

## Original Article

# Recent Advances in Biomaterials: Exploring Cutting-Edge Features, Diverse Applications and Expanding Scope

Ganesh Kumar Sharma<sup>1</sup>, Vikas Kukshal<sup>1</sup>, Kalia R.B.<sup>2</sup>

<sup>1</sup>Department of Mechanical Engineering, National Institute of Technology, Uttarakhand, Srinagar (Garhwal) 246174, India

<sup>2</sup>Department of Orthopedics, All India Institute of Medical Sciences, Rishikesh, Uttarakhand 249203, India

Received: 17 September 2025

Accepted: 15 July 2026

Published online: 30 July 2026

**Keywords:** *metallic biomaterial, fabrication, characterization, biocompatibility, finite element method*

Biomaterials encompasses a diverse array of engineering techniques employed for generating materials suitable for repairing or replacing biological structures within living systems. Biomaterials have proven successful in effectively replacing numerous parts of humans including bones, teeth, tendons, ligaments, and other load-bearing implants. The primary and paramount prerequisite is the biomaterial's ability to be seamlessly accepted by the human body. The use of biomaterials in medical implants is complemented by biocompatibility as a prominent aspect. Recent developments in smart/4D biomaterials created accessible by additive manufacturing and lattice-based metallic biomaterials are examined critically in this review. Correlation between structure and property, fabrication-dependent mechanical performance, and modelling difficulties are highlighted. In numerous domains of biology, surgery, and medicine, the assessment of mechanical properties plays a vital role in determining the significance of biomaterials. This study aims to comprehensively examine key aspects of biomaterial characterization, material selection procedures, mechanical properties, fabrication techniques, and tribological behavior, highlighting their significance in the field of biomaterials. The functional sustainability and biocompatibility limits of recent advancements in shape-morphing and nano-engineered biomaterials are assessed. This review identifies important obstacles to clinical translation and lays forth priority paths for the design of next-generation biomaterials by combining comparative findings and emphasizing current limits.

## Introduction

Biomaterial is specifically designed using the classes of purely synthetic materials such as metallic, biodegradable Polymers, non-biodegradable polymers, Composite, Ceramic, and protein based natural biomaterials. Biomaterials, excluding drugs, are defined as substances of either synthetic or natural origin that can be utilized for any period to supplement, replace, or enhance tissue, organ, or bodily function, with the aim of safeguarding or enhancing an individual's quality of life [1]. Medical engineering equipment constantly interacts with a diverse range of biomaterials, such as soft brain tissue or hard bone, that vary in rigidity and brittleness. Engineering new biological materials, strictly synthetic materials inspired by biology, and bio-inspired materials for use in medical devices depend on understanding the mechanical interaction between biotic or biotic interfaces. Similarly, improving current materials to ensure dependability, stability, and the best possible immune responses also relies on this understanding. The principal appli-

cations for biomaterials are in dentistry, skin, orthopedics, tissue engineering, medication delivery and cardiovascular devices [2]. Prior to considering the material for implantation, it is essential to ascertain its biocompatibility, ensuring that it does not pose any harm to the human body.

Biocompatibility refers to the ability of an implant material to function within the body without inducing any unfavorable local or systemic reactions. Before even being utilized to treat human fractures, biomaterials are subjected to tissue and animal testing to guarantee their safety and effectiveness [3,4]. The mechanical properties of biomaterials are significantly influenced by micro structural traits such pore geometry, porosity distribution, and porosity degree. One component of implants that is often neglected is the structure. Nevertheless, the two most frequent reasons for joint arthroplasty failure are corrosion and wear, which result in aseptic loosening or joint infections must be reduced [5].

\*Corresponding author: Dr. Vikas Kukshal  
E-mail address: [vikaskukshal@nituk.ac.in](mailto:vikaskukshal@nituk.ac.in)

<https://doi.org/10.65795/tzbzhf90>

#20019026/©2026 The Author(s). Published by the Society for Biomaterials and Artificial Organs (India), Thiruvananthapuram, India. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<https://creativecommons.org/licenses/by-nc-nd/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. The terms on which this article has been published allow the posting of the published article in a repository by the author(s) or with their consent.



Recent advancements in biomaterials have produced smart and 4D systems that may actively react to physiological or external inputs like temperature, humidity, and chemical environment, in contrast to conventional passive implants. Innovative approaches for controlled deployment and flexible performance in medical applications are made possible by these responsive materials. Thus, the current study emphasizes recent developments in shape-transformable polymers and nano-enabled composite designs, with a particular focus on smart and 4D biomaterials. Instead of providing a purely descriptive overview, this work highlights the main issues that need to be resolved in order to achieve dependable long-term clinical use by rigorously analysing their response mechanisms, operational durability, and biocompatibility issues.

In the field of materials science, biomaterials are categorized into four fundamental divisions: metal alloys, ceramics, polymers, and composites [6]. Each biomaterial type possesses distinct properties and has a wide variety of unique advantages. Because of this, such biomaterials are largely employed in medical engineering to repair or replace damaged hard bone, joint, hip, cardiovascular, organ tissue. The structure of a material is responsible for the distinguished properties of composite materials. The implant metals commonly used are much stiffer than bone metals [7]. To address the shortcomings of current implant materials, new metallic alloys are being produced. It's critical to create materials that are durable, biocompatible, wear-resistant, bioactive, corrosion-resistant, and capable of lasting for long periods of time. The efficient and effective design and development of biomaterial implants is aided by a combined numerical-experimental approach.

Three-dimensional (3D) printing, also known as additive manufacturing, has seen tremendous technological development in the last several years. The discipline is still relatively young, with many inventions and process optimizations still in the early stages of development, despite its quick advancement. As a result, even though 3D printing offers a lot of promise, the manufacturing sector has not yet seen a significant transformation. Using additive manufacturing principles, this method fabricates components layer by layer from digital design data [8]. There are many different 3D printing methods, and each one is unique in its workings, suitability for different materials, and features tailored to a particular use case.

Intelligent materials that are designed to change their shape or functional characteristics in a predetermined and regulated way in response to environmental triggers like temperature, moisture, or electromagnetic fields are used in four-dimensional (4D) printing. The word "4D printing" highlights the significance of time as an extra dimension, signifying the alteration of printed components after manufacturing. These features have been made possible by the widespread integration of shape memory materials into additive manufacturing methods. Shape memory polymers (SMPs) and shape memory polymer composites (SMPCs) have been noted for their multifunctional nature in numerous research. Yangu Li, in particular, gave a targeted overview of SMPs and SMPCs for aerospace applications, emphasizing their application in truss boom structures, hinges, reflector antennas, and morphing lunar colonies. However, after several actuation cycles, thermoplastic-based shape memory materials frequently show deterioration in shape recovery properties. Because thermoset-based systems are more stiff, dimensionally stable, and resistant to environmental factors, they are becoming more and more popular for structural and space applications. The efficient and effective design and development of biomaterial implants is aided by a combined numerical-experimental approach.

The Finite Element Method (FEM) is commonly used for evaluating biomechanical behavior of biomaterials. In bioengineering issues, FEM has become commonplace and is ostensibly a normal practice in the functioning of biomedical systems [9]. The finite element method is utilized to address issues with the boundary value problem, providing a numerical approach to solve both integral and differential techniques. In biomedical fields, particularly in structural mechanics, FEM is experiencing a growing surge in popularity. Evidently, the most extensive applications of FEM are evident in orthopedics and dentistry, where mechanical loading plays a crucial role. Bio-functional and biocompatibility are the main feature to differentiate the performance of biomaterials. The simulation method can be used to analyze mechanical behavior,

including fatigue, strength, deformation, and fracture [10]. Nevertheless, the intricacy of material properties makes biomechanics simulation difficult. To evaluate mechanical behavior and enhance postprocessing that lengthens the lifespan of biomaterials, simulation has been very effective.

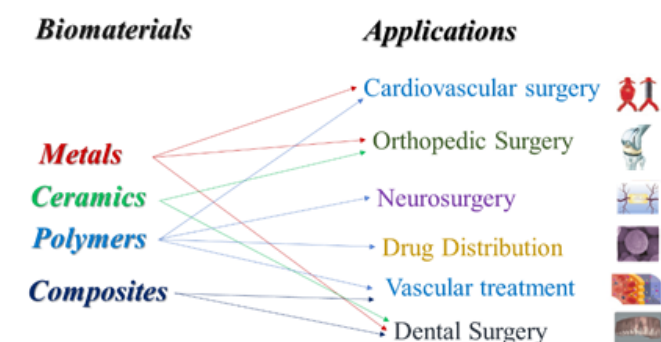
This review article explores the development of diverse metal alloys, ceramics, polymers, and composites, which are commonly employed in biomedical applications. Additionally, it investigates the various methods utilized to tackle the challenges encountered in the medical field.

## Material Selection

Biomaterials have been proven to be beneficial to people in the field of medical science in today's technological world. Developing biomaterials to resolve medical implant difficulties has traditionally entailed the creation of a novel biomaterial, such as a new bio-composite, biopolymer, or metallic alloy. The demand for biomaterials is steadily rising to address the needs of an ageing population. As a result, biomaterials are the subject of substantial research [11]. The traditional meaning of "biomaterials" refers to their intended application rather than their inherent qualities. In other words, the term "biomaterials" refers to any type of materials that meets a biological entity and interacts with a biological environment [12]. Mostly people first meet biomaterials during dental filling, but there is an increase in the number of people relying on more crucial implants like joint replacements, particularly hip replacements, and cardiovascular repairs.

Biomaterials are an imbalanced substance intended for biological processes to communicate. Inside a biological medium, its use is feasible including effective and efficient biomaterial properties [13]. These major benefits are described with combinations of different characteristics, including mechanical, biological, and physical to develop efficient biomaterials [14]. To evaluate the mechanical properties of biomaterials in the fields of physiology, medicine, and surgery. Finite element computational models for Biomedical Engineering: Analysis of Uncertainty and Variability: Characterization and Propagation [15]. To emphasize the use mechanical behavior, simulation method can be used to analyze phenomena like fatigue, strength, fracture behavior, and deformations [16]. The application of the finite element method in dental implant research, Computer Methods in Biomechanics and Biomedical Engineering [17]. The increasing potential of smart biomaterials made using cutting-edge additive manufacturing and 4D printing technology. A 4D-printed thermos-responsive polymeric vascular stent demonstrated regulated radial expansion at physiological temperature, allowing for less invasive implantation and enhanced vessel conformity [18]. The study's finite element simulations used nonlinear viscoelastic material models to account for significant deformation behaviour; nevertheless, fatigue performance under cyclic hemodynamic loading was not assessed, which restricts the ability to forecast long-term structural integrity. In a similar vein, a shape-memory scaffold designed for bone tissue engineering demonstrated sufficient initial stiffness for defect filling and temperature-triggered form recovery [19]. Elastic-plastic constitutive formulations were used to characterize its mechanical response, however degradation-dependent property evolution was overlooked, which could eventually result in an overestimation of load-bearing capacity. In a different study, a biodegradable biomaterial with a nanostructure was created for stimulus-controlled drug administration. pH-sensitive polymer networks controlled the release behaviour [20]. Although drug release kinetics were predicted using diffusion-based computational models, the results' physiological significance was diminished since the effects of fluid-structure interaction and mechanical deformation were not taken into account. All of these results show that while functional biomaterials show promise in terms of actuation and therapy, coupled mechanical, fatigue, and transport processes must be included in future modelling frameworks in order to produce accurate long-term performance predictions.

To provide reducing health care solutions, the multidisciplinary field of biomaterials research and engineering combines materials science, engineering, and biomedical sciences. A growing number of patients are improving their quality of life and survival chances because of biomaterials. Examples of biomaterial uses include joint and limb re-



**Figure 1: Different types of biomaterials with medical application**

placements, dental implants, vascular grafts, corneal replacements, and skin augmentation. However, more research and development are being focused on the production and design of biomaterials that have characteristics and properties that are like those of real tissues or organs. Degradation is essential to the long-term mechanical stability and biological performance of biodegradable biomaterials. However, since it depends on several interconnected processes, such as hydrolysis, enzymatic activity, and mechanical loading, predicting degradation behaviour is difficult. Over time, progressive mass loss modifies the implant's stress distribution and structural stability. The homogeneous degradation assumed by the majority of computational models fails to capture the spatially variable material loss seen in experiments. Degradation-induced mechanical weakening must thus be realistically simulated using sophisticated time-dependent material models. In the following part, some of the most important applications in the subject of biomaterials are provided in this review (figure 1). During the Industrial Revolution in the nineteenth century, metal-based materials were first used for medical implants.

#### Metal based biomaterial

Metallic biomaterial employed should have good biodegradability and aesthetic properties. Due to their superior ductility and excellent resilience to stress, metal biomaterials are used for the treatment of bone fractures. Stainless steel, chromium alloys, titanium alloys, and aluminum alloys are a few examples of metallic biomaterials that have been chosen for a variety of medical device applications because of their

attractive mechanical characteristics, particularly their fracturing and ultimate strength. The instant growth and advancement in the biomaterials field has led to the development of numerous metal medical products, including dental implants, craniofacial plates and screws, prosthetic and orthodontic devices, bone fixation devices, dental materials, medical radiation shielding products, pieces of artificial hearts, clips, pacemakers, balloon catheters, valves, medical equipment, and devices.

#### Polymer based biomaterial

Polymeric biomaterials are frequently utilized in the implantation of prosthetic devices and are crucial in the improvement of health issues. Due to their poor mechanical qualities, polymeric biomaterials are only used in limited circumstances. Polymers are crucial curative components in biomedical research that are used as tools to replace and rebuild diverse tissues. In the composition and structure of contingent macromolecules, the properties of polymers are explored [21]. Polymeric biomaterials have the following advantages over other types of materials: (i) ease of fabrication, (ii) secondary processability, (iii) availability of specified physical and mechanical qualities, and (iv) acceptable cost. The two types of polymers employed in biomedical applications are synthetic and natural.

#### Ceramic based biomaterial

Ceramic biomaterials, which are non-toxic, have good biocompatibility and osteoconductive properties, are frequently employed as plating materials. Dental implants are made of a ceramic biomaterial because it has good inert features, such as minimum interactions and good cosmetic qualities. Ceramics are used in cardiac valves, the musculoskeletal system, artificial knees, hip prostheses, bone grafts, orbital and middle ear implants, dental and orthopedic implants, and coatings on metallic implants to promote biocompatibility [22]. Because of their brittleness and low tensile strength, ceramics' applications are sometimes severely limited. Phosphate bio ceramics are frequently used to create perfect biomaterials because of their superior biocompatibility and bone integration, as well as the fact that they are the materials that are most like the mineral component of spine.

#### Composite based biomaterial

Composites are engineered materials made up of two or more physically and/or chemically diverse, appropriately organized, or dispersed constituent materials with physical properties that differ from those of the individual constituent materials. Composites are stronger than the raw materials from which they are made and have distinct characteristics, hence they are used to solve several complex challenges requiring

**Table 1: Factors affecting material selection for biomedical field**

| Factors                                       | Chemical/biological characteristics                                                           | Physical                                                                                                                                                                             | Mechanical                                                                                                    | References |
|-----------------------------------------------|-----------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|------------|
| Material characteristics at the initial phase | Composition of substances (Bulk and surface)                                                  | Density, Lubricity                                                                                                                                                                   | Poisson's ratio, young's modulus, Ultimate tensile strength, and compressive strength                         | [27]       |
| Material characteristics at the second phase  | Adhesion Surface<br>Adherent oxide film                                                       | Topology (Texture and Surface Roughness, Microstructure                                                                                                                              | Hardness, Fracture modulus, yield point, Tensile strengths, flexural modulus                                  | [28]       |
| Specific functioning needs                    | Biocompatibility, Bio-inertia, Bioactivity, Biostability, Biodegradation and Bio functioning. | Structure (Solid, porous, coating, film, powder), Geometry, Thermal Expansion Coefficient, Conductivity of electricity Aesthetic appeal, refractive indices, shading or transparency | Fracture strength, stiffness fatigue and creep resistance, friction and wear, Adhesion, and impact resistance | [29-31]    |
| Manufacturing and preparation                 | Reproducibility, quality, serializability, packaging and secondary packaging                  |                                                                                                                                                                                      |                                                                                                               | [32,33]    |
| Properties of the organism                    | Tissue, species, organ, age, race, health status, activities, and systemic responses          |                                                                                                                                                                                      |                                                                                                               | [34,35]    |

tissue in-growth. Because biomedical composite materials offer innovative alternative options for loadbearing tissue components, scientific research has focused on developing a variety of biomedical composite materials in recent years.

Additive manufacturing technologies have created previously imagined possibilities for fabricating functionally graded biomaterials bone graft substitutes with potential bone tissue engineering features [23]. In the past, traditional production procedures such as reproducing polymeric sponges, gas foaming, sintering metal powder and investment casting posed a considerable barrier to developing biomimetic scaffold materials. Powder bed fusion methods are frequently used to produce BTE (bone tissue engineering) scaffold materials with intricate structural components that match the functionality required for load-bearing construction.

Researchers have devised several novel procedures for evaluating the mechanical properties of biomaterials and have demonstrated their efficacy using quasi-static testing methods [24,25]. The microstructural features, surface characteristics, mechanical and biological capabilities, corrosion resistance, and tribological characterization are all examined in depth in this work [26]. Mechanical properties and finite element modelling (FEM) in relation to biomaterial mechanics were explored in this paper, which included elastic modulus, stress, deformation analysis, fracture, and fatigue.

The biomaterial must be able to support the biological and biochemical processes necessary for the development of new tissue in the human body. A biomaterial's effectiveness is further influenced by several additional factors, such as orthopedic implants, surgical treatment, patient activities, and health conditions. Table 1 outlines the material selection for biomedical applications with different factors and properties.

The selection of a biomaterial is so critical and numerous factors must be examined prior to implantation to ensure success. These were among the most important considerations to consider when designing and selecting biomaterials for use in human systems. After that, the numerical and experimental findings were compared. Based on the differences measured between the as-designed and as-produced specimens, this work provides mathematical models capable of predicting the real elastic modulus, porosity, strength, and deformation utilizing as input the model CAD dimensions for a specific geometry.

## Design and Characteristics of Biomaterials

A biomaterial is a nonviable substance that interacts with biological sys-

tems and can function successfully after implantation. Because of the biomaterials' efficient and consistent features, they can be used in a physiological medium [36]. Based on their structure and qualities, biomaterials can be generically classed as metals, ceramics, polymers, and composites. Most biomaterials on the market today are created using one or more of these groups of materials. These materials have a variety of atomic arrangements, resulting in a wide range of structural, physical, chemical, and mechanical properties, and hence a wide range of applications in the body.

It's important to remember that because of their mechanical properties, polymers are often used in soft-tissue applications while metals and ceramics are typically used in hard-tissue applications. This information provides an aid in selecting the appropriate material for a certain application. Dental materials, skin substitute materials, orthopedic materials and vascular graft materials are examples of biomaterials that can be categorized based on their applications. Reliable biomechanical predictions depend on accurate depictions of interactions between dissimilar materials or between the implant and surrounding tissue. The total performance of coated implants and composite scaffolds is greatly impacted by interfacial debonding, slide, and stress transfer. However, because bonding is heterogeneous and there are no well-defined constitutive characteristics, it is challenging to quantify interface behaviour. In order to model interfacial damage and failure, cohesive zone models and contact-based formulations have been developed; nevertheless, their use is still constrained by inadequate experimental calibration. Recent studies have analyzed the relationship between the micro-architecture of porous materials and their biological and physical properties using a variety of computational and experimental methods due to the significance of micro-architecture in determining the mechanical, biological, and physical properties of porous biomaterials [37,38].

## Biomaterials Structure

The results indicate that the physical, biological, and mechanical properties of porous biomaterials are determined by the unit cell. Three-dimensional unit cells such as the truncated cube, rhombic dodecahedron, cube, pyramidal, truncated cube octahedron, honeycomb, octahedral, and diamond lattice make up porous structures. Analytically, statistically, and numerically, lattice structures have been examined. Lattice-related structures are becoming more and more popular in biomedical implants because of their adjustable mechanical performance and lightweight design. However, due to the fact that both geometric arrangement and material qualities influence the behaviour of lattice systems, it is still

**Table 2: Classification of biomaterials with advantages and disadvantages**

| Class of Biomaterials  | Advantages                                                                         | Disadvantages                                                             | Applications                                                                      | Materials                                                     | References |
|------------------------|------------------------------------------------------------------------------------|---------------------------------------------------------------------------|-----------------------------------------------------------------------------------|---------------------------------------------------------------|------------|
| Metal and their Alloys | High mechanical strength and ductility                                             | High density corrosion in a physiological environment                     | Dental implants, biomedical prosthesis                                            | Stainless steel, Titanium, cobalt Ti-6Al-4V alloys            | [39,40]    |
| Polymer                | Produced in a less dense manner.                                                   | Low mechanical resistance and biodegradability                            | Implants in the teeth, ears, nose, heart valves, and testicles                    | PMMA, Nylon Polyethylene, Polypropylene                       | [41,42]    |
| Ceramics               | Low heat conductivity, biocompatible, anti-corrosive                               | Low impact resistance and manufacturing challenges                        | Dental components, coatings, bone fillings, and medical instruments and equipment | Aluminium oxides, titanium oxides, calcium phosphates, carbon | [43-45]    |
| Composites             | Corrosion resistance and high biocompatibility                                     | Continuity and consistency lacking, making production difficult to repeat | Heart valves, knee implants, prosthetic articulations, and hip implants           | Ceramic coatings with metals, carbon coated material          | [46]       |
| Nano-biomaterials      | High surface reactivity, better Cellular adherence, and higher mechanical strength | Size homogeneity is difficult to control.                                 | Tissue engineering, orthopaedics, dental rehabilitation, and drug delivery        | PLLA nanofibers, Nano-HA, Nano-alumina, collagen Nanofibers   | [47-50]    |

**Table 3: Biomaterial structure study with the different techniques and evaluated mechanical properties**

| Structure                                                                                      | DOF | Numerical analysis                                         | Analytical Analysis                            | Experimental                                                                                                    | Mechanical properties                                                              | Ref. |
|------------------------------------------------------------------------------------------------|-----|------------------------------------------------------------|------------------------------------------------|-----------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|------|
| Truncated cube repeating unit cells                                                            | 6   | Finite element Method, Timoshenko beam elements            | Relative density, Stiffness matrix derivation  | INSTRON 5989 1000 kN mechanical testing machine                                                                 | Elastic modulus, Poisson's ratio, yield stress, and buckling load                  | [56] |
| Octahedral unit cells (lattice structure)                                                      | 2   | ANSYS, Timoshenko beam theories, Euler-Bernoulli           | Relative density Stiffness matrix derivation   | Instron Electro Plus E1000 machine, 10 kN load cells, displacement rate was 0.3 mm/min.                         | Elastic modulus, Poisson 's ratio, and yield stress                                | [57] |
| Honeycomb structures (octagonal honeycomb)                                                     | -   | Timoshenko beam theories, Euler-Bernoulli                  | Relative density, Stiffness matrix derivation  | Electro Plus E10000 machine with a 10 kN load cell and displacement rate of 5 mm/min                            | Elastic modulus, yield stress, Poisson's ratio, and buckling stress                | [58] |
| Truncated cuboctahedron                                                                        | 15  | Finite element method Timoshenko beam, Euler-Bernoulli     | Relative density, Stiffness matrix derivation  | INSTRON 5989 1000 kN mechanical testing machine and                                                             | Poisson's ratio, Elastic modulus, and yield stress                                 | [59] |
| Thick honeycombs                                                                               | 4   | Finite element method Timoshenko beam, Euler-Bernoulli     | Relative density, Stiffness matrix derivation  | INSTRON 5989 machine 1000kN load cells and displacement rate 2 mm/min.                                          | Poisson's ratio, Elastic modulus, and yield stress                                 | [60] |
| Double hexagonal pyramid cell                                                                  | 4   | FE models, ANSYS Workbench, LSDYNA                         | Cantilever beam                                | Static compression test using Hounsfield. H10KS machine with a 10 kN load cell and displacement rate 0.5 mm/min | Elastic modulus, yield stress and Poisson's ratio                                  | [61] |
| BCC, hexagonal packing, rhombicuboctahedron, diamond, truncated cube, and truncated octahedron | -   | ANSYS, Euler-Bernoulli and Timoshenko beam theories        | Cantilever beam                                | -                                                                                                               | Elastic modulus, yield stress and Poisson's ratio                                  | [62] |
| Double pyramid dodecahedron unit cell                                                          | -   | Finite-volume method (COMSOL Multiphysics)                 | -                                              | -                                                                                                               | Density (kg/m <sup>3</sup> ) Young's modulus (GPa) Poisson's                       | [63] |
| Diamond unit cells                                                                             | -   | Abaqus (Dassault Systems Simulia Corp, France) RVE         | -                                              | Topological design, morphology                                                                                  | Elastic modulus, yield stress                                                      | [64] |
| Face-centred cubic (FCC)                                                                       | -   | FEM (Abaqus)                                               | -                                              | Geometric defects                                                                                               | Density Poisson's ratio Young's modulus Yield strength Ultimate strength Pore size | [65] |
| Truncated cube lattice                                                                         | 6   | FEM-                                                       | Size-dependent modelling of a micro-/Nano-beam | -                                                                                                               | -                                                                                  | [66] |
| Cubic, tetrahedron, hexagon, octagon, and rhombic dodecahedron                                 | -   | FEA using Netfabb software                                 | Design and optimization                        | -                                                                                                               | Stress and deformation                                                             | [67] |
| Face-centred cubic (FCC) unit cell                                                             | 12  | finite element analysis using shear flexible beam elements | RVE, Cantilever beam                           | -                                                                                                               | Young's moduli, shear moduli and Poisson's ratios                                  | [68] |
| Diamond lattice unit cells                                                                     | -   | FE package linear integration element (type B31)           | Euler-Bernoulli and Timoshenko beam theories,  | static test machine (Instron 5980, 10 kN load cell) and deformation rate 2 mm/min.                              | Poisson's ratio, Elastic modulus, yield stress critical buckling load              | [69] |

**Table 4: Analysis of Conventional Lattice Unit Cell Characteristics**

| Unit Cell Geometry       | Stiffness-to-Weight Efficiency | Fluid Permeability | Primary Limitation                                                    | Reference |
|--------------------------|--------------------------------|--------------------|-----------------------------------------------------------------------|-----------|
| Truncated Cube           | High                           | Moderate           | Susceptible to manufacturing inaccuracies due to geometric complexity | [70]      |
| Octahedral               | High                           | Moderate           | Challenging strut connectivity leading to print-induced defects       | [71]      |
| Diamond                  | Moderate                       | High               | Reduced fatigue durability under cyclic loading                       | [72]      |
| Hexagonal                | Moderate                       | Moderate to High   | Direction-dependent mechanical response                               | [73]      |
| Gyroid (TPMS)            | High                           | Moderate           | Requires high-resolution printing to avoid surface irregularities     | [74]      |
| Body-Centred Cubic (BCC) | Low                            | High               | Stress localization at nodal junctions                                | [75]      |

difficult to anticipate their mechanical reaction. Strength, fatigue life, and stiffness are influenced by size-dependent effects and local stress concentrations at strut joints. It is frequently necessary to use beam-based, homogenization, or micromechanical techniques in order to accurately define lattice mechanics because conventional linear models are unable to capture these effects.

#### Truncated cube unit cell

The truncated cube, sometimes referred to as the truncated hexahedron, is one of a select few unit cells that can be repeatedly repeated in space to create a crystal lattice. The open-cell unit-cell is used in this investigation, and the inclined and uninclined struts might have equal or different lengths. Here, the length ratio between inclined and uninclined (horizontal or vertical) struts is indicated, and its effects on the resulting elastic properties are investigated. The three sub-parts of this section cover the derivation of analytical solutions, and the description of finite element models used to approximate the mechanical properties of porous materials [51].

#### Octahedral unit cell

The octahedral unit cell is a previously unstudied form. Two previous studies looked at a simplified form of this unit cell that did not have the horizontal struts that are critical for structure strength [52,53]. The lattice structure's isotropic properties are also enhanced by the horizontal struts. Furthermore, in both researches stated above, there was a lack of consistency between analytical, numerical, and experimental data. The creation of biomaterials, where both biomechanical and physiologically pertinent features must be taken into consideration at the same time, necessitates having access to a vast library of unit cells. To expand the pool of unit cells from which the fundamental unit cells might be chosen, the current study contributes to the line of research by analyzing the topology-property relationship for a novel unit cell, the octahedral unit cell.

#### Hexagonal unit cell

The hexagonal cell lattice, often known as honeycomb, is the much popular used lattice geometry. Sandwich structures with aluminum honeycomb cores are stiff, strong, and light. From aircraft to the construction industry, cellular materials are employed in a variety of applications that require lightweight constructions. The hexagonal lattice component design, as well as the coordinate system for describing part orientation during printing and testing the inclined and vertical walls' truss lengths, wall thickness and inclined wall angle, establish the geometry of each cell [54].

#### Diamond unit cell

The diamond cubic unit cell has fourteen vertices and sixteen identical edges and is an isotropic geometry. Each node is joined to four other nodes by struts that are spaced apart at an angle of 109.51 degrees. The mechanical properties of diamond-type cellular solids are calculated using structural theories created for high porosity materials. It is presumable

that the solid material is linearly elastic with minute deformations. Given that the geometry is isotropic, and the cellular structure is mechanically an isotropic structure, the diamond cubic unit cell has the same mechanical properties in all directions. Two theories, the Euler–Bernoulli and Timoshenko beam theories, are used to calculate the elastic modulus of diamond-type cellular structures. Truncated cube, Truncated cube octahedron, Face-centered cubic, Rhombic dodecahedron, Double hexagonal pyramid, cube, octahedral, pyramidal, honeycomb and diamond lattice have all been investigated analytically, computationally, and experimentally. To investigate the impact of pore architecture and porosity in radial and longitudinal fluid flow directions used both experimental and numerical methodologies [55]. A comparison of the mechanical effectiveness, permeability properties, and intrinsic structural limits of the most widely used lattice unit cell shapes in biomaterial and additive manufacturing applications. Biomaterial structure study with the different techniques and evaluated mechanical properties in table 3.

Functionally Graded Biomaterial Material (FGBM) is used in a variety of domains of materials. Even though metallic or ceramic-based FGBMs account for the vast majority of FGMs, polymer-based FGBMs are gaining popularity. Despite the great features of polymer nanocomposites and their widespread use in everyday life, typical polymer nanocomposites have significant limitations in terms of realizing their full potential. Table 4 lattice unit cell characteristics.

### Fabrication of biomaterial

Biomaterials are also important in cell movement, biological activity, drug delivery and cell growth. Natural biomaterials are necessary for tissue - engineered on account of their inherent bioactivity, which includes cell proliferation, adhesion, and non-toxicity to native healthy tissue. To address the issue of repeatability, specifics of the biomaterial production study methods should be carefully addressed. Different mechanical findings are found in recent studies that compare metallic biomaterials produced by additive manufacturing with their conventionally processed counterparts. Due to their finer microstructures and quick solidification rates, components made by selective laser melting (SLM) and electron beam melting (EBM) often exhibit greater yield strengths than cast or wrought Ti-6Al-4V alloys. Nevertheless, a number of studies show a discernible decrease in fatigue endurance, which is mostly linked to process-induced flaws such direction-dependent grain orientation, un-melted powder particles, and lack-of-fusion porosity. On the other hand, specimens of laser powder bed fusion (LPBF) that were exposed to hot isostatic pressing (HIP) demonstrated enhanced fatigue resistance, indicating that post-processing can help reduce the number of internal flaws. Although these advancements, there are still contradictory findings in the literature: some scientists report persisting crack initiation at subsurface pores even after densification treatments, while others report near-wrought fatigue performance following surface polishing and heat treatment. Lattice structures made by additive techniques show more stress localization at strut joints than bulk specimens made by conventional forging, which causes premature fatigue failure under cyclic loading, according to a comparative evaluation of fabrication routes.

Furthermore, good life prediction using isotropic constitutive models is complicated by the fact that anisotropic mechanical behaviour is still more noticeable in implants made of SLM and LPBF than in cast alloys. These results suggest that while improved manufacturing procedures provide better geometric control and increased static strength, micro-structural heterogeneity and defect sensitivity continue to limit their long-term durability for load-bearing biomedical applications.

### Selective laser melting (SLM)

SLM is a new technology that can be used to make a variety of metallic biomaterials. This procedure not only allows for the fabrication of complicated geometrical structures and fully dense parts, but it also aids in the improvement of their mechanical behavior. The final produced mechanical properties of the components are influenced by processing settings and various SLM manufacturing part designs, such as solid, porous, and hybrid. SLM has been widely employed in the biomedical and aerospace industries due to enhanced mechanical behavior of metallic biomaterials. The scanned and solidified layers are then stacked on top of one another to produce a fully functional three-dimensional component, tool, or sample. Most metallic materials SLM research is focused on ferrous, nickel, and titanium-based alloys. In most cases, spherical powders with a diameter of 15–50  $\mu\text{m}$  are employed in the procedure. With the advancement of technology, SLM of aluminum, copper, and magnesium-based materials has become one of the emphasis areas [76].

### Electron beam melting (EBM)

EBM is a particular sort of electron optical column in which a powder layer is equally scraped using a gravity-supplied electron beam that is produced, focused, and scanned across. Each layer, which is 45 to 95  $\mu\text{m}$  thick, is heated to temperatures between 700 and 900°C through a series of beam passes at scan speeds >105 mm/s at high current. This is followed by a melt scan at a higher scan speed and lower beam current (>101 mm/s; 8 mA). In a vacuum chamber that can accommodate up to 0.3 m<sup>3</sup> of building components, a 3D-CAD (computer-aided design) software model selectively drives the melt scan, which melts just certain layer pieces that are placed in the construction direction to generate intricate, 3D structures. Depending on the powder parameters, especially melting point, process optimization entails selecting a beam focus and a melt scan beam current. Additive manufacturing (AM) with electron beam melting (EBM) has recently demonstrated the capability of creating not just complicated, porous, monolithic implant components, but also patient-specific implant components [77].

### Electrospinning

Electro spraying gave rise to electrospinning, which was initially discovered by Rayleigh in 1882, explored in depth by Zeleny, and patented by Formals in 1934. Taylor's work on electrically powered jets created the foundation for electrospinning. The three components of an electrospinning setup are a high voltage power source, a syringe needle, and a grounded target (usually a metal screen, plate, or rotating mandrel). The spinneret carrying the spinning solution is connected to one electrode of the high voltage power source, while the other is connected to the collector, which is normally grounded. During electrospinning, a solution is first supplied through a spinneret, and then a high voltage is applied to the solution at a critical value (typically more than 7 kV). A jet will erupt from the spinneret's tip when the electric force is greater than the surface tension of the solution. Despite being stable close to the spinneret's tip, the jet swiftly enters a stage of bending instability, with the solution jet enlarging as the solvent evaporates because of electrostatic forces in the mixture [78]. The improved coaxial electrospinning can generate nanotubes and core/shell structural nanofibers. Electrospinning is a particularly low-cost, simple, and adaptable process for producing nanofibers from various materials [79].

### Fused deposition modeling (FDM)

One of the first AM techniques is fused deposition modelling (FDM), sometimes referred to as 3D printing. According to the printing process, the melted thermoplastic used as a support for bioinks is produced

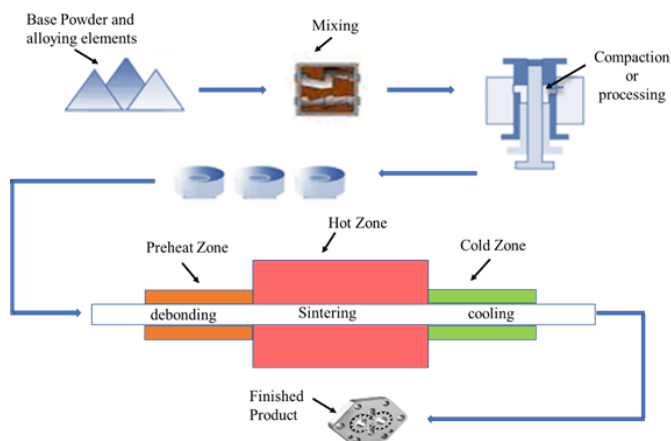
by feeding a thermoplastic polymer into a liquefier and then extruding a filament [80]. Complex tissues and organ constructs have been created using this technology. Depending on how they operate, 3D bioprinting is divided into various categories [81]. To achieve the desired tissue production, these procedures can be used separately or in combination. What follows includes both an explanation of each technique and its corresponding designed graphic. The three main methods for 3D bioprinting are biomimicry, autonomous self-assembly, and mini tissue building blocks. As opposed to autonomous self-assembly, which uses early cells embryonic components to create its own ECM, cell signaling, and cellular architecture, biomimicry type approaches arrange and replicate cellular components to mimic a live tissue [82].

### Powder metallurgy

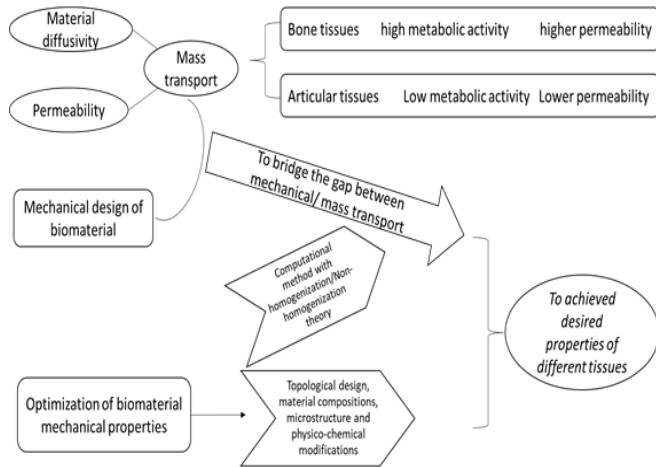
To create a denser component, powder metallurgy compaction of metallic powders is followed by a heat treatment. The method allows for the creation of nearly non-porous shaped pieces with extremely tight dimensional tolerance that are nearly identical in characteristics to their fully dense parent materials. It is challenging to melt or cast metallic powders at high melting temperatures. PM on the powders that have been mixed with the appropriate number of binders, followed by a heat treatment, can produce regular lattice with the desired qualities. Additionally, items with complex designs can be produced quickly using the metal injection molding (MIM) technology. Basic Powder Metallurgy process shown in Fig. 2. There is a growing market and high demand for PM sintered porous metal materials for biomedical applications. For instance, the development of artificial organs and implants is crucial for orthopedic surgery to replace diseased and injured hard tissues including teeth, bones, and joints [83].

In recent years, porous biomaterials may now be manufactured using additive manufacturing processes. Selective laser melting (SLM), Electrospinning, 3D printing, SLA and electron beam melting (EBM), Powder Metallurgy are the most prevalent procedures for this material. From this review Powder Metallurgy is the predominate fabrication method for Proposed Ti based alloy materials. These approaches can be used to create three-dimensional scaffolds with an interconnected porosity that are suited for tissue ingrowth and vasculature. These approaches, on the other hand, allow for mechanical qualities that are like those of human bone, such as compressive strength and elastic modulus. As a result, strain effects upon implantation may be minimized [84].

Alginate is a natural biopolymer that is biocompatible, biodegradable, and hydrophilic. Alginate scaffolds supported cell growth for a long time, and the fibroblasts cells connected and spread in a circular morphology on them [85]. Chitin is the second most abundant natural biopolymer in the world, and it is widely employed in bioengineering. In bioengineering, chitin nanofibers are utilized to support biological activity such as cell proliferation and adhesion [86,87].



**Figure 2: Basic powder metallurgy process for finished material**



**Figure 3: Strategies for optimizing the mechanical characteristics of biomaterials**

## Biocompatibility

The term “biocompatibility” refers to a material’s capacity to carry out its intended functions in relation to a therapeutic intervention, to elicit the proper host response in each application, and to interact with biological systems without causing harm, toxicity, immune system rejection, as well as unneeded or improper systemic or local effects [88,89]. Biocompatibility is critical for the health of patients, dental staff (including laboratory professionals), and practitioners. Furthermore, biocompatibility difficulties are frequently linked to dentists’ legal cul-

pability. Practitioners should have enough knowledge of biocompatibility testing procedures to evaluate advertising claims critically and ask pertinent questions of manufacturers [90-92].

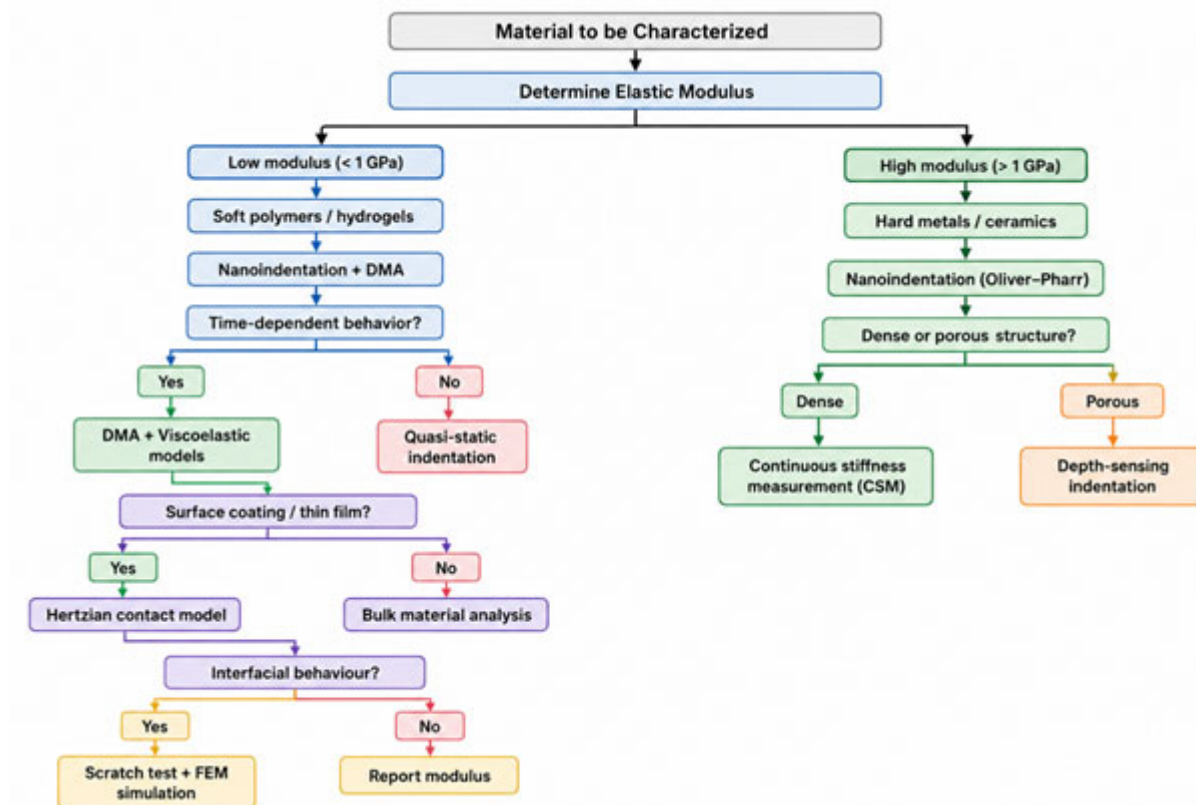
As the engineering and science of biomaterials expands, with a greater focus on the development of biomaterials, Nano-biomaterials, and scaffolds for tissue engineering, adequate and appropriate approaches to biomaterial biocompatibility/biological response evaluation in vivo and in vitro must be prioritized.

## Mechanical Characterization

In many domains of physiology, medicine, and surgery, determining the mechanical properties of biomaterials is a critical topic. After the qualities of biological substances have been identified, the difference between diagnostics and functional information should be made. A straightforward analytical technique that was first created for open cellular structures is used to determine the mechanical properties of porous biomaterials [93]. However, a few experimental studies, including, have shown that analytical models cannot accurately predict the mechanical properties of porous biomaterials produced using additive manufacturing methods. Understanding the material’s mechanical characteristics given its micro-architecture and matrix material properties is an essential practical difficulty in the application of open-cell biomaterials.

It also allows for an assessment of biomaterials research in biomedical applications and encourages the study of mechanical properties of biomaterials. mechanical behavior has aided in validating the proposed model as successful in creating optimal biomaterials capable of improving mechanical properties while providing a structural distribution suitable for medical engineering applications [94].

In order to capture both elastic and viscoelastic responses, materials with low elastic modulus, like hydrogels and polymers, are mainly assessed using nanoindentation in conjunction with dynamic mechanical analysis. On the other hand, instrumented indentation techniques are used to describe high-modulus materials, such as metals and ceramics,



**Figure 4: Decision framework for choosing appropriate mechanical characterization procedures**

**Table 5: Numerical analysis of biomaterials with properties and applications**

| Types of Biomaterials                                                     | Modelling/Simulation /Fabrication                        | Software            | Properties                                                                     | Applications                                                                         | References |
|---------------------------------------------------------------------------|----------------------------------------------------------|---------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|------------|
| Granules of calcium/phosphate biomaterials                                | Computational fluid dynamics (CFD)                       | ANSYS               | Porosity and micro architectural characteristics                               | Small bone defects in oral and maxilla-facial surgery                                | [102,103]  |
| Brittle biomaterials (zirconia-based, ceramic tissue scaffold)            | Phase-field model to simulate the crack propagation      | ABAQUS              | Fracture                                                                       | Prosthetic application                                                               | [104,105]  |
| 3D printed porous scaffold implant material.                              | Modelling and simulations (Monte Carlo method)           | ANSYS 16.0          | Blood/nutrient flow                                                            | Patient-specific biodegradable knee implants                                         | [106,107]  |
| Ti-6Al-4V alloy.                                                          | three-dimensional finite element model                   | ABAQUS              | Fatigue crack growth fracture toughness                                        | Hip implant                                                                          | [108,109]  |
| Mono-material Ti6Al4V and multi-material Ti6Al4V-PEEK cellular structures | Selective laser melting CAD model<br>Mathematical models | COMSOL Multiphysics | Elastic modulus                                                                | Orthopaedic implants                                                                 | [110,111]  |
| UHMWPE biomaterials                                                       | Finite element method (FEM).                             | ABAQUS              | Von Mises stress                                                               | Orthopaedic field specially to replace the damaged hip joint.                        | [112-114]  |
| Organ-on-a-chip                                                           | Finite element modelling, Finite-difference method       | COMSOL              | Fluid velocity, particle trajectories, pressure distribution, and shear stress | Tissue engineering                                                                   | [115-117]  |
| Structurally porous biomaterials                                          | Design of additively manufactured porous biomaterials    | ABAQUS              | Morphology & Mechanical properties (Strength, stiffness)                       | Bone replacement implants                                                            | [118,119]  |
| PF bone-FG plate system                                                   | Finite element modelling                                 | ANSYS 15.0.         | Compressive and torsional stresses, fracture fixation                          | Paediatric femur (PF) bones                                                          | [120]      |
| Lattice and porous structures                                             | Finite element modelling                                 | Abaqus              | Young's modulus, shear modulus and Poisson's ratio                             | Lightweight applications, such as aerospace, automotive or biomechanical engineering | [121]      |
| AM functionally graded porous iron                                        | Experimental and computational analyses                  | Ansys               | Permeability<br>Biodegradation<br>Mechanical properties<br>Biocompatibility    | Bone substitute                                                                      | [122]      |

and the Oliver-Pharr method is used to extract the elastic modulus and hardness. Depth-dependent property evaluation is made possible by continuous stiffness measurement for porous or architected objects made with additive manufacturing. Contact mechanics models like Hertzian or composite modulus methods are necessary for thin films and surface coatings in order to take substrate effect into consideration. Scratch testing combined with finite element modelling is used to measure adhesion strength and stress distribution where interfacial integrity is crucial. Across a range of biomaterial classes and geometrical scales, this systematic selection process guarantees accurate mechanical evaluation. Fig 3. Strategies for optimizing the mechanical characteristics of biomaterials.

Mechanical characteristics are used to evaluate a material's perfor-

mance under a variety of load circumstances, which are frequently described by the material's resulting stresses and strains in fault elastic deformation [95]. To obtain the appropriate qualities for tissue engineering, it is difficult to reconcile mechanical and mass transport properties in biomaterial mechanical design. Figure 4 provides a decision framework for choosing appropriate mechanical characterization procedures.

#### Tensile strength

The ability to determine a material's tensile strength is a useful property. A universal testing device was used to assess the tensile strength of test composite specimens. When a tensile load is given to a bulk material with defined geometry, the machine exerts a force on the material that

**Table 6: Biomaterials with tribological characteristics and utilization**

| Material                                                  | Utilization                                          | Tribological Characteristics                                                                        | References |
|-----------------------------------------------------------|------------------------------------------------------|-----------------------------------------------------------------------------------------------------|------------|
| Metal and their alloys (Ti alloys, Ti-Al-V alloy)         | Total replacement of joints                          | Resistance to oxidation and wear                                                                    | [124]      |
| Inorganic: carbon and diamond                             | Biocompatible materials for coating                  | Minimized friction and increased wear resistance.                                                   | [125]      |
| Polymer (PMMA, Nylon Polyethylene)                        | Joint socket, implant with interposition, joint bone | Low friction coefficient, resistance to wear and oxidation elasticity with a decreased rate of wear | [126]      |
| Ceramics (Aluminium oxides, titanium oxides)              | Coating of bone joints                               | Wear and Corrosion resistance                                                                       | [127]      |
| Composite (ceramic coatings with metals, carbon material) | Joint of bone                                        | Fatigue and wear resistance                                                                         | [128]      |

can be measured by the load cell. Metals have the strongest tensile strength, a somewhat high elastic modulus, and varied degrees of elasticity [96]. The least strong and elastic modulus materials are polymers. The law of mixture applies to the properties of carbon fiber. Ceramics exhibit a significant young's modulus and their biggest strength, yet they exhibit brittle behavior during linear elastic deformation fractures.

### Elastic modulus

The ratio of stress to strain within the proportional limit is the simplest definition of elastic modulus. It is significant from a therapeutic standpoint since it shows that the chosen biomaterial shares similar deformable characteristics with the component it would replace. High young's modulus and minimal deflection are necessary for such force-bearing material [97]. Due to the ease with which deflection can be detected in this scenario as opposed to very minor elongation in compressive or tensile load, the elastic modulus of a material is typically estimated using bending test. The young's modulus of bio ceramic coatings applied to titanium orthopedic implants can now be measured using an ultrasound method.

### Fracture strength

The highest stresses a material can withstand before fracturing is referred to as its strength. Due to their brittle nature, biomaterials' strength (also known as bio-ceramics' strength) is a crucial mechanical attribute. The strength of a material can be determined using a variety of techniques, including the Weibull methodology, biaxial flexural strength test, and bending flexural test [98]. The greatest imperfection or crack will do the most damage to the material, in accordance with Griffith's theory of fracture in tension. Since defect size is constrained by the cross-sectional area of a material, strength also depends on specimen volume.

### Fatigue

The consistency of the material reveals fatigue properties under cyclical loads. The above-mentioned implants must also have high biocompatibility to be used for a long time, work well, and be reliable. Microstructures have a strong relationship with fatigue characteristics [99-101]. For example, systematic studies or comparisons of fretting fatigue features have been made in relation to associated microstructures. Biological materials like bone are especially likely to lack fracture toughness since even low-stress loading can induce elastic fibers in the material to transfer across several cycles.

## Finite Element Method

Finite element analysis is now a commonly used computational approach to examine the mechanical properties of biologically generated structures and biomaterials. As it can simulate complicated geometries and heterogeneous material systems, it is especially well-suited for assessing load-bearing capacity, deformation patterns, and stress distribution in biological complex structure. Table 5. Numerical analysis of biomaterials with properties and applications. The present paper provides a summary of numerical techniques for using finite element simulations to anticipate the mechanical reaction of biomaterials. Modelling approaches that take into account nonlinear constitutive behaviour, architectural anisotropy, and the mechanical interaction at tissue implant interfaces are given particular consideration. Under physiologically realistic loading situations, these methods improve the accuracy of computer forecasts.

Finite element modelling of biomaterials that are additively generated poses a number of difficulties despite their extensive application. Accurate material representation in numerical models is made more difficult by the inherent anisotropy, process-induced flaws, and intricate microstructures of printed components. Nonlinear deformation, viscoelasticity, and damage progression seen under physiological loading conditions are frequently missed by simplified constitutive rules. Furthermore, when simulating porous systems with intricate geometric features, mesh reliance and high computational cost continue to be major drawbacks. These problems show that in order to increase predicted

accuracy, multiscale and empirically proven FEM frameworks are required.

The suggested structure's mechanical parameters (elastic modulus, yield stress and Poisson's ratio) were calculated using an analytical solution. Furthermore, several tools such as ANSYS Workbench, Abaqus and COMSOL were used to do a numerical analysis for the proposed structures. The numerical and analytical results were found to be in good agreement.

## Tribological Characteristics of Biomaterial

Tribological processes occur frequently in humans, particularly in the living body's bones, valves, heart, teeth, skin, and eyes. It is crucial to understand how these processes work in the body and to create biomaterials artificially to replace injured tissue to help patients with their pain. Using a Pin-on-Disc and Ball-on-Disc tribometer in ambient settings, friction and wear experiments were performed under various circumstances and sliding velocities with and without lubricant. In the evaluation of biomaterial efficiency, friction and wear play a significant role. Table 6. Biomaterials with tribological characteristics and utilization.

In terms of cracking, adhesion, and abrasion, tribo-mechanical wear is the dominant wear mechanism. The successes in the field of biomedical material tribology research have been briefly discussed in this paper, with a focus on biomaterials and suggested methods for their evaluation [123].

### Wear testing method

It is imperative to describe the wear and friction of generated biomaterials using a suitable test approach, given the limitations, especially in terms of the tribological properties. To analyze the tribological behavior of metallic biomaterials, the literature most usually uses the ball-on-disc, block-on-disc, and pin-on-disc methodologies. A simulated body fluid containing sodium chloride and phosphate-buffered solutions were used for the wear tests. But in a few cases, testing was also carried out with dry sliding. To mimic natural or ambient circumstances, a temperature of 370.1 °C was chosen for the experiments.

### Techniques for characterizing the wear of biomaterials

The assessment of tribological behavior has been carried out using several methods. To ascertain the compositions of some locations, chemical investigations like energy-dispersive X-ray spectroscopy (EDXS/EDS) have been used. The surface chemistry has been examined using X-ray photoelectron spectroscopy (XPS). A 3D optical profilometer was used to measure the volume loss in the wear track. A scanning electron microscopy/light microscope (SEM/LM) has been used for post-test inspections or to pinpoint the wear process. A 3D Talysurf instrument was used to measure the 3D surface roughness. AFM with a depth-sensing indentation device also allowed for the determination of fascinating mechanical properties like the modulus of elasticity and hardness [129].

### Friction and Wear behavior

According to ISO 7148, ASTM G133-94 and ASTM G99-95 standards, experiments and tests using an oscillating tribometer have been conducted in ambient air. According to ASTM F86-01, ASTM F136-02 and ASTM E1078-02, samples were prepared for analysis. Each sample was carefully cleaned with ethylene, cleaned in an ultrasonic bath for 80 minutes, and then dried in hot air. After immersing the samples in the solution for 60 minutes, they were washed with isopropyl alcohol. After washing, the samples were dried in hot air. The sliding velocities under varied normal loads (2, 10, and 15 mm/s) are within the range typically experienced in hip joints (2, 6, 8, and 10 N) [130]. Throughout the testing, the friction coefficient, also known as the dynamic friction coefficient, was automatically recorded using data collection software. Tribomechanical wear is the most prevalent type of deterioration, which is evident by abrasion, adhesion, ploughing and cracking. Today, bioengineers and biologists are the "key actors" in this subject. Accord-

ing to Ratner et al. 2020, the need to bridge the gap between clinical practice and scientific research will likely be what spurs the creation of new biomaterials [131].

## Concluding Remarks

This paper gives a broad review of biomaterials, from their origins through modern developments. Biocompatibility and mechanical behavior, wear resistance, corrosion and osseointegration are the most important elements to consider when using biomaterials in the long run. It is very desired to design biomaterials with good biocompatibility and functional qualities. Among other biomaterials, metals, ceramics, polymers, and their composites are frequently used in biological applications and have significantly reduced disease and injury morbidity and mortality. Technological improvements in a few outstanding biomaterial systems; technological improvements have enabled the creation of novel biomaterials as well as new fabrication procedures for existing materials. The biomaterial adopted to replace the bone has mechanical properties that are like this, such as a modulus of elasticity that is equivalent to bone's, avoiding the stress shielding effect and its implications. The field of biomaterials is currently undergoing a revolution because to the emerging fields of nanotechnology, biomimetics, and tissue engineering, which will surely have a major impact on the creation of the next generation of biomaterials, known as nan biomaterials. For non-biomaterial and implant biomaterial to continue to succeed, numerous researchers from the fields of materials science and engineering, physical sciences, nanotechnology biological sciences and medicine must work together.

## Future Scope

The selection of a biomaterial for a certain application in the present and the future must consider a lot of factors. Medical studies keep pushing the boundaries of science to identify, treat, prevent, and cure diseases at the genetic and molecular level. Prosthetic joints require the implants to bear physiological repetitive forces in a biological Milieu for very long periods of time. The most important requirement that every biomaterial must satisfy is biocompatibility.

Even with the significant advancements in 4D biomaterials and smart implant design, there are still a number of important issues that need to be looked at further. Specifically with respect to inflammatory response and ion release under cyclic physiological settings, the long-term biological effects of breakdown products from shape-adaptive polymers and bioresorbable metals systems remain unclear. Concurrently, limited power availability, signal instability, and sensor drift during extended in vivo operation impede the integration of real-time biosensing into lattice and porous implants.

In the past, engineers, chemists, and physicists dominated the field of biomaterials science. To combine qualities like high strength, corrosion, wear resistance and biocompatibility, it is essential to choose the right matrix system, reinforcing materials, and volume fraction form and size of reinforcing phase. This review may be useful for that researcher who really is interested in the most recent developments in biomaterial assessment and biomaterial selections.

A significant issue is fatigue degradation with repetitive mechanical loading since designed structures are vulnerable to microcrack development and stress concentration during actuation. Particularly in multi-material and functionally graded structures, mechanical and chemical incompatibility at the implant–tissue interface still hinders load transmission and long-term fixation. Therefore, bio-safe degradation mechanisms, energy-harvesting or self-powered sensing systems, fatigue-tolerant metamaterial designs, and interface-engineered surfaces that more closely mimic the characteristics of original tissue should be the main focus of future study. To create long-lasting, flexible, and clinically dependable smart implants, these interrelated constraints must be overcome.

## References

- Dee, Kay C & Puleo, David & Bizios, Rena. . An Introduction To Tissue-Biomaterial Interactions. An Introduction to Tissue-Biomaterial Interactions, by Kay C. Dee, David A. Puleo, Rena Bizios, pp. 248 (2002).
- Williams DF: On the nature of biomaterials. *Biomaterials* 30: 5897–5909 (2009).
- Park, J.B., & Bronzino, J.D. (Eds.) *Biomaterials: Principles and Applications* (1st ed.). CRC Press (2002).
- Tran Le Bao Ha, To Minh Quan, Doan Nguyen Vu, Do Minh Si. Naturally derived biomaterials: Preparation and application (2013).
- Ratner BD, Hoffman AS, Schoen FJ, Lemons JE, Wagner WR, Sakiyama-Elbert S, Zhang G, Yaszemski MJ. Introduction to biomaterials science. In: *Biomaterials Science*. Elsevier (2020).
- Dohan Ehrenfest DM, Coelho PG, Kang BS, Sul YT, Albrektsson T. Classification of osseointegrated implant surfaces: Materials, chemistry and topography. *Trends Biotechnol.* 28: 198–206 (2010).
- Leite AJ, Mano JF. Biomedical applications of natural-based polymers combined with bioactive glass nanoparticles. *J. Mater. Chem. B* 5: 4555–4568 (2017).
- Kaur G, Pandey OP, Singh K, Homa D, Scott B, Pickrell G. A review of bioactive glasses: Their structure, properties, fabrication, and apatite formation. *J. Biomed. Mater. Res. A* 102: 254–274 (2014).
- Ratner BD, Hoffman AS, Schoen FJ, Lemons JE. *Biomaterials Science*. Elsevier Academic Press, Oxford (2004).
- Thompson ID, Hench LL. Mechanical properties of bioactive glasses, glass-ceramics, and composites. *Proc. Inst. Mech. Eng. H* 212: 127–136 (1998).
- Kalaiyarasan A, Sankar KS, Sundaram S. Finite element analysis and modeling of fractured femur bone. *Mater. Today Proc.* 22: 649–653 (2020).
- Merolli A, Joyce TJ (Eds.). *Biomaterials in Hand Surgery*. Springer-Verlag Italia (2009).
- Mangado N, Pons-Prats J. Analysis of uncertainty and variability in finite element computational models for biomedical engineering: Characterization and propagation. *Front. Bioeng. Biotechnol.* 4: 85 (2016).
- Ichim I, Li Q, Li W, Swain MV, Kieser J. Modelling of fracture behavior in biomaterials. *Biomaterials* 28: 1317–1326 (2007).
- Kulkarni SV, Nemade AC, Sonawane PD. An overview on metallic and ceramic biomaterials. In: Dave HK, Dixit US, Nedelcu D (Eds.). *Recent Advances in Manufacturing Processes and Systems*. Lecture Notes in Mechanical Engineering. Springer, Singapore (2022).
- Hench LL, Wilson J. An Introduction to Bioceramics. World Scientific, Singapore (1993).
- Capurro M, Barberis F. Evaluating the mechanical properties of biomaterials. In: *Biomaterials for Bone Regeneration*. Woodhead Publishing, pp. 270–323 (2014)..
- Van Staden RC, Guan H, Loo YC. Application of the finite element method in dental implant research. *Comput. Methods Biomech. Biomed. Engin.* 9: 257–270 (2006).
- Aherwar A, Singh AK, Patnaik A. Cobalt based alloy: A better choice biomaterial for hip implants. *Trends Biomater. Artif. Organs* 30: 50–55 (2016).
- Rack HJ, Qazi JI. Titanium alloys for biomedical applications. *Mater. Sci. Eng. C* 26: 1269–1277 (2006).
- Pandey A, Awasthi A, Saxena KK. Metallic implants with properties and latest production techniques: A review. *Adv. Mater. Process. Technol.* 6: 405–440 (2020).
- Vrana NE. Introduction to biomaterials for tissue/organ regeneration. In: *Biomaterials for Organ and Tissue Regeneration*. pp. 3–17 (2020).
- Punj S, Singh J, Singh K. Ceramic biomaterials: Properties, state of the art and future perspectives. *Ceram. Int.* 47: 28059–28074 (2021).
- Pérez RA, Won JE, Knowles JC, Kim HW. Naturally and synthetic smart composite biomaterials for tissue regeneration. *Adv. Drug Deliv. Rev.* 65: 471–496 (2013).
- Baig N, Kammakam I, Falath WS. Nanomaterials: A review of synthesis, properties, recent progress, and challenges. *Mater. Adv.* 2 (2021).
- Zadpoor AA. Mechanical performance of additively manufactured meta-biomaterials. *Acta Biomater.* 85: 41–59 (2019).
- Tan X, Tan Y, Chow C, Tor S, Yeong W. Metallic powder-bed based 3D printing of cellular scaffolds for orthopedic implants: A state-of-the-art review on manufacturing, topological design, mechanical properties and biocompatibility. *Mater. Sci. Eng. C* 76: 1328–1343 (2017).
- Sing SL, An J, Yeong WY, Wiria FE. Laser and electron-beam powder-bed additive manufacturing of metallic implants: A review on processes, materials and designs. *J. Orthop. Res.* 34: 369–385 (2016).
- van Grunsven W, Hernandez-Nava E, Reilly GC, Goodall R. Fabrication and mechanical characterization of titanium lattices with graded porosity. *Metals* 4: 401–409 (2014).
- Han C, Li Y, Wang Q, Wen S, Wei Q, Yan C, Hao L, Liu J, Shi Y. Continuous functionally graded porous titanium scaffolds manufactured by selective laser melting for bone implants. *J. Mech. Behav. Biomed. Mater.* (2018).
- Iannace S, Sabatini G, Ambrosio L, Nicolais L. Mechanical behavior of composite artificial tendons and ligaments. *Biomaterials* 16: 675–680 (1995).
- Zhang XY, Fang G, Slangen SL, Zadpoor AA, Zhou J. Topological design, permeability and mechanical behavior of additively manufactured functionally graded porous metallic biomaterials. *Acta Biomater.* 84: 437–452 (2019).
- Ramakrishna S, Mayer J, Wintermantel E, Leong KW. Biomedical applications of polymer-composite materials: A review. *Compos. Sci. Technol.* 61: 1189–1224 (2001).
- Helmus MN, Gibbons DF, Cebon D. Biocompatibility: Meeting a key functional requirement of next-generation medical devices. *Toxicol. Pathol.* 36: 70–80 (2008).
- Huzum B, Puha B, Necoara RM, et al. Biocompatibility assessment of biomaterials used in orthopedic devices: An overview. *Exp. Ther. Med.* 22: 1315 (2021).
- Meyers MA, Chen PY, Lin AYM, Seki Y. Biological materials: Structure and mechanical properties. *Prog. Mater. Sci.* 53: 1–206 (2008). DOI: 10.1016/j.pmatsci.2007.
- Li C, Ouyang L, Armstrong JPK, Stevens MM. Advances in the fabrication of biomaterials for gradient tissue engineering. *Trends Biotechnol.* 39: 150–164 (2021).
- Elhattab K, Bhaduri SB, Lawrence JG, Sikder P. Fused filament fabrication (three-dimensional printing) of amorphous magnesium phosphate/polylactic acid macroporous biocomposite scaffolds. *ACS Appl. Bio Mater.* 4: 3276–3286 (2021).
- Shick TM, Abdul Kadir AZ, Ngadiman NHA, Ma'aram A. A review of biomaterials scaffold fabrication in additive manufacturing for tissue engineering. *J. Bioact. Compat. Polym.* 34: 415–435 (2019).

40. Kyriakides TR. Molecular events at tissue-biomaterial interface. In: Badylak SF (Ed.). Host Response to Biomaterials. Academic Press, pp. 81–116 (2015).
41. Lopresti ST, Brown BN. Host response to naturally derived biomaterials. In: Badylak SF (Ed.). Host Response to Biomaterials. Academic Press, pp. 53–79 (2015).
42. Niinomi M. Metallic biomaterials. *J. Artif. Organs* 11: 105–110 (2008).
43. Prasad K, Bazaka O, Chua M, Rochford M, Fedrick L, Spoor J, Symes R, Tieppo M, Collins C, Cao A, Markwell D, Ostrikov K, Bazaka K. Metallic biomaterials: Current challenges and opportunities. *Materials* 10: 884 (2017).
44. Seal BL, Otero TC, Panitch A. Polymeric biomaterials for tissue and organ regeneration. *Mater. Sci. Eng. R Rep.* 34: 147–230 (2001).
45. Griffith LG. Polymeric biomaterials. *Acta Mater.* 48: 263–277 (2000).
46. Punj S, Singh J, Singh K. Ceramic biomaterials: Properties, state of the art and future perspectives. *Ceram. Int.* 47: 28059–28074 (2021).
47. Egbo MK. A fundamental review on composite materials and some of their applications in biomedical engineering. *J. King Saud Univ. Eng. Sci.* 33: 557–568 (2021).
48. Baig N, Kammakam I, Falath WS. Nanomaterials: A review of synthesis methods, properties, recent progress and challenges. *Mater. Adv.* 2: 1821–1871 (2021).
49. Konur O. Scientometric overview regarding the surface chemistry of nano-biomaterials. In: Grumezescu AM (Ed.). Surface Chemistry of Nanobiomaterials. William Andrew Publishing, pp. 463–486 (2016).
50. Amorim MJB, Fernández-Cruz ML, Hund-Rinke K, et al. Environmental hazard testing of nano-biomaterials. *Environ. Sci. Eur.* 32: 101 (2020).
51. Mullen L, Stamp R, Brooks W, Jones E, Sutcliffe CJ. Selective laser melting: A regular unit cell approach for the manufacture of porous titanium bone ingrowth constructs suitable for orthopedic applications. *J. Biomed. Mater. Res. Part B Appl. Biomater.* 89: 325–334 (2009).
52. Hedayati R, Sadighi M, Mohammadi-Aghdam M, Zadpoor AA. Mechanical properties of regular porous biomaterials made from truncated cube repeating unit cells: Analytical solutions and computational models. *Mater. Sci. Eng. C* 60: 163–183 (2016).
53. Murr LE, et al. Microstructure and mechanical properties of open-cellular biomaterials prototypes for total knee replacement implants fabricated by electron beam melting. *J. Mech. Behav. Biomed. Mater.* 4: 1396–1411 (2011).
54. McGregor D, Tawfik S, King WP. Mechanical properties of hexagonal lattice structures fabricated using continuous liquid interface production additive manufacturing. *Addit. Manuf.* (2018).
55. Ahmadi SM, et al. Mechanical behavior of regular open-cell porous biomaterials made of diamond lattice unit cells. *J. Mech. Behav. Biomed. Mater.* 34: 106–115 (2014).
56. Hedayati R, Sadighi M, Mohammadi-Aghdam M, Zadpoor AA. Mechanical properties of regular porous biomaterials made from truncated cube repeating unit cells: Analytical solutions and computational models. *Mater. Sci. Eng. C* 60: 163–183 (2016).
57. Hedayati R, Sadighi M, Mohammadi-Aghdam M, Zadpoor AA. Analytical relationships for the mechanical properties of additively manufactured porous biomaterials based on octahedral unit cells. *Appl. Math. Model.* (2017).
58. Hedayati R, Sadighi M, Mohammadi-Aghdam M, Zadpoor AA. Mechanical properties of additively manufactured octagonal honeycombs. *Mater. Sci. Eng. C* 69 (2016).
59. Hedayati R, Sadighi M, Mohammadi-Aghdam M, Zadpoor AA. Mechanical behavior of additively manufactured porous biomaterials made from truncated cuboctahedron unit cells. *Int. J. Mech. Sci.* 106: 19–38 (2016).
60. Hedayati R, Sadighi M, Mohammadi-Aghdam M, Zadpoor AA. Mechanical properties of additively manufactured thick honeycombs. *Materials* 9: 613 (2016).
61. Mahbod M, Asgari M. Elastic and plastic characterization of a newly developed additively manufactured functionally graded porous lattice structure: Analytical and numerical models. *Int. J. Mech. Sci.* 155: 248–266 (2019).
62. Hedayati R, Ghavidelnia N, Sadighi M, Bodaghi M. Improving the accuracy of analytical relationships for mechanical properties of additively manufactured lattice structures (2020).
63. Aljaberi M, Al-Baghdadi M, Al-Waily M, Mohammadi-Aghdam M, Goudarzi T. Numerical investigation of mechanical behavior for lattice structures with the effect of different nanomaterial types. *IOP Conf. Ser. Mater. Sci. Eng.* 1094: 012172 (2021).
64. Zhang XY, Fang G, Leeftang S, Zadpoor AA, Zhou J. Topological design, permeability and mechanical behavior of additively manufactured functionally graded porous metallic biomaterials. *Acta Biomater.* 84: 437–452 (2019).
65. Sahmani S, Fotouhi M, Mohammadi-Aghdam MM. Size-dependent nonlinear secondary resonance of micro-/nano-beams made of nano-porous biomaterials including truncated cube cells. *Acta Mech.* 230: 1077–1103 (2019).
66. Abate KM, Nazir A, Yeh YP, et al. Design, optimization, and validation of mechanical properties of different cellular structures for biomedical application. *Int. J. Adv. Manuf. Technol.* 106: 1253–1265 (2020).
67. Alaña M, Lopez-Arancibia A, Pradera-Mallabiarrena A, Ruiz de Galarreta S. Analytical model of the elastic behavior of a modified face-centered cubic lattice structure. *J. Mech. Behav. Biomed. Mater.* 98: 357–368 (2019).
68. Ahmadi SM, Campoli G, Yavari SA, et al. Mechanical behavior of regular open-cell porous biomaterials made of diamond lattice unit cells. *J. Mech. Behav. Biomed. Mater.* 34: 106–115 (2014).
69. Montazerian H, Zhihanmanesh M, Davoodi E, Milani AS, Hoorfar M. Longitudinal and radial permeability analysis of additively manufactured porous scaffolds: Effect of pore shape and porosity. *Mater. Des.* 122: 146–156 (2017).
70. Wan Harun WS, Kadirgama K, Samykano M, Ramasamy D, Ahmad I, Moradi M. Mechanical behavior of selective laser melting-produced metallic biomaterials. In: Davim JP (Ed.). *Mechanical Behaviour of Biomaterials*. Woodhead Publishing, pp. 101–116 (2019).
71. Anselme K, Biggerelle M. Topography effects of pure titanium substrates on human osteoblast long-term adhesion. *Acta Biomater.* 1: 211–222 (2005).
72. Murr LE, Amato KN, Li SJ, et al. Microstructure and mechanical properties of open-cellular biomaterials prototypes for total knee replacement implants fabricated by electron beam melting. *J. Mech. Behav. Biomed. Mater.* 4: 1396–1411 (2011).
73. Teo WE, Ramakrishna S. A review on electrospinning design and nanofibre assemblies. *Nanotechnology* 17: R89–R106 (2006).
74. Liu Q, Zhu J, Zhang L, Qiu Y. Recent advances in energy materials by electrospinning. *Renew. Sustain. Energy Rev.* 81: 1825–1858 (2018).
75. Li J, Chen M, Fan X, Zhou H. Recent advances in bioprinting techniques: Approaches, applications and future prospects. *J. Transl. Med.* 14: 271 (2016).
76. Liao JD, Lee H, Yao CK. Powder metallurgy based porous metal biomaterials. *J. Powder Metall. Min.* 2: 109 (2013).
77. Shin M, Ishii O, Sueda T, Vacanti JP. Contractile cardiac grafts using a novel nanofibrous mesh. *Biomaterials* 25: 3717–3723 (2004).
78. Doshi J, Reneker DH. Electrospinning process and applications of electrospun fibers. *J. Electrostat.* 35: 151–160 (1995).
79. Zein I, Hutmacher DW, Tan KC, Teoh SH. Fused deposition modeling of novel scaffold architectures for tissue engineering applications. *Biomaterials* 23: 1169–1185 (2002).
80. Aliheidari N, Tripuraneni R, Ameli A, Nadimpalli S. Fracture resistance measurement of fused deposition modeling 3D printed polymers. *Polym. Test.* 60: 94–101 (2017). DOI: 10.1016/j.polymertesting.2017.03.016.
81. Rimell JT, Marquis PM. Selective laser sintering of ultra-high molecular weight polyethylene for clinical applications. *J. Biomed. Mater. Res.* 53: 414–420 (2000).
82. Lohfeld S, Tyndyk MA, Cahill S, Flaherty N, Barron V, McHugh PE. A method to fabricate small features on scaffolds for tissue engineering via selective laser sintering. *J. Biomed. Sci. Eng.* 3: 138–147 (2010).
83. Kang E, Choi YY, Chae SK, Moon JH, Chang JY, Lee SH. Microfluidic spinning of flat alginate fibers with grooves for cell-aligning scaffolds. *Adv. Mater.* 24: 4271–4277 (2012).
84. Pan H, Jiang H, Chen W. Interaction of dermal fibroblasts with electrospun composite polymer scaffolds prepared from dextran and poly(lactide-co-glycolide). *Biomaterials* 27: 3209–3220 (2006).
85. Murphy CM, Haugh MG, O'Brien FJ. The effect of mean pore size on cell attachment, proliferation and migration in collagen-glycosaminoglycan scaffolds for bone tissue engineering. *Biomaterials* 31: 461–466 (2010).
86. Niinomi M. Metallic biomaterials. *J. Artif. Organs* 11: 105–110 (2008).
87. Prasad K, Bazaka O, Chua M, Rochford M, Fedrick L, Spoor J, Symes R, Tieppo M, Collins C, Cao A, Markwell D, Ostrikov K, Bazaka K. Metallic biomaterials: Current challenges and opportunities. *Materials* 10: 884 (2017).
88. Seal BL, Otero TC, Panitch A. Polymeric biomaterials for tissue and organ regeneration. *Mater. Sci. Eng. R Rep.* 34: 147–230 (2001).
89. Sharma GK, Kukshal V. Assessment of mechanical behavior of functionally graded biomaterials using finite element method. *Mater. Today Proc.* 62: 7487–7493 (2022).
90. Griffith LG. Polymeric biomaterials. *Acta Mater.* 48: 263–277 (2000).
91. Amani H, Kazerooni H, Hassanpoor H, Akbarzadeh A, Pazoki-Toroudi H. Tailoring synthetic polymeric biomaterials towards nerve tissue engineering: A review. *Artif. Cells Nanomed. Biotechnol.* 47: 3524–3539 (2019).
92. Punj S, Singh J, Singh K. Ceramic biomaterials: Properties, state of the art and future perspectives. *Ceram. Int.* 47: 28059–28074 (2021).
93. Egbo MK. A fundamental review on composite materials and some of their applications in biomedical engineering. *J. King Saud Univ. Eng. Sci.* 33: 557–568 (2021).
94. Elias CN, Lima JHC, Valiev R. Biomedical applications of titanium and its alloys. *JOM* 60: 46–49 (2008).
95. Raval A, Choubey A, Engineer C, Kothwala D. Development and assessment of 316LVM cardiovascular stents. *Mater. Sci. Eng. A* 386: 331–343 (2004).
96. Tang HP, Zhao P, Xiang CS, Liu N, Jia L. Ti-6Al-4V orthopedic implants made by selective electron beam melting. In: *Titanium in Medical and Dental Applications*. Woodhead Publishing, pp. 239–249 (2018).
97. Mohanty M. Medical applications of alumina ceramics. *Trans. Indian Ceram. Soc.* 54: 200–204 (1995).
98. Lin H, Yin C, Mo A. Zirconia-based dental biomaterials: Structure, mechanical properties, biocompatibility, surface modification, and applications as implant. *Front. Dent. Med.* 2: 689198 (2021).
99. Lin H, Yin C, Mo A. Zirconia-based dental biomaterials: Structure, mechanical properties, biocompatibility, surface modification, and applications as implant. *Front. Dent. Med.* 2: 689198 (2021).
100. Piconi C, Maccaro G. Zirconia as a ceramic biomaterial. *Biomaterials* 20: 1–25 (1999).
101. Verma S, Sharma N, Kango S, Sharma S. Developments of PEEK (polyetheretherketone) as a biomedical material: A focused review. *Eur. Polym. J.* 147: 110295 (2021).
102. Lü JM, Wang X, Marin-Muller C, Wang H, Lin PH, Yao Q, Chen C. Current advances in research and clinical applications of PLGA-based nanotechnology. *Expert Rev. Mol. Diagn.* 9: 325–341 (2009).
103. Makadia HK, Siegel SJ. Poly(lactic-co-glycolic acid) (PLGA) as biodegradable controlled drug delivery carrier. *Polymers* 3: 1377–1397 (2011).
104. Frazer RQ, Byron RT, Osborne PB, West KP. PMMA: An essential material in medicine and dentistry. *J. Long Term Eff. Med. Implants* 15: 629–639 (2005).
105. Hermawan H, Ramdan D, Djuansjah JRP. Metals for biomedical applications. In: Fazel-Rezai R (Ed.). *Biomedical Engineering – From Theory to Applications*. IntechOpen (2011).
106. Kaur M, Singh K. Review on titanium and titanium-based alloys as biomaterials for orthopaedic applications. *Mater. Sci. Eng. C* 102: 844–862 (2019).
107. Huang J. Design and development of ceramics and glasses. In: *Biology and Engineering of Stem Cell Niches*. Academic Press, pp. 315–329 (2017).
108. Radin S, Ducheyne P, Falaize S, Hammond A. In vitro transformation of bioactive glass granules into Ca-P shells. *J. Biomed. Mater. Res.* 49: 264–272 (2000).
109. Douek E. Otolitic applications of bioglass implants. In: Bonfield W, Hastings GW, Tanner KE (Eds.). *Bioceramics*, Vol. 4. Butterworth-Heinemann, Oxford (1991).
110. Chappard D, Kün-Darbois JD, Guillaume B. Computational fluid dynamics simulation from micro-CT stacks of commercial biomaterials usable for bone grafting. *Micron* 133: 102861 (2020).

111. Wu C, Fang J, Zhang Z, Entezari A, Sun G, Swain MV, Li Q. Fracture modeling of brittle biomaterials by the phase-field method. *Eng. Fract. Mech.* 224: 106752 (2020).
112. Sahai N, Saxena KK, Gogoi M. Modelling and simulation for fabrication of 3D printed polymeric porous tissue scaffolds. *Adv. Mater. Process. Technol.* 6: 530–539 (2020).
113. Sedmak A, Eolite K, Grbović A, Balac I, Burzić M. Numerical analysis of fatigue crack growth of hip implant. *Eng. Fract. Mech.* 216: 106492 (2019).
114. Sharma GK, Kukshal V. Mechanical behavior and finite element analysis of biomaterials: A review. In: *Composite Materials for Extreme Loading. Lecture Notes in Mechanical Engineering*. Springer, Singapore (2022).
115. Sharma GK, Kukshal V, Shekhawat D, Patnaik A. Fabrication and characterization of metallic biomaterials in medical applications. In: *Advanced Materials and Manufacturing Processes*. CRC Press (2021).
116. Aziz AUR, Geng C, Fu M, Yu X, Qin K, Liu B. The role of microfluidics for organ-on-chip simulations. *Bioengineering* 4: 39 (2017).
117. Lozanovski B, Downing D, Tran JP, Shidid DP, Qian M, Choong P, Brandt M, Leary M. A Monte Carlo simulation-based approach to realistic modelling of additively manufactured lattice structures. *Addit. Manuf.* 32: 101092 (2020).
118. Melancon D, Bagheri ZS, Johnston RB, Liu L, Tanzer M, Pasini D. Mechanical characterization of structurally porous biomaterials built via additive manufacturing: Experiments, predictive models, and design maps for load-bearing bone replacement implants. *Acta Biomater.* 63: 350–368 (2017).
119. Zhang XY, Fang G, Leeftang M, Zadpoor AA, Zhou J. Topological design, permeability and mechanical behavior of additively manufactured functionally graded porous metallic biomaterials. *Acta Biomater.* 84: 437–452 (2019).
120. Li Y, Jahr H, Pavanram P, Bobbert F, Paggi U, Zhang X, Pourn B, Leeftang M, Weinans H, Zhou J, Zadpoor AA. Additively manufactured functionally graded biodegradable porous iron. *Acta Biomater.* (2019).
121. Fellah FM, Labaiz M, Assala O, et al. *Adv. Tribol.* 2014: 13 (2014).
122. Hussein MA, Mohammed AS, Al-Aqeeli N. Wear characteristics of metallic biomaterials: A review. *Materials* 8: 2749–2768 (2015).
123. Biesiekierski A, Munir K, Li Y, Wen C. Characterization techniques for metallic biomaterials. In: Wen C (Ed.). *Metallic Biomaterials Processing and Medical Device Manufacturing*. Woodhead Publishing, pp. 517–545 (2020).
124. Rong MZ, Zhang MQ, Shi G, Ji QL, Wetzel B, Friedrich K. Graft polymerization onto inorganic nanoparticles and its effect on tribological performance improvement of polymer composites. *Tribol. Int.* 36: 697–707 (2003).
125. Faga MG, Vallée A, Bellosi A, Mazzocchi M, Thinh NN, Martra G, Coluccia S. Chemical treatment on alumina-zirconia composites inducing apatite formation with maintained mechanical properties. *J. Eur. Ceram. Soc.* 32: 2113–2120 (2012).
126. Cvijovic AI, Cvijovic Z, Mitrovic S, Rakin M, Veljovic D, Babic M. Tribological behaviour of orthopaedic Ti-13Nb-13Zr and Ti-6Al-4V alloys. *Tribol. Lett.* 40: 59–70 (2010).
127. Suresh KS, Geetha M, Richard C, Landoulsi J, Ramasawmy H, Suwas S, Asokamani R. Effect of equal channel angular extrusion on wear and corrosion behavior of the orthopedic Ti-13Nb-13Zr alloy in simulated body fluid. *Mater. Sci. Eng. C* 32: 763–771 (2012).
128. Niinomi M, Hattori T, Niwa S. Material characteristics and biocompatibility of low rigidity titanium alloys for biomedical applications. In: Yaszemski MJ, Wise DL, et al. (Eds.). *Biomaterials in Orthopedics*. Marcel Dekker, New York, pp. 41–91 (2004).
129. Zhang E, Yin D, Xu L, Yang L, Yang K. Microstructure, mechanical and corrosion properties and biocompatibility of Mg-Zn-Mn alloys for biomedical application. *Mater. Sci. Eng. C* 29: 987–993 (2009).
130. Ratner BD, Zhang G. A history of biomaterials. In: Ratner BD, Hoffman AS, Schoen FJ, Lemons JE (Eds.). *Biomaterials Science: An Introduction to Materials in Medicine*, 4th ed. Elsevier Academic Press, London (2020).
131. Ratner BD. Biomaterials: Been there, done that, and evolving into the future. *Annu. Rev. Biomed. Eng.* 21: 171–191 (2019).