaxel for HER2+ breast cancer local therapy. *Carbohydr. Polym.* **2022**, *294*, 119732. [CrossRef]
135. Kim, W.K.; Choi, J.H.; Shin, M.E.; Kim, J.W.; Kim, P.Y.; Kim, N.; Song, J.E.; Khang, G. Evaluation of cartilage regeneration of chondrocyte encapsulated gellan gum-based hyaluronic acid blended hydrogel. *Int. J. Biol. Macromol.* **2019**, *141*, 51–59. [CrossRef] [PubMed]
136. Shin, E.Y.; Park, J.H.; Shin, M.E.; Song, J.E.; Carlomagno, C.; Khang, G. Evaluation of Chondrogenic Differentiation Ability of Bone Marrow Mesenchymal Stem Cells in Silk Fibroin/Gellan Gum Hydrogels Using miR-30. *Macromol. Res.* **2019**, *27*, 369–376. [CrossRef]
137. Izawa, H.; Nishino, S.; Maeda, H.; Morita, K.; Ifuku, S.; Morimoto, M.; Saimoto, H.; Kadokawa, J.-I. Mineralization of hydroxyapatite upon a unique xanthan gum hydrogel by an alternate soaking process. *Carbohydr. Polym.* **2014**, *102*, 846–851. [CrossRef]
138. Piola, B.; Sabbatini, M.; Gino, S.; Invernizzi, M.; Renò, F. 3D Bioprinting of Gelatin-Xanthan Gum Composite Hydrogels for Growth of Human Skin Cells. *Int. J. Mol. Sci.* **2022**, *23*, 539. [CrossRef] [PubMed]

139. Chelu, M.; Popa, M.; Ozon, E.A.; Pandele Cusu, J.; Anastasescu, M.; Surdu, V.A.; Calderon Moreno, J.; Musuc, A.M. High-Content Aloe vera Based Hydrogels: Physicochemical and Pharmaceutical Properties. *Polymers* **2023**, *15*, 1312. [CrossRef]
140. Chelu, M.; Musuc, A.M.; Aricov, L.; Ozon, E.A.; Iosageanu, A.; Stefan, L.M.; Prelipcean, A.-M.; Popa, M.; Moreno, J.C. Antibacterial Aloe vera Based Biocompatible Hydrogel for Use in Dermatological Applications. *Int. J. Mol. Sci.* **2023**, *24*, 3893. [CrossRef]
141. Alves, A.; Miguel, S.P.; Araujo, A.R.T.S.; de Jesús Valle, M.J.; Sánchez Navarro, A.; Correia, I.J.; Ribeiro, M.P.; Coutinho, P. Xanthan Gum–Konjac Glucomannan Blend Hydrogel for Wound Healing. *Polymers* **2020**, *12*, 99. [CrossRef]
142. Popa, N.; Novac, O.; Profire, L.; Lupusoru, C.E.; Popa, M.I. Hydrogels based on chitosan-xanthan for controlled release of theophylline. *J. Mater. Sci. Mater. Med.* **2010**, *21*, 1241–1248. [CrossRef]
143. Athamneh, T.; Hajnal, A.; Al-Najjar, M.A.A.; Alshweiat, A.; Obaidat, R.; Awad, A.A.; Al-Alwany, R.; Keitel, J.; Wu, D.; Kieserling, H.; et al. In vivo tests of a novel wound dressing based on agar aerogel. *Int. J. Biol. Macromol.* **2023**, *239*, 124238. [CrossRef] [PubMed]
144. Li, W.; Wu, Z.; Zhao, J.; Jiang, M.; Yuan, L.; Guo, Y.; Li, S.; Hu, L.; Xie, X.; Zhang, Y.; et al. Fabrication of dual physically cross-linked polyvinyl alcohol/agar hydrogels with mechanical stability and antibacterial activity for wound healing. *Int. J. Biol. Macromol.* **2023**, *247*, 125652. [CrossRef] [PubMed]
145. Wróblewska-Krepsztul, J.; Rydzkowski, T.; Michalska-Pozoga, I.; Thakur, V.K. Biopolymers for biomedical and pharmaceutical applications: Recent advances and overview of alginate electrospinning. *Nanomaterials* **2019**, *9*, 404. [CrossRef]
146. Raus, R.A.; Nawawi, W.M.F.W.; Nasaruddin, R.R. Alginate and alginate composites for biomedical applications. *Asian J. Pharm. Sci.* **2021**, *16*, 280–306. [CrossRef]
147. Vijian, R.S.; Yusefi, M.; Shameli, K. Plant Extract Loaded Sodium Alginate Nanocomposites for Biomedical Applications: A Review. *J. Res. Nanosci. Nanotechnol.* **2022**, *6*, 14–30. [CrossRef]
148. Cano-Vicent, A.; Hashimoto, R.; Takayama, K.; Serrano-Aroca, Á. Biocompatible Films of Calcium Alginate Inactivate Enveloped Viruses Such as SARS-CoV-2. *Polymers* **2022**, *14*, 1483. [CrossRef]
149. Aparicio-Collado, J.L.; Zheng, Q.; Molina-Mateo, J.; Cabanilles, C.T.; Vidaurre, A.; Serrano-Aroca, Á.; Serra, R.S. Engineered Highly Porous Polyvinyl Alcohol Hydrogels with Poly(3-hydroxybutyrate-co-3-hydroxyvalerate) and Graphene Nanosheets for Musculoskeletal Tissue Engineering: Morphology, Water Sorption, Thermal, Mechanical, Electrical Properties, and Biocompatibility. *Materials* **2023**, *16*, 3114. [CrossRef] [PubMed]
150. Roquero, D.M.; Katz, E. "Smart" alginate hydrogels in biosensing, bioactuation and biocomputing: State-of-the-art and perspectives. *Sens. Actuators Rep.* **2022**, *4*, 100095. [CrossRef]
151. Iravani, S.; Varma, R.S. Alginate-Based Micro- and Nanosystems for Targeted Cancer Therapy. *Mar. Drugs* **2022**, *20*, 598. [CrossRef]
152. Łopusiewicz, Ł.; Macieja, S.; Śliwiński, M.; Bartkowiak, A.; Roy, S.; Sobolewski, P. Alginate Biofunctional Films Modified with Melanin from Watermelon Seeds and Zinc Oxide/Silver Nanoparticles. *Materials* **2022**, *15*, 2381. [CrossRef]
153. Liu, F.; Duan, G.; Yang, H. Recent advances in exploiting carrageenans as a versatile functional material for promising biomedical applications. *Int. J. Biol. Macromol.* **2023**, *235*, 123787. [CrossRef] [PubMed]
154. Wei, Q.; Fu, G.; Wang, K.; Yang, Q.; Zhao, J.; Wang, Y.; Ji, K.; Song, S. Advances in research on antiviral activities of sulfated polysaccharides from seaweeds. *Pharmaceuticals* **2022**, *15*, 581. [CrossRef] [PubMed]
155. Panggabean, J.A.; Adiguna, S.P.; Rahmawati, S.I.; Ahmadi, P.; Zainuddin, E.N.; Bayu, A.; Putra, M.Y. Antiviral activities of algal-based sulfated polysaccharides. *Molecules* **2022**, *27*, 1178. [CrossRef] [PubMed]
156. Madruga, L.Y.C.; Sabino, R.M.; Santos, E.C.G.; Popat, K.C.; Balaban, R.C.; Kipper, M.J. Carboxymethyl-kappa-carrageenan: A study of biocompatibility, antioxidant and antibacterial activities. *Int. J. Biol. Macromol.* **2020**, *152*, 483–491. [CrossRef] [PubMed]
157. Vijayakumar, S.; Saravanakumar, K.; Malaikozhundan, B.; Divya, M.; Vaseeharan, B.; Duran-Lara, E.F.; Wang, M.H. Biopolymer K-carrageenan wrapped ZnO nanoparticles as drug delivery vehicles for anti MRSA therapy. *Int. J. Biol. Macromol.* **2020**, *144*, 9–18. [CrossRef] [PubMed]
158. Dev, A.; Mohanbhai, S.J.; Kushwaha, A.C.; Sood, A.; Sardoiwala, M.N.; Choudhury, S.R.; Karmakar, S. Kappa-carrageenan-C-phycocyanin based smart injectable hydrogels for accelerated wound recovery and real-time monitoring. *Acta Biomater.* **2020**, *109*, 121–131. [CrossRef] [PubMed]
159. Mokhtari, H.; Tavakoli, S.; Safarpour, F.; Kharaziha, M.; Bakhsheshi-Rad, H.R.; Ramakrishna, S.; Berto, F. Recent advances in chemically-modified and hybrid carrageenan-based platforms for drug delivery, wound healing, and tissue engineering. *Polymers* **2021**, *13*, 1744. [CrossRef]
160. Beachley, V.; Ma, G.; Papadimitriou, C.; Gibson, M.; Corvelli, M.; Elisseeff, J. Extracellular matrix particle-glycosaminoglycan composite hydrogels for regenerative medicine applications. *J. Biomed. Mater. Res.* **2018**, *106*, 147–159. [CrossRef]
161. Mahmood, A.; Patel, D.; Hickson, B.; DesRochers, J.; Hu, X. Recent Progress in Biopolymer-Based Hydrogel Materials for Biomedical Applications. *Int. J. Mol. Sci.* **2022**, *23*, 1415. [CrossRef]
162. Arnold, J.; Chapman, J.; Arnold, M.; Dinu, C.Z. Hyaluronic Acid Allows Enzyme Immobilization for Applications in Biomedicine. *Biosensors* **2022**, *12*, 28. [CrossRef]
163. Winters, C.; Zamboni, F.; Beaucamp, A.; Culebras, M.; Collins, M.N. Synthesis of Conductive Polymeric Nanoparticles with Hyaluronic Acid Based Bioactive Stabilizers for Biomedical Applications. *Mater. Today Chem.* **2022**, *25*, 100969. [CrossRef]
164. Gadomska, M.; Musiał, K.; Bełdowski, P.; Sionkowska, A. New Materials Based on Molecular Interaction between Hyaluronic Acid and Bovine Albumin. *Molecules* **2022**, *27*, 4956. [CrossRef]

165. Kim, K.; Choi, H.; Choi, E.S.; Park, M.-H.; Ryu, J.-H. Hyaluronic acid-coated nanomedicine for targeted cancer therapy. *Pharmaceutics* **2019**, *11*, 301. [CrossRef]
166. Zhang, K.; Feng, Q.; Xu, J.; Xu, X.; Tian, F.; Yeung, K.W.; Bian, L. Self-assembled injectable nanocomposite hydrogels stabilized by bisphosphonate-magnesium (Mg^{2+}) coordination regulates the differentiation of encapsulated stem cells via dual crosslinking. *Adv. Funct. Mater.* **2017**, *27*, 1701642. [CrossRef]
167. da Silva, R.S.M.; Barbosa, R.C.; dos Santos Chagas, C.; da Silva, E.B.; Feder, D.; Fonseca, F.L.A.; Fook, M.V.L. Development, preparation and characterization of chitosan, gelatin and heparin membranes for biomedical applications. *SN Appl. Sci.* **2022**, *4*, 44. [CrossRef]
168. Liu, Q.; Yang, S.; Seitz, I.; Pistikou, A.M.; de Greef, T.F.A.; Kostiainen, M.A. A Synthetic Protocell-Based Heparin Scavenger. *Small* **2023**, *19*, e2201790. [CrossRef]
169. Lima, M.; Rudd, T.; Yates, E. New Applications of Heparin and Other Glycosaminoglycans. *Molecules* **2017**, *22*, 749. [CrossRef]
170. Mizumoto, S.; Kwok, J.C.F.; Whitelock, J.M.; Li, F.; Perris, R. Editorial: Roles of Chondroitin Sulfate and Dermatan Sulfate as Regulators for Cell and Tissue Development. *Front. Cell Dev. Biol.* **2022**, *10*, 941178. [CrossRef] [PubMed]
171. Tang, T.; Muneta, T.; Ju, Y.J.; Nimura, A.; Miyazaki, K.; Masuda, H.; Mochizuki, T.; Sekiya, I. Serum keratan sulfate transiently increases in the early stage of osteoarthritis during strenuous running of rats: Protective effect of intraarticular hyaluronan injection. *Arthritis Res. Ther.* **2008**, *10*, R13. [CrossRef] [PubMed]
172. Wu, S.C.; Hsu, H.C.; Liu, M.Y.; Ho, W.F. Characterization of nanosized hydroxyapatite prepared by an aqueous precipitation method using eggshells and mulberry leaf extract. *J. Korean Ceram. Soc.* **2021**, *58*, 116–122. [CrossRef]
173. Priyadarsini, M.; Biswal, T.; Dash, S. Biodegradable superabsorbent with potential biomedical application as drug delivery system of "pectin-g-P(AN-co-AM)/chicken eggshell" bio-composite. *Polym. Bull.* **2021**, *78*, 6337–6349. [CrossRef]
174. Deffo, G.; Basumatary, M.; Hussain, N.; Hazarika, R.; Kalita, S.; Njanja, E.; Puzari, P. Eggshell nano-$CaCO_3$ decorated PANi/rGO composite for sensitive determination of ascorbic acid, dopamine, and uric acid in human blood serum and urine. *Mater. Today Commun.* **2022**, *33*, 104357. [CrossRef]
175. Sund, M.; Xie, L.; Kalluri, R. The contribution of vascular basement membranes and extracellular matrix to the mechanics of tumor angiogenesis. *APMIS* **2004**, *112*, 450–462. [CrossRef]
176. Sewell-Loftin, M.K.; Chun, Y.W.; Khademhosseini, A.; Merryman, W.D. EMT-inducing biomaterials for heart valve engineering: Taking cues from developmental biology. *J. Cardiovasc. Transl. Res.* **2011**, *4*, 658–671. [CrossRef]
177. Anand, N.; Pal, K. Evaluation of biodegradable Zn-1Mg-1Mn and Zn-1Mg-1Mn-1HA composites with a polymer-ceramics coating of PLA/HA/TiO_2 for orthopaedic applications. *J. Mech. Behav. Biomed. Mater.* **2022**, *136*, 105470. [CrossRef]
178. Moaref, R.; Shahini, M.H.; Eivaz Mohammadloo, H.; Ramezanzadeh, B.; Yazdani, S. Application of sustainable polymers for reinforcing bio-corrosion protection of magnesium implants–A review. *Sustain. Chem. Pharm.* **2022**, *29*, 100780. [CrossRef]
179. Rojo, L.; García-Fernández, L.; Aguilar, M.R.; Vázquez-Lasa, B. Antimicrobial polymeric biomaterials based on synthetic, nanotechnology, and biotechnological approaches. *Curr. Opin. Biotechnol.* **2022**, *76*, 102752. [CrossRef] [PubMed]
180. Suchanek, W.; Yoshimura, M. Processing and properties of hydroxyapatite-based biomaterials for use as hard tissue re-placement implants. *J. Mater. Res.* **1998**, *13*, 94–117. [CrossRef]
181. Müller, L.; Tunger, A.; Wobus, M.; von Bonin, M.; Towers, R.; Bornhäuser, M.; Dazzi, F.; Wehner, R.; Schmitz, M. Immunomodulatory Properties of Mesenchymal Stromal Cells: An Update. *Front. Cell Dev. Biol.* **2021**, *9*, 637725. [CrossRef]
182. Ielo, I.; Calabrese, G.; De Luca, G.; Conoci, S. Recent Advances in Hydroxyapatite-Based Biocomposites for Bone Tissue Regeneration in Orthopedics. *Int. J. Mol. Sci.* **2022**, *23*, 9721. [CrossRef]
183. Vidal, C.; Alves, P.; Alves, M.M.; Carmezim, M.J.; Fernandes, M.H.; Grenho, L.; Inácio, P.L.; Ferreira, F.B.; Santos, T.G.; Santos, C. Fabrication of a biodegradable and cytocompatible magnesium/nanohydroxyapatite/fluorapatite composite by upward friction stir processing for biomedical applications. *J. Mech. Behav. Biomed. Mater.* **2022**, *129*, 105137. [CrossRef]
184. El Baakili, S.; El Mabrouk, K.; Bricha, M. Acellular bioactivity and drug delivery of new strontium doped bioactive glasses prepared through a hydrothermal process. *RSC Adv.* **2022**, *12*, 15361–15372. [CrossRef]
185. Omidian, S.; Nazarpak, M.H.; Bagher, Z.; Moztarzadeh, F. The effect of vanadium ferrite doping on the bioactivity of mesoporous bioactive glass-ceramics. *RSC Adv.* **2022**, *12*, 25639–25653. [CrossRef] [PubMed]
186. Sharma, A.; Singh, A.; Chawla, V.; Grewal, J.S.; Bansal, A. Microwave processing and characterization of alumina reinforced HA cladding for biomedical applications. *Mater. Today Proc.* **2022**, *57*, 650–656. [CrossRef]
187. Hou, Y.; Fei, Y.; Liu, Z.; Liu, Y.; Li, M.; Luo, Z. Black phosphorous nanomaterials as a new paradigm for postoperative tumor treatment regimens. *J. Nanobiotechnol.* **2022**, *20*, 366. [CrossRef]
188. Padmanabhan, V.P.; Sivashanmugam, P.; Kulandaivelu, R.; Sagadevan, S.; Sridevi, B.; Govindasamy, R.; Thiruvengadam, M. Biosynthesised Silver Nanoparticles Loading onto Biphasic Calcium Phosphate for Antibacterial and Bone Tissue Engineering Applications. *Antibiotics* **2022**, *11*, 1780. [CrossRef] [PubMed]
189. Jiang, Z.; Zheng, Z.; Yu, S.; Gao, Y.; Ma, J.; Huang, L.; Yang, L. Nanofiber Scaffolds as Drug Delivery Systems Promoting Wound Healing. *Pharmaceutics* **2023**, *15*, 1829. [CrossRef]
190. Mashak, A.; Bazraee, S.; Mobedi, H. Advances in drug delivery and biomedical applications of hydroxyapatite-based systems: A review. *Bull. Mater. Sci.* **2022**, *45*, 183. [CrossRef]
191. Spagnuolo, G. Bioactive Dental Materials: The Current Status. *Materials* **2022**, *15*, 2016. [CrossRef]

192. Pourmadadi, M.; Farokh, A.; Rahmani, E.; Shamsabadipour, A.; Eshaghi, M.M.; Rahdar, A.; Ferreira, L.F.R. Porous alumina as potential nanostructures for drug delivery applications, synthesis and characteristics. *J. Drug Deliv. Sci. Technol.* **2022**, *77*, 103877. [CrossRef]
193. Jimenez-Marcos, C.; Mirza-Rosca, J.C.; Baltatu, M.S.; Vizureanu, P. Experimental Research on New Developed Titanium Alloys for Biomedical Applications. *Bioengineering* **2022**, *9*, 686. [CrossRef]
194. Verestiuc, L.; Spataru, M.C.; Baltatu, M.S.; Butnaru, M.; Solcan, C.; Sandu, A.V.; Voiculescu, I.; Geanta, V.; Vizureanu, P. New Ti-Mo-Si materials for bone prosthesis applications. *J. Mech. Behav. Biomed. Mater.* **2021**, *113*, 104198. [CrossRef]
195. Thanigaivel, S.; Priya, A.K.; Balakrishnan, D.; Dutta, K.; Rajendran, S.; Soto-Moscoso, M. Insight on recent development in metallic biomaterials: Strategies involving synthesis, types and surface modification for advanced therapeutic and biomedical applications. *Biochem. Eng. J.* **2022**, *187*, 108522. [CrossRef]
196. Arifin, A.; Sulong, A.B.; Muhamad, N.; Syarif, J.; Ramli, M.I. Material processing of hydroxyapatite and titanium alloy (HA/Ti) composite as implant materials using powder metallergy: A review. *Mater. Des.* **2014**, *55*, 165–175. [CrossRef]
197. Fernandes, J.S.; Gentile, P.; Pires, R.A.; Reis, R.L.; Hatton, P.V. Multifunctional bioactive glass and glass-ceramic biomaterials with antibacterial properties for repair and regeneration of bone tissue. *Acta Biomater.* **2017**, *59*, 2–11. [CrossRef]
198. Zhou, Y.; Wu, C.; Chang, J. Bioceramics to regulate stem cells and their microenvironment for tissue regeneration. *Mater. Today* **2018**, *24*, 41–56. [CrossRef]
199. Baino, F.; Hamzehlou, S.; Kargozar, S. Bioactive Glasses: Where Are We and Where Are We Going? *J. Funct. Biomater.* **2018**, *9*, 25. [CrossRef]
200. Reddy, M.; Ponnamma, D.; Choudhary, R.; Sadasivuni, K. A Comparative Review of Natural and Synthetic Biopolymer Composite Scaffolds. *Polymers* **2021**, *13*, 1105. [CrossRef]
201. Liu, S.; Qin, S.; He, M.; Zhou, D.; Qin, Q.; Wang, H. Current applications of poly(lactic acid) composites in tissue engineering and drug delivery. *Compos. Part B Eng.* **2020**, *199*, 108238. [CrossRef]
202. Elkhoury, K.; Morsink, M.; Sanchez-Gonzalez, L.; Kahn, C.; Tamayol, A.; Arab-Tehrany, E. Biofabrication of natural hydrogels for cardiac, neural, and bone Tissue engineering Applications. *Bioact. Mater.* **2021**, *6*, 3904–3923. [CrossRef]
203. Zhang, Y.; Huang, Y. Rational Design of Smart Hydrogels for Biomedical Applications. *Front. Chem.* **2021**, *8*, 15665. [CrossRef]
204. Hosoyama, K.; Lazurko, C.; Muñoz, M.; McTiernan, C.D.; Alarcon, E.I. Peptide-Based Functional Biomaterials for Soft-Tissue Repair. *Front. Bioeng. Biotechnol.* **2019**, *7*, 205. [CrossRef]
205. Zouhair, S.; Sasso, E.D.; Tuladhar, S.R.; Fidalgo, C.; Vedovelli, L.; Filippi, A.; Borile, G.; Bagno, A.; Marchesan, M.; De Rossi, G.; et al. A Comprehensive Comparison of Bovine and Porcine Decellularized Pericardia: New Insights for Surgical Applications. *Biomolecules* **2020**, *10*, 371. [CrossRef]
206. Todesco, M.; Zardin, C.; Iop, L.; Palmosi, T.; Capaldo, P.; Romanato, F.; Gerosa, G.; Bagno, A. Hybrid membranes for the production of blood contacting surfaces: Physicochemical, structural and biomechanical characterization. *Biomater. Res.* **2021**, *25*, 26. [CrossRef]
207. Ijaz, M.F.; Héraud, L.; Castany, P.; Thibon, I.; Gloriant, T. Superelastic Behavior of Biomedical Metallic Alloys. *Metall. Mater. Trans. A* **2020**, *51*, 3733–3741. [CrossRef]
208. Davis, R.; Singh, A.; Jackson, M.J.; Coelho, R.T.; Prakash, D.; Charalambous, C.P.; Ahmed, W.; da Silva, L.R.R.; Lawrence, A.A. A comprehensive review on metallic implant biomaterials and their subtractive manufacturing. *Int. J. Adv. Manuf. Technol.* **2022**, *120*, 1473–1530. [CrossRef]
209. Liu, J.; Liu, J.; Attarilar, S.; Wang, C.; Tamaddon, M.; Yang, C.; Xie, K.; Yao, J.; Wang, L.; Liu, C.; et al. Nano-Modified Titanium Implant Materials: A Way Toward Improved Antibacterial Properties. *Front. Bioeng. Biotechnol.* **2020**, *8*, 576969. [CrossRef] [PubMed]
210. Saffioti, M.R.; Bertolini, R.; Umbrello, D.; Ghiotti, A.; Bruschi, S. Experimental and Numerical Investigation Of Large Strain Extrusion Machining of AZ31 Magnesium Alloy For Biomedical Applications. *Procedia CIRP* **2022**, *110*, 36–40. [CrossRef]
211. Jamel, M.M.; Jamel, M.M.; Lopez, H.F. Designing Advanced Biomedical Biodegradable Mg Alloys: A Review. *Metals* **2022**, *12*, 85. [CrossRef]
212. West, P.; Shunmugasamy, V.C.; Usman, C.A.; Karaman, I.; Mansoor, B. Part II.: Dissimilar friction stir welding of nickel titanium shape memory alloy to stainless steel—Microstructure, mechanical and corrosion behavior. *J. Adv. Join. Process.* **2021**, *4*, 100072. [CrossRef]
213. Bai, L.; Gong, C.; Chen, X.; Sun, Y.; Zhang, J.; Cai, L.; Zhu, S.; Xie, S.Q. Additive Manufacturing of Customized Metallic Orthopedic Implants: Materials, Structures, and Surface Modifications. *Metals* **2019**, *9*, 1004. [CrossRef]
214. Antonarelli, G.; Corti, C.; Zucali, P.A.; Perrino, M.; Manglaviti, S.; Lo Russo, G.; Varano, G.M.; Salvini, P.; Curigliano, G.; Catania, C.; et al. Continuous sunitinib schedule in advanced platinum refractory thymic epithelial neoplasms: A retrospective analysis from the ThYmic MalignanciEs (TYME) Italian collaborative group. *Eur. J. Cancer* **2022**, *174*, 31–36. [CrossRef]
215. Khodair, Z.T.; Ibrahim, N.M.; Kadhim, T.J.; Mohammad, A.M. Synthesis and characterization of nickel oxide (NiO) nanoparticles using an environmentally friendly method, and their biomedical applications. *Chem. Phys. Lett.* **2022**, *797*, 139564. [CrossRef]
216. Padrós, R.; Punset, M.; Molmeneu, M.; Velasco, A.B.; Herrero-Climent, M.; Rupérez, E.; Gil, F.J. Mechanical Properties of CoCr Dental-Prosthesis Restorations Made by Three Manufacturing Processes. Influence of the Microstructure and Topography. *Metals* **2020**, *10*, 788. [CrossRef]

217. Bernini, M.; Colombo, M.; Dunlop, C.; Hellmuth, R.; Chiastra, C.; Ronan, W.; Vaughan, T.J. Oversizing of self-expanding Nitinol vascular stents—A biomechanical investigation in the superficial femoral artery. *J. Mech. Behav. Biomed. Mater.* **2022**, *132*, 105259. [CrossRef]
218. Tadic, M.; Panjan, M.; Tadic, B.V.; Kralj, S.; Lazovic, J. Magnetic properties of mesoporous hematite/alumina nanocomposite and evaluation for biomedical applications. *Ceram. Int.* **2022**, *48*, 10004–10014. [CrossRef]
219. Nakonieczny, D.S.; Martynková, G.S.; Hundáková, M.; Kratošová, G.; Holešová, S.; Kupková, J.; Pazourková, L.; Majewska, J. Alkali-Treated Alumina and Zirconia Powders Decorated with Hydroxyapatite for Prospective Biomedical Applications. *Materials* **2022**, *15*, 1390. [CrossRef]
220. Zhao, W.; Chang, J.; Wang, J.; Zhai, W.; Wang, Z. In vitro bioactivity of novel tricalcium silicate ceramics. *J. Mater. Sci. Mater. Med.* **2007**, *18*, 917–923. [CrossRef] [PubMed]
221. Borges, R.; Mendonça-Ferreira, L.; Rettori, C.; Pereira, I.S.O.; Baino, F.; Marchi, J. New sol-gel-derived magnetic bioactive glass-ceramics containing superparamagnetic hematite nanocrystals for hyperthermia application. *Mater. Sci. Eng. C* **2021**, *120*, 111692. [CrossRef]
222. Montazerian, M.; Hosseinzadeh, F.; Migneco, C.; Fook, M.V.L.; Baino, F. Bioceramic coatings on metallic implants: An overview. *Ceram. Int.* **2022**, *48*, 8987–9005. [CrossRef]
223. Kölle, L.; Ignasiak, D.; Ferguson, S.J.; Helgason, B. Ceramics in total disc replacements: A scoping review. *Clin. Biomech.* **2022**, *100*, 105796. [CrossRef] [PubMed]
224. Bahati, D.; Bricha, M.; Mabrouk, K.E. Synthesis, characterization, and in vitro apatite formation of strontium-doped sol-gel-derived bioactive glass nanoparticles for bone regeneration applications. *Ceram. Int.* **2023**, *49*, 23020–23034. [CrossRef]
225. Cannio, M.; Bellucci, D.; Roether, J.A.; Boccaccini, D.N.; Cannillo, V. Bioactive Glass Applications: A Literature Review of Human Clinical Trials. *Materials* **2021**, *14*, 5440. [CrossRef] [PubMed]
226. Hench, T.L.L. The story of Bioglass®. *J. Mater. Sci. Mater. Med.* **2006**, *17*, 967–978. [CrossRef] [PubMed]
227. Jones, J.R. Review of bioactive glass: From Hench to hybrids. *Acta Biomater.* **2013**, *9*, 4457–4486. [CrossRef] [PubMed]
228. Nicholson, J.W. Periodontal Therapy Using Bioactive Glasses: A Review. *Prosthesis* **2022**, *4*, 648–663. [CrossRef]
229. Shaikh, M.S.; Fareed, M.A.; Zafar, M.S. Bioactive Glass Applications in Different Periodontal Lesions: A Narrative Review. *Coatings* **2023**, *13*, 716. [CrossRef]
230. Pajares-Chamorro, N.; Chatzistavrou, X. Bioactive glass nanoparticles for tissue regeneration. *ACS Omega* **2020**, *5*, 12716–12726. [CrossRef]
231. Ding, Y.; Souza, M.T.; Li, W.; Schubert, D.W.; Boccaccini, A.R.; Roether, J.A. Bioactive Glass-Biopolymer Composites for Applications in Tissue Engineering. In *Handbook of Bioceramics and Biocomposites*; Antoniac, I., Ed.; Springer: Cham, Germany, 2016; Volume 1, pp. 325-356. [CrossRef]
232. Richter, R.F.; Ahlfeld, T.; Gelinsky, M.; Lode, A. Composites consisting of calcium phosphate cements and mesoporous bioactive glasses as a 3D plottable drug delivery system. *Acta Biomater.* **2023**, *156*, 146–157. [CrossRef]
233. Atkinson, I.; Seciu-Grama, A.M.; Petrescu, S.; Culita, D.; Mocioiu, O.C.; Voicescu, M.; Mitran, R.-A.; Lincu, D.; Prelipcean, A.-M.; Craciunescu, O. Cerium-Containing Mesoporous Bioactive Glasses (MBGs)-Derived Scaffolds with Drug Delivery Capability for Potential Tissue Engineering Applications. *Pharmaceutics* **2022**, *14*, 1169. [CrossRef]
234. Damian-Buda, A.-I.; Nawaz, Q.; Unalan, I.; Beltrán, A.M.; Boccaccini, A.R. Quaternary and pentanary mesoporous bioactive glass nanoparticles as novel nanocarriers for gallic acid: Characterisation, drug release and antibacterial activity. *Ceram. Int.* **2023**, *49*, 29923–29932. [CrossRef]
235. Atkinson, I. Antibiofilm Activity of Biocide Metal Ions Containing Bioactive Glasses (BGs): A Mini Review. *Bioengineering* **2022**, *9*, 489. [CrossRef] [PubMed]
236. Montazerian, M.; Zanotto, E.D. History and trends of bioactive glass-ceramics. *J. Biomed. Mater. Res. Part A* **2016**, *104A*, 1231–1249. [CrossRef]
237. De Ceanne, A.V.; Rodrigues, L.R.; Wilkinson, C.J.; Mauro, J.C.; Zanotto, E.D. Examining the role of nucleating agents within glass-ceramic systems. *J. Non-Cryst. Solids* **2022**, *591*, 121714. [CrossRef]
238. Fu, L.; Engqvist, H.; Xia, W. Glass-Ceramics in Dentistry: A Review. *Materials* **2020**, *13*, 1049. [CrossRef]
239. Chatzistavrou, X.; Esteve, D.; Hatzistavrou, E.; Kontonasaki, E.; Paraskevopoulos, K.M.; Boccaccini, A.R. Sol–gel based fabrication of novel glass-ceramics and composites for dental applications. *Mater. Sci. Eng. C* **2010**, *30*, 730–739. [CrossRef]
240. Chatzistavrou, X.; Tsigkou, O.; Amin, H.D.; Paraskevopoulos, K.M.; Salih, V.; Boccaccini, A.R. Sol–gel based fabrication and characterization of new bioactive glass–ceramic composites for dental applications. *J. Eur. Ceram. Soc.* **2012**, *32*, 3051–3061. [CrossRef]
241. Reyes-Peces, M.V.; Félix, E.; Martínez-Vázquez, F.J.; Fernández-Montesinos, R.; Bomati-Miguel, Ó.; del Mar Mesa-Díaz, M.; Alcántara, R.; Vilches-Pérez, J.I.; Salido, M.; De la Rosa-Fox, N.; et al. Robocasting and Laser Micromachining of Sol-Gel Derived 3D Silica/Gelatin/β-TCP Scaffolds for Bone Tissue Regeneration. *Gels* **2022**, *8*, 634. [CrossRef]
242. de Oliveira, A.A.R.; de Carvalho, B.B.; Mansur, H.S.; de Magalhães Pereira, M. Synthesis and characterization of bioactive glass particles using an ultrasound-assisted sol–gel process: Engineering the morphology and size of sonogels via a poly(ethylene glycol) dispersing agent. *Mater. Lett.* **2014**, *133*, 44–48. [CrossRef]

243. Zouai, S.; Harabi, A.; Karboua, N.; Harabi, E.; Chehlatt, S.; Barama, S.E.; Zaiou, S.; Bouzerara, F.; Guerfa, F. A new and economic approach to synthesize and fabricate bioactive diopside ceramics using a modified domestic microwave oven. Part 2: Effect of P_2O_5 additions on diopside bioactivity and mechanical properties. *Mater. Sci. Eng. C Mater. Biol. Appl.* **2016**, *61*, 553–563. [CrossRef] [PubMed]
244. Alinda Shaly, A.; Hannah Priya, G.; Mahendiran, M.; Mary Linet, J. A behavioural study of hydrothermally derived novel alumina/magnesia/hydroxyapatite (Al_2O_3/MgO/HA) bioceramic nanocomposite. *J. Mech. Behav. Biomed. Mater.* **2022**, *133*, 105313. [CrossRef] [PubMed]
245. Liu, R.; Zhang, Q.; Zhou, Q.; Zhang, P.; Dai, H. Nondegradable magnetic poly (carbonate urethane) microspheres with good shape memory as a proposed material for vascular embolization. *J. Mech. Behav. Biomed. Mater.* **2018**, *82*, 9–17. [CrossRef]
246. Subramaniam, A.; Sethuraman, S. Chapter 18—Biomedical Applications of Nondegradable Polymers. In *Natural and Synthetic Biomedical Polymers*; Sangamesh, G., Kumbar, Laurencin, C.T., Deng, M., Eds.; Elsevier: Amsterdam, The Netherlands, 2014; pp. 301–308. [CrossRef]
247. Song, R.; Murphy, M.; Li, C.; Ting, K.; Soo, C.; Zheng, Z. Current development of biodegradable polymeric materials for biomedical applications. *Drug Des. Dev. Ther.* **2018**, *12*, 3117–3145. [CrossRef] [PubMed]
248. DeStefano, V.; Khan, S.; Tabada, A. Applications of PLA in modern medicine. *Eng. Regen.* **2020**, *1*, 76–87. [CrossRef]
249. Russias, J.; Saiz, E.; Nalla, R.K.; Gryn, K.; Ritchie, R.O.; Tomsia, A.P. Fabrication and mechanical properties of PLA/HA composites: A study of in vitro degradation. *Mater. Sci. Eng. C Biomim. Supramol. Syst.* **2006**, *26*, 1289–1295. [CrossRef] [PubMed]
250. Firoozabadi, F.D.; Saadatabadi, A.R.; Asefnejad, A. In Vitro Studies and Evaluation of Antibacterial Properties of Biodegradable Bone Joints Based on PLA/PCL/HA. *J. Clin. Res. Paramed. Sci.* **2022**, *11*, e124080. [CrossRef]
251. Idumah, C.I. Emerging trends in Poly(lactic-co-glycolic) acid bionanoarchitectures and applications. *Clean. Mater.* **2022**, *5*, 100102. [CrossRef]
252. Iwata, H.; Matsuda, S.; Mitsuhashi, K.; Itoh, E.; Ikada, Y. A novel surgical glue composed of gelatin and N-hydroxysuccinimide activated poly(L-glutamic acid): Part 1. Synthesis of activated poly(L-glutamic acid) and its gelation with gelatin. *Biomaterials* **1998**, *19*, 1869–1876. [CrossRef]
253. Brugnera, M.; Vicario-de-la-Torre, M.; Andrés-Guerrero, V.; Bravo-Osuna, I.; Molina-Martínez, I.T.; Herrero-Vanrell, R. Validation of a Rapid and Easy-to-Apply Method to Simultaneously Quantify Co-Loaded Dexamethasone and Melatonin PLGA Microspheres by HPLC-UV: Encapsulation Efficiency and In Vitro Release. *Pharmaceutics* **2022**, *14*, 288. [CrossRef]
254. Ilkar Erdagi, S.; Isik, S. Preparation and characterization of steroid and umbelliferone-based hetero-bifunctional poly(ε-caprolactone)s for potential drug delivery systems: Antimicrobial and anticancer activities. *J. Polym. Res.* **2022**, *29*, 240. [CrossRef]
255. Liu, R.; Pang, Y.; Xiao, T.; Zhang, S.; Liu, Y.; Min, Y. Multifunctional PCL composite nanofibers reinforced with lignin and ZIF-8 for the treatment of bone defects. *Int. J. Biol. Macromol.* **2022**, *218*, 1–8. [CrossRef]
256. Ganji, S.M.; Tehranchi, M.; Ehterami, A.; Semyari, H.; Taleghani, F.; Habibzadeh, M.; Tayeed, M.H.; Mehrnia, N.; Karimi, A.; Salehi, M. Bone tissue engineering via application of a PCL/Gelatin/Nanoclay/Hesperetin 3D nanocomposite scaffold. *J. Drug Deliv. Sci. Technol.* **2022**, *76*, 103704. [CrossRef]
257. Ghosh, R.; Arun, Y.; Siman, P.; Domb, A.J. Synthesis of Aliphatic Polyanhydrides with Controllable and Reproducible Molecular Weight. *Pharmaceutics* **2022**, *14*, 1403. [CrossRef]
258. Tabet, A.; Jensen, M.P.; Parkins, C.C.; Patil, P.G.; Watts, C.; Scherman, O.A. Designing Next-Generation Local Drug Delivery Vehicles for Glioblastoma Adjuvant Chemotherapy: Lessons from the Clinic. *Adv. Healthc. Mater.* **2019**, *8*, e1801391. [CrossRef] [PubMed]
259. Piozzi, A.; Francolini, I.; Occhiaperti, L.; Venditti, M.; Marconi, W. Antimicrobial activity of polyurethanes coated with antibiotics: A new approach to the realization of medical devices exempt from microbial colonization. *Int. J. Pharm.* **2004**, *280*, 173–183. [CrossRef] [PubMed]
260. Theron, J.P.; Knoetze, J.H.; Sanderson, R.D.; Hunter, R.; Mequanint, K.; Franz, T.; Zilla, P.; Bezuidenhout, D. Modification, crosslinking and reactive electrospinning of a thermoplastic medical polyurethane for vascular graft applications. *Acta Biomater.* **2010**, *6*, 2434–2447. [CrossRef]
261. Nakamori, K.; Abe, Y.; Takeuchi, M.; Kagawa, K.; Yoshihara, K.; Yoshida, Y.; Tsuga, K. Antimicrobial adhesive polyurethane gel sheet with cetylpyridinium chloride-montmorillonite for facial and somato prosthesis fastening. *J. Prosthodont. Res.* **2023**, *67*, 180–188. [CrossRef]
262. Motiwale, S.; Russell, M.D.; Conroy, O.; Carruth, J.; Wancura, M.; Robinson, A.; Hernandez, E.C.; Sacks, M.S. Anisotropic elastic behavior of a hydrogel-coated electrospun polyurethane: Suitability for heart valve leaflets. *J. Mech. Behav. Biomed. Mater.* **2022**, *125*, 104877. [CrossRef]
263. Alves, P.; Cardoso, R.; Correia, T.R.; Antunes, B.P.; Correia, I.J.; Ferreira, P. Surface modification of polyurethane films by plasma and ultraviolet light to improve haemocompatibility for artificial heart valves. *Colloids Surf B Biointerfaces* **2014**, *113*, 25–32. [CrossRef]
264. Polaskova, M.; Sedlacek, T.; Kasparkova, V.; Filip, P. Substantial drop of plasticizer migration from polyvinyl chloride catheters using co-extruded thermoplastic polyurethane layers. *Mater. Today Commun.* **2022**, *32*, 103895. [CrossRef]

265. Sanati, A.; Kefayat, A.; Rafienia, M.; Raeissi, K.; Moakhar, R.S.; Salamat, M.Z.; Sheibani, S.; Presley, J.F.; Vali, H. A novel flexible, conductive, and three-dimensional reduced graphene oxide/polyurethane scaffold for cell attachment and bone regeneration. *Mater. Des.* **2022**, *221*, 110955. [CrossRef]
266. Dirauf, M.; Muljajew, I.; Weber, C.; Schubert, U.S. Recent advances in degradable synthetic polymers for biomedical applications—Beyond polyesters. *Prog. Polym. Sci.* **2022**, *129*, 101547. [CrossRef]
267. Fathi-Karkan, S.; Banimohamad-Shotorbani, B.; Saghati, S.; Rahbarghazi, R.; Davaran, S. A critical review of fibrous polyurethane-based vascular tissue engineering scaffolds. *J. Biol. Eng.* **2022**, *16*, 6. [CrossRef]
268. Yang, H.; Li, Q.; Li, L.; Chen, S.; Zhao, Y.; Hu, Y.; Wang, L.; Lan, X.; Zhong, L.; Lu, D. Gastrodin modified polyurethane conduit promotes nerve repair via optimizing Schwann cells function. *Bioact. Mater.* **2021**, *8*, 355–367. [CrossRef] [PubMed]
269. de Souza, M.G.M.; Batista, J.P.; de Faria, E.H.; Ciuffi, K.J.; Rocha, L.A.; Nassar, E.J.; da Silva, J.V.L.; Oliveira, M.F.; Maia, I.A. Silver nanoparticle incorporation into flexible polyamide 12 membranes. *J. Sol-Gel Sci. Technol.* **2022**, *102*, 219–228. [CrossRef]
270. Nur, P.F.; Pınar, T.; Uğur, P.; Ayşenur, Y.; Murat, E.; Kenan, Y. Fabrication of polyamide 6/honey/boric acid mats by electrohydrodynamic processes for wound healing applications. *Mater. Today Commun.* **2021**, *29*, 102921. [CrossRef]
271. Dardouri, M.; Aljnadi, I.M.; Deuermeier, J.; Santos, C.; Costa, F.; Martin, V.; Fernandes, M.H.; Gonçalves, L.; Bettencourt, A.; Gomes, P.S.; et al. Bonding antimicrobial rhamnolipids onto medical grade PDMS: A strategy to overcome multispecies vascular catheter-related infections. *Colloids Surf. B Biointerfaces* **2022**, *217*, 112679. [CrossRef]
272. Arif, Z.U.; Khalid, M.Y.; Zolfagharian, A.; Bodaghi, M. 4D bioprinting of smart polymers for biomedical applications: Recent progress, challenges, and future perspectives. *React. Funct. Polym.* **2022**, *179*, 105374. [CrossRef]
273. Díez-Pascual, A.M. PMMA-Based Nanocomposites for Odontology Applications: A State-of-the-Art. *Int. J. Mol. Sci.* **2022**, *23*, 10288. [CrossRef] [PubMed]
274. Nayak, G.S.; Mouillard, F.; Masson, P.; Pourroy, G.; Palkowski, H.; Carradò, A. Adhesion Behavior of Ti–PMMA–Ti Sandwiches for Biomedical Applications. *JOM J. Miner. Met. Mater. Soc.* **2021**, *74*, 96–101. [CrossRef]
275. Nezhad, E.Z.; Sarraf, M.; Musharavati, F.; Jaber, F.; Wang, J.I.; Hosseini, H.Z.M.; Bae, S.; Chowdhury, M.; So, H.; Sukiman, N.L. Effect of zirconia nanotube coating on the hydrophilicity and mechanochemical behavior of zirconium for biomedical applications. *Surf. Interfaces* **2022**, *28*, 101623. [CrossRef]
276. Keshavarz, S.; Okoro, O.V.; Hamidi, M.; Derakhshankhah, H.; Azizi, M.; Nabavi, S.M.; Gholizadeh, S.; Amini, S.M.; Shavandi, A.; Luque, R.; et al. Synthesis, surface modifications, and biomedical applications of carbon nanofibers: Electrospun vs. vapor-grown carbon nanofibers. *Coord. Chem. Rev.* **2022**, *472*, 214770. [CrossRef] [PubMed]
277. Katsaros, I.; Zhou, Y.; Welch, K.; Xia, W.; Persson, C.; Engqvist, H. Bioactive Silicon Nitride Implant Surfaces with Maintained Antibacterial Properties. *J. Funct. Biomater.* **2022**, *13*, 129. [CrossRef] [PubMed]
278. Abraham, A.M.; Venkatesan, S. A review on application of biomaterials for medical and dental implants. *Proc. Inst. Mech. Eng. Part L J. Mater. Des. Appl.* **2023**, *237*, 249–273. [CrossRef]
279. Chelu, M.; Musuc, A.M. Polymer Gels: Classification and Recent Developments in Biomedical Applications. *Gels* **2023**, *9*, 161. [CrossRef]
280. Chen, C.; Hou, Z.; Chen, S.; Guo, J.; Chen, Z.; Hu, J.; Yang, L. Photothermally responsive smart elastomer composites based on aliphatic polycarbonate backbone for biomedical applications. *Compos. Part B Eng.* **2022**, *240*, 109985. [CrossRef]
281. Chozhanathmisra, M.; Murugesan, L.; Murugesan, A.; Palanisamy, G.; Rajavel, R. Enhancement on physical, chemical, and biological properties of HNT-PVA-ALG-HAp biocomposite coating on implant substrate for biomedical application. *Ceram. Int.* **2022**, *48*, 16868–16876. [CrossRef]
282. Erdem, U.; Dogan, D.; Bozer, B.M.; Turkoz, M.B.; Yıldırım, G.; Metin, A.U. Fabrication of mechanically advanced polydopamine decorated hydroxyapatite/polyvinyl alcohol bio-composite for biomedical applications: In-vitro physicochemical and biological evaluation. *J. Mech. Behav. Biomed. Mater.* **2022**, *136*, 105517. [CrossRef]
283. Daulbayev, C.; Sultanov, F.; Korobeinyk, A.V.; Yeleuov, M.; Taurbekov, A.; Bakbolat, B.; Umirzakov, A.; Baimenov, A.; Daulbayev, O. Effect of graphene oxide/hydroxyapatite nanocomposite on osteogenic differentiation and antimicrobial activity. *Surf. Interfaces* **2022**, *28*, 101683. [CrossRef]
284. Donya, H.; Darwesh, R.; Ahmed, M.K. Morphological features and mechanical properties of nanofibers scaffolds of polylactic acid modified with hydroxyapatite/CdSe for wound healing applications. *Int. J. Biol. Macromol.* **2021**, *186*, 897–908. [CrossRef]
285. Liu, P.; Man, Y.; Bao, Y. Bioactive Porous Biocomposites Coated Magnesium Alloy Implant for Bone Rejuvenation Using a Fracture in Rat Model. *Biotechnol. Bioproc. E* **2021**, *26*, 359–368. [CrossRef]
286. Anbu, P. Chemical synthesis of $NiFe_2O_4$/NG/cellulose nanocomposite and its antibacterial potential against bacterial pathogens. *Biotehnol. Appl. Biochem.* **2022**, *69*, 867–875. [CrossRef]
287. Hackenhaar, C.R.; Rosa, C.F.; Esparza Flores, E.E.; Santagapita, P.R.; Klein, M.P.; Hertz, P.F. Development of a biocomposite based on alginate/gelatin crosslinked with genipin for β-galactosidase immobilization: Performance and characteristics. *Carbohydr. Polym.* **2022**, *291*, 119483. [CrossRef]
288. Ruiz, S.; Tamayo, J.A.; Ospina, J.D.; Navia Porras, D.P.; Valencia Zapata, M.E.; Hernandez, J.H.M.; Valencia, C.H.; Zuluaga, F.; Grande Tovar, C.D. Antimicrobial Films Based on Nanocomposites of Chitosan/Poly(vinyl alcohol)/Graphene Oxide for Biomedical Applications. *Biomolecules* **2019**, *9*, 109. [CrossRef]

289. Samanta, A.P.; Ali, M.S.; Orasugh, J.T.; Ghosh, S.K.; Chattopadhyay, D. Crosslinked nanocollagen-cellulose nanofibrils reinforced electrospun polyvinyl alcohol/methylcellulose/polyethylene glycol bionanocomposites: Study of material properties and sustained release of ketorolac tromethamine. *Carbohydr. Polym. Technol. Appl.* **2022**, *3*, 100195. [CrossRef]
290. Irwansyah, F.S.; Noviyanti, A.R.; Eddy, D.R.; Risdiana, R. Green Template-Mediated Synthesis of Biowaste Nano-Hydroxyapatite: A Systematic Literature Review. *Molecules* **2022**, *27*, 5586. [CrossRef] [PubMed]
291. Kalantari, E.; Naghib, S.M.; Iravani, N.J.; Esmaeili, R.; Jamal, M.R.N.; Mozafari, M. Biocomposites based on hydroxyapatite matrix reinforced with nanostructured monticellite ($CaMgSiO_4$) for biomedical application: Synthesis, characterization, and biological studies. *Mater. Sci. Eng. C* **2019**, *105*, 109912. [CrossRef]