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Review Article

Sustainable Materials and Technologies for Biomedical Applications

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Over the past few years, 3D-printed biomaterials have gained widespread usage in the manufacturing of orthopaedic implants. 3D-printed implants have low weight, minimal material waste, ease of creation, the capacity to create complex topological implants that are patient specific, and a porous structure that permits tissue development. 3D printing has the potential to reduce material waste, cut transportation costs, optimise manufacturing costs, streamline the supply chain in supply chain management (SCM), and enhance environmental sustainability by utilising the concept of production-on-demand (POD). Biopolymer-based composites consisting of cellulose, chitin, and chitosan are sustainable materials that may be utilised as necessary. In light of the present biomedical issues, hydroxyapatite and starch combinations have immense potential for generating sustainable biomaterials. Carbon, which is a key category of sustainable biomaterials, is found in a wide range of carbonaceous gels and biomaterials based on cellulose fibres and carbon nanotube. The goal of this article is to give a thorough review of a few of the most recent developments, uses, and challenges for biomaterials made from sustainable resources. In this article, the authors have initially covered different biomaterials such as metallic, polymeric, ceramic, and composite and their properties and applications. Sustainable manufacturing techniques for biomaterials such as 3D and 4D printing are also covered in this article. Different sustainable biomaterials are covered with their properties and applications such as protein-based, cellulose, chitin, and chitosan composite-based, hydroxyapatite-starch-based and carbonaceous biomaterials. At last, future scope and opportunities in sustainable biomaterials and manufacturing techniques are covered. It has been found out that 3D printing technologies may support circular production systems across a range of sectors including biomedical by permitting the use of recycled and recovered materials as raw materials only when necessary.

1. Introduction

Biomaterials are the materials that have been produced and designed to work with biological systems. They can be bioactive substances that quickly integrate into human tissue. They have good biodegradability. They are often used in the manufacture of medications, tissue engineering, and human body parts. The creation of fresh, environmentally friendly materials and the development of biomaterials are supported by each other, as is the introduction of cutting-edge technical methods such as bioprinting, nanotechnology, use of biodegradable materials, incorporation of bioactive molecules, and surface modifications. Eco-friendly biomaterials are produced utilising green technology or taken from various biological resources. A number of biomaterials have been developed and created as potential replacements for traditional materials, and they have been employed effectively in a number of biomedical fields. Major applications include breast implants, reproduction therapy for nerve generation, ligament and tendon repair, orthopaedics, wound healing, and ophthalmology applications for contact lens design. They also serve a variety of non-biomedical applications [1, 2]. Filter and membrane, energy products, packaging materials, textiles, construction materials, food packaging, sporting goods, personal care, and cosmetics are few examples of nonbiomedical applications.

Applications of certain biomaterials for biomedical use have expanded rapidly over the last 20 years due to the growth of the pharmaceutical industry and the emphasis on enhancing patient compliance. By definition, a biomaterial is one that is composed wholly or primarily of living material. An example of one would be a polymer scaffolding that has been perfused with cells. As a therapeutic enhancement or replacement for natural tissue, these materials may be used in medical devices. Cartilages, heart valves, bones, and other tissues may be more easily rejuvenated using the mixture of artificial and biological material made from stem cells [2]. This is accomplished by replacing or attempting to reinstate the broken part and by using of materials that are immune to immunological rejection because they are genetically similar to the patient. Metals, ceramics, and polymeric materials make-up the majority of biomaterials. While ceramics and metals are predominantly employed to replace hard tissue, polymeric materials can be used to temporarily replace both soft and hard tissues (orthopaedics) [3–5]. Chemistry, biology, elements of medicine, materials science, and tissue engineering are some of the subfields of biomaterial science [2, 6]. First, biomaterials made of gold and ivory were utilised to replace cranial abnormalities.

After World War II, polymethyl methacrylate (PMMA) was the first type of polymer employed. In the 1980s and 1990s, bioactive chemicals were introduced to express particular biological reactions at the materials' interface, and the field of biomaterials changed toward inert materials [7]. Any material, whether created naturally or artificially, can be a biomaterial. It is a component of a biological structure that functions naturally by exhibiting, spiking, and shifting. It could be used as a heart valve. In addition, it can be used for interaction activities like hydroxyapatite- (HA-) coated hip implants. In everyday life, biomaterials can be used for medicine delivery and dental surgery. In addition, they can be used for contact lenses, cochlear replacements, bone plates, skin repair tools, bone cement, blood vessel prosthesis, artificial ligaments, and tendons [8]. According to how the tissues respond, they are divided into three types. First are bioinert materials, which are in constant touch with the surrounding bone tissue. The tissue and implant will not interact chemically in any way. Bioactive substances are biotolerant substances that are kept apart from the bone tissues by a fibre tissue layer. These materials exhibit an osseointegration properties, which is the ability to form chemical linkages with bone tissue.

The various excipients in the formulation should work well with the biomaterial. The body should not respond negatively to the biomaterial in any way, and vice versa. It should not affect the body in a way that causes cancer. It ought to be harmless. It must have adequate mechanical and physical characteristics to function as a replacement for or enhancement of bodily tissues. It will be suitable for commercial use so that it can be shaped differently. Biomaterials should be inexpensive and easily accessible. It ought to have a special defence mechanism against deterioration, like a defence against corrosion for metals or a defence against biological degradation for polymers. To reduce the generation of wear debris, it ought to be highly wear resistant. To reduce bone reabsorption, it should have a lower elastic modulus. The following traits which are depicted in Figure 1 should be present in a perfect biomaterial. Different biopolymer-based composite degradation mechanisms and sustainability factors have been covered by earlier studies [9]. The initial subjects covered by the authors in this article are different biomaterials, including metallic, polymeric, ceramic, and composite materials, as well as their properties and applications. This article also discusses 3D printing and other environmentally friendly biomaterial production methods. Protein-based, cellulose, chitin, and chitosan composite-based, hydroxyapatite-starch-based, and carbonaceous biomaterials are just a few examples of the several sustainable biomaterials that are discussed along with their features and uses.

1.1. Different Types of Biomaterials. Biomaterials are synthetic or naturally occurring artificial substances that are used to create implants or other structures that can replace missing or damaged biological structures and restore function and form [6]. Some examples of naturally available biomaterials are cellulose, gelatine, alginate, chitosan, and collagen [9–11]. Metal, composites, ceramics, polymers, and hydrogels are examples of synthetically manufactured biomaterials. As a result, biomaterials are improving humans' quality of life and lifespan, and the field of biomaterials has quickly developed to meet the demands of an ageing population. Artificial heart valves, shoulder replacement implants, knee joints, elbow joints, ears, orodental structures, and hip joints are just a few of the bodily parts that use biomaterials [12, 13]. Various materials have been used for implants, depending on the requirements of a particular application. Metals, alloys, polymers, ceramics, and composites are the most commonly utilised biomaterials [14, 15]. Different types of biomaterials are discussed in the following sections.

1.1.1. Metallic Biomaterials. Metal biomaterials such as Cr-Co alloy, stainless steel, Au-Ag-Cu-Pd alloys, magnesium and related alloys, and nitinol (Ni-Ti) are frequently employed [14, 16, 17]. From last many years, Ti alloys have been a popular implant material in a variety of medical applications. They have a high level of corrosion resistance and great mechanical qualities, which have made these possible. One of the main benefits of the titanium implant as originally stated was its osseous integration with the jaw bone [14]. But in more recent times, the term "tight apposition" or "mechanical fit" has been used more accurately to describe this attachment than "real bonding" [14].

1.1.2. Polymeric Biomaterials. Biopolymers are materials that display great promise for use in a variety of industries, including biomedicine. They are also ecologically friendly, chemically adaptable, sustainable, biocompatible,

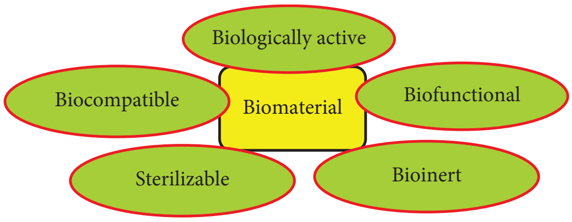


Figure 1: Characteristic properties of biomaterials [6].

biodegradable, and naturally functioning [9]. High-density polyethylene (HDPE), polytetrafluroethylene (PTFE), polymethylmethacrylate (PMMA), and other biopolymers are commonly utilised in biomedical applications because of their greater moldability, good biocompatibility, availability, and affordability. Other polymer biomaterials are acrylic, polyamide, polyester, polyethylenes, polysiloxanes, and polyurethanes. Applications of polymeric biomaterials are joint replacements, artificial skin, pacemakers, soft-tissue replacements, encapsulations, artificial blood vessels, and sutures. Other applications include pancreas, artificial hearts, livers, kidneys, and bladders [18–20].

1.1.3. Ceramic Biomaterials. In the last few decades, significant research efforts have been made to create bioactive composites as a replacement for bone by incorporating bioactive HAp ceramic particles into a bioinert high-density polyethylene matrix. The most often utilised ceramic implant material includes graphite, calcium phosphate, apatites, and aluminium oxide. In addition, glasses have been created for use in medicine [14, 16, 18]. Ceramics were employed because they were nontoxic to humans, had great wear properties in some circumstances, could be formed into a variety of shapes and porosities, and were inert in the body. A few applications for ceramics include heart valves, hip prostheses, artificial knees, bone grafts, and various tissue in-growth-related orthopaedic, dental, and other applications. Ceramics often have poor mechanical properties when it comes to load-bearing and stress applications. Implant devices that need to withstand large tensile stresses need to be carefully developed and manufactured if ceramics are to be used safely [18, 21].

1.1.4. Composite Biomaterials. Composite biomaterials are currently being employed in various applications by prosthesis designers after being widely used in dentistry. Usually, carbon fibres are used to reinforce an ultrahigh-molecular-weight polyethylene (UHMWPE) matrix. In order to develop an oriented graphitic structure with a higher young modulus and tensile strength, these carbon fibres are developed from pyrolyzing acrylic fibres. The carbon fibres are randomly aligned in the matrix and range in diameter from 6 to 15 nm. Although the matrix's strength is increased by the reinforcing fibres' higher Young modulus, the manufacturing process must provide an interfacial connection between the fibre and matrix that is strong enough [17, 18]. Then, using this fibre-reinforced composite, a range of implants, including intramedullary rods and artificial joints, can be created. Because of these composites' mechanical properties and the amount of carbon fibres they include, it is possible to change the material design's flexibility to fit the prosthesis' final design. Composites have unique properties and are often stronger than any homogeneous substance from which they are made. This characteristic has been used by experts in the area, who have used it to tackle several challenging issues where tissue in-growth is required. Examples include Al_2O_3 that has been deposited on carbon, carbon and PTFE, Al_2O_3 and PTFE, and carbon fibres that have been coated on PLA [18, 22].

1.1.5. Nanocellulose. Nanocellulose is really thought of as a novel biomaterial with a variety of possible applications because of its distinctive properties and biocompatibility. Cellulose, which is mostly found in plant cell walls, is the most common natural polymer on Earth. When cellulose is refined to the nanoscale and extracted as cellulose nanofibers or nanocrystals, the term "nanocellulose" is used. For biologists and material scientists, one of the most pressing issues is the creation of innovative biomedical materials from natural polymers for use in clinical and practical applications. "Bio cellulose" is a name that has been used in some studies to refer to information on nanocellulose and its applications. This is because of the material's special qualities and potential for use in the research of various biomedical materials [23]. It is possible to separate bacteria, plant cell walls, or cotton linters into nanoscaled cellulose fibrils and nanocrystals, an excellent material known as nanocellulose using mechanical, enzymatic, or chemical techniques [24]. Nanocellulose, which has a diameter of around 100 nm and a length of a few micrometres, is created from natural cellulose fibres. It may be classified into three main groups: nanofibrillated cellulose (NFC), bacterial nanocellulose (BNC), and cellulose nanocrystals (CNC). High elastic modulus (110–220 GPa), tensile strength (7.5–7.7 GPa), customised aspect ratios, huge specific surface area, ease of surface functionality, adjustable crystallinity, a significant amount of polymerization, as well as excellent chemical resistance are just a few of the remarkable characteristics of nanocellulose [25]. Because of their unique physicochemical characteristics, nanocellulose sustainable biomaterials are becoming more significant in aerospace, automotive, packaging, energy devices, and different transdisciplinary areas. In the upcoming years, it will be crucial to switch to these sustainable nanomaterials [26]. The significance and potential of various celluloses, particularly nanocellulose, have recently come to light in engineering, biomaterials, and different high-end usages. These materials have frequently been employed in veterinary medicine, medical services, and water filtration. Since the efficacy of nanocellulose-based products is dependent on the attained precision in nanocellulose dimensions, it is crucial to comprehend the dimensions of nanocellulose recovered from various plants and NFs [27].

2. Sustainable Manufacturing Methods for Biomaterials

2.1. 3D Printing Technology. Millions of individuals suffer from orthopaedic issues as a result of ageing, illnesses like osteoporosis, and unintentional injury. While some of these issues can be treated naturally, most of them need surgical intervention to repair the affected bone [28]. As a result, the cost of bone-related surgeries is steadily rising. However, at least two surgeries are required to handle these implants: one to repair them and another to remove them once they have healed [14]. Metal implants are employed in modern surgical therapy approaches. Pain and financial load are both experienced by the patient after the removal of these metal implants from the body [29]. In addition, because metallic implants are not created using patient-specific data, they run the risk of breaking, becoming loose, or infecting the body. Biodegradable biomaterial-based patient-specific implants that provide biological signals, cells, and growth factors to enhance bone regeneration and osseointegration are produced using 3D printing technology [30]. These patient-specific, 3D-printed biodegradable implants offer better healing capabilities than conventional metal implants [31]. Fully customisable 3D models may be made with the use of 3DP technology by stacking materials and adding extra, as necessary.

Numerous three-dimensional printing methods, like fuse deposition modelling (FDM), selective laser sintering (SLS), material extrusion, stereolithography (SLA), vat photopolymerization, binder jetting, powder bed fusion, and material jetting, have been widely utilised to process a variety of materials [15]. The advancement of 3DP (3D printing) techniques creates opportunities for restructuring the industrial system. 3D printing, which is already state-of-the-art, is gaining popularity for making intricate implants like heart valves, blood arteries, and tracheas [32]. The movement of bioimplants and medical devices as a result of substantial advancements in 3D printing methods in the orthopaedic industry may affect the supply chain and have a positive impact on sustainability [33]. These benefits might boost industrial resource efficiency by eliminating the concept of waste and bringing the system one step closer to a circular economy (CE) [34]. Among other important potential, 3D printing may use the production-on-demand (POD) concept to minimise material waste, slash transportation costs, optimise manufacturing costs, streamline the supply chain in supply chain management (SCM), and improve environmental sustainability [34].

Benefits of 3DP include customizing, design revisions, topology optimization, and new business models [35–37]. 3DP has numerous uses in multiple sectors, including aerospace, pharmaceuticals, and the healthcare sector, where patient specificity is important for devices like hearing aids, braces, prostheses, and orthopaedic implants [38]. Owing to their complementary nature, the concepts of circularity and sustainability are integrated into 3DP methodologies by facilitating circular production systems in a variety of industries through the sparing use of recycled and reclaimed raw materials, such as metals and polymers [28, 39]. According to a study on metal 3D printing by a researcher [40], 95% of the metal powder is filtered and used right away, with the remaining 5% perhaps being transferred to a central recycling plant to create new material. Using waste plastic extruders, filament generated from polymers and plastics like PET, PLA, and ABS among others, can be formed at a cheaper cost and with less environmental impact. The use of biomaterials in 3D printing orthopaedic implants and other medical equipment is totally sustainable [41]. 3D printing makes it feasible for the implant manufacturing industry to have a closed-loop supply chain [42]. A comprehensive circular production system uses 3DP and 3D-printed biomaterials to produce patient-specific implants on demand. 3DP technology recycles the implant material as a new biomaterial for the manufacturing of an implant [43]. Utilizing biomaterials in 3D printing techniques can support the circular economy in a number of different ways, including implant and medical device reuse and recycling.

Another aspect of 3DP is the requirement for several 3D printers when manufacturing things in large quantities. However, the most efficient way to create a circular and sustainable economy is with 3DP orthopaedic implants, which can run on renewable energy and bioresorbable biomaterials [44]. Sustainability, which has gained importance over time [45], has been included in the supply chain via 3DP manufacturing. The potential of 3D printing and 3D printable biomaterials to tailor and improve product design, as well as their longer lifespan and high reuse value, completely complement the principles of circular economy and sustainability. The production method for 3D printing is more customisable because of the use of various software tools to construct 3D models using pictures from MRI and CT scans [46]. These implants are recycled after being used, as seen in Figure 2, and are subsequently used as the building blocks for 3D printing.

The R-framework integrates three growing circular economy strategies that enhance orthopaedic healthcare capacities surpassing those of traditional methods and pave the way for the creation of durable patient-specific implants. These redundancy approaches promote the circular economy by employing 3D-printed bioresorbable materials for on-demand patient-specific implant manufacture and supply chain management, thereby preventing the fabrication of implants for stocks. The risk of using more natural resources than the earth can support is increased by widespread use. When the environment and natural resources are preserved, operation management-related CE will be completed. A circular economic model (renew, restructure, share) has replaced the linear (take, make, dispose) approach. Along

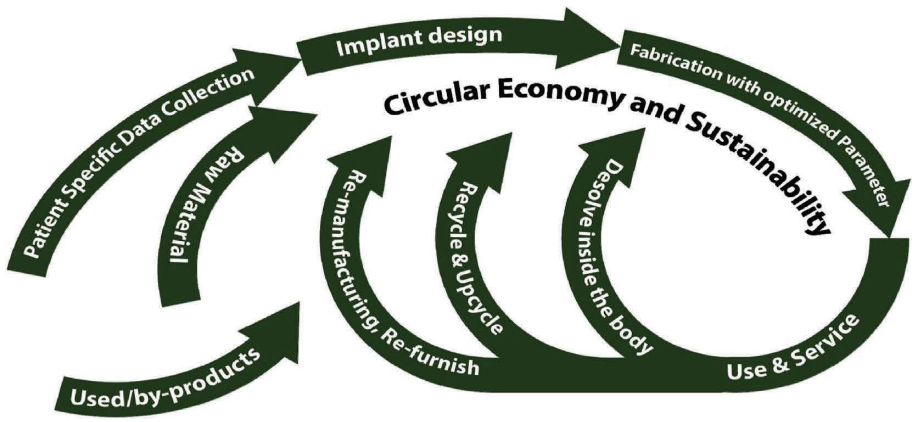


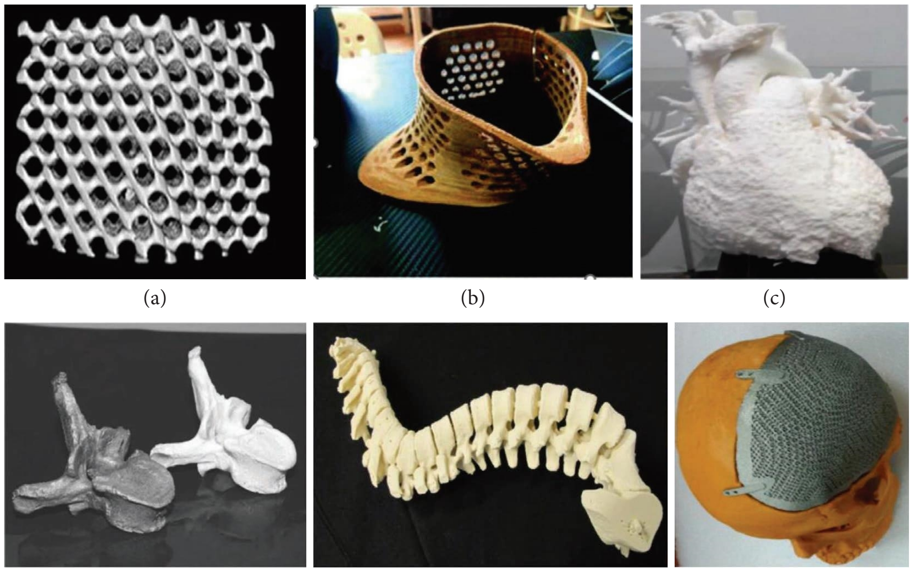
Figure 2: 3D-printable orthopaedic implant's sustainability and circular economy.

with the 3R approach, operation management also uses the ReSOLVE framework, i.e., to organise circularity concepts in a company model, use regenerate, share, optimise, loop, virtualize, and exchange [28]. The operation management (OM) changes occur in a variety of domains, including supply chain management and product creation. In every industry, a circular economy-based business model is supported by three pillars: designers, operations managers, and logistic managers. Implants should be designed for the 3R idea, especially in orthopaedics. Big data analytics should be used to create ecodesign systems that create trash disposal solutions.

The production system is made more ecoefficient toward the circular economy by the flexible planning abilities of the operation manager related to the 3R idea, such as the development of dematerialization methods, applications of 3D printing, digital manufacturing, customization, and the fabrication of new resorbable biomaterials, as well as the contouring of implants and other surgical items [47]. With improved reverse logistic actions, logistic managers should increase the traceability and transparency of the movement of raw and ready items. The take-back solution is enhanced by user awareness and engagement in reverse chains. Biomaterials are frequently employed in bone restoration via tissue engineering and for orthopaedic implants [48, 49]. Due to the large number of individuals who have bone abnormalities, bone replacement is desperately needed. It causes the development of bone healing materials to receive a lot of attention. The capacity to exploit immune rejection reactions is the main barrier to the use of metallic biomaterials, which is why chemically produced bone repair materials are advantageous due to their endurance and design flexibility [50]. As a result, new bone repair materials and improvements to existing bone grafts have been created. Some of the examples of 3D-printed scaffolds and medical devices are mentioned subsequently (Figures 3 and 4).

Although the use of 3D-printed models in orthopaedic surgery training has not been documented, the advantages are clear. The majority of surgeons only receive operating room training. When surgeons are still on their early learning curve and striving to perfect particular surgical abilities, this might put patients in danger. Senior surgeons may communicate their surgical experience to trainees considerably more effectively when they use actual concrete replicas. In addition, since complex or uncommon cases like bone tumour resection, deformity correction, or fracture fixation may not typically be encountered during resident training, 3D-printed models of the cases can offer residents or junior surgeons' special chances for realistic simulation-based surgical training. Along with improving surgeons' knowledge of orthopaedic disorders, 3D-printed prototypes allow doctors to practise on patients in order to get more comfortable with patient-specific circumstances before carrying out the same treatments in a true clinical environment. It may make patients safer. According to the 3D surface model of bone anatomy created by image segmentation from a patient's imaging data, PSI is individually tailored. After that, the design is produced using 3D printing technology for orthopaedic uses (Figure 3). This specialised equipment is used to make it simple to replicate surgical designs that call for steering a saw or drill in a predetermined path [13]. Figure 4 demonstrates that (a) scaffolds produced using SLA; (b) 3D prototypes of honeycomb neck orthoses

Figure 3: 3D-printed PSI made prior to surgery for a tumour excision that saves a joint [13].



(a) (b) (c) (d) (e) (f)

Figure 4: Illustration of (a) 3D scaffold printed by SLA, (b) the neck orthosis printed by FDM, (c) 3D print of heart with blood vessels prototypes by SLS, (d) 3D prosthesis part printed by DLP, (e) 3D-printed scoliosis backbone by the binder jetting (BJ) method, and (f) cranial implant printed part by EBM [51].

printed using the FDM technique; (c) prototypes of hearts with blood vessels printed using the SLS technique; (d) prosthetic parts printed using the DLP technique; (e) scoliosis backbones printed using the binder Jetting (BJ) technique; and (f) titanium alloys (Ti-6Al-4V) used to print 3D cranial implants for patient treatment [51].

A new technique called 4D printing builds on 3D printing by include the fourth dimension-time. Objects are built up by the stacking of materials in a three-dimensional space in traditional 3D printing. In 4D printing, materials are created that may self-assemble, change shape over time, or react to outside stimuli. This results in dynamic structures or things. When compared to 3D printing methods, 4D printing can produce any complicated object utilising a variety of materials while keeping superior quality, precision, accuracy, and performance capabilities [52]. Active origami systems or shape-morphing materials, which are advanced materials for 4D printing, deposit new materials or polymer composites one layer at a time to produce 3D items [53]. The material kinds and nature of the bioprinters should be carefully considered. Significant developments in the field of 4D printing, especially in the modern world, have allowed for improvements in a wide range of fields, such as aerospace, prototype, biotechnologies, and biomedicine [54]. Tissue engineering (TE), scaffolds, and dentistry are only a few of the biomedical sector disciplines where 4D printing has a spectacular impact. These fields strengthen our healthcare systems and enhance patient lives. In addition, the implantation of any tissue or organ that needs regeneration is also necessary in the case of an accident. The formation of artificial organs and tissues using living cells is eventually encouraged by these variables. This launches the bioprinting technique, which depends on devices called bioprinters that can precisely duplicate and print organs and stem cells. Various dynamic microenvironment TE fields, including tissue cardiac, vascularization, muscle, neural, bone tissue engineering (BTE), and manufacturing of vascular stents, have seen significant advancements in 4D printing technology to date [20].

It has been demonstrated that a simple 3D structure may develop into a more complex structure over time [55]. As a result, a new printing era known as 4D printing technology appeared, adding the fourth dimension of time to 3D printing. Since time is the fourth dimension, 4D printing may be defined as 3D printing plus a fourth dimension, time. Or, we might argue that 4D-printed things seem like 3D-printed materials change through time. One of the key characteristics of 4D printing is its ability to alter shape over time with the help of a preprogrammed computer command. There are several definitions for 4D printing. First, 4D printing was actually just 3D printing that had been given additional time [56]. However, the description of "4D printing" that describes it the best is "4D printing is the evolution in the shape, property, and functionality of a 3D-printed structure with time when it is exposed to heat, light, water, pH, etc. [57, 58]." Another description of 4D printing that sums it up wonderfully is that 4D printing is the fabrication of items that change shape when taken out of a 3D printer. Combining a 3D printer, intelligent material, and a carefully planned design is known as 4D printing [59]. In 4D printing, different metamaterial structures are formed as a result of environmental changes. A large portion of current 4D printing research is concerned with the materials' ability to alter shape through elongation, bending, corrugation, and twisting. These characteristics allow for the creation of toys, robots, lifters, microtubes, and lockers utilising 4D printed materials [57]. Several advantages of 4D printing over 3D printing include the speedy creation of smart and multimaterials, more flexible and deformable structures, and the capacity to broaden the possible uses of both technologies. The most current data on the subject shows an increase in 4D printing research papers every year. Since 4D-printed structures have the potential to enhance their own qualities, they also offer improved effectiveness, quality, and performance when compared to conventional methods. The minimal material consumption of 4D printing helps to maintain sustainable development [60].

2.1.1. Current Challenges and Future Opportunities of 3D Printing. In the modern world, both the 3D printing needs of the age and the technologies utilised to address those needs are expanding, which is changing and developing every day. According to 3D printing technology, which has several beneficial uses in numerous industries [32], the future is incredibly open. It is hoped that it will work well in resolving some of the issues we have recently faced. Unquestionably, the masks created using this technique to safeguard against the coronavirus pandemic, which has recently been on everyone's mind, are among the best illustrations of this predicament. A key issue during pandemic crises is a lack of protective face masks, particularly for those in the medical field, such as paramedics, nurses, and doctors. As a result, 3D printing masks are created for medical workers who were dealing with the COVID-19 outbreak, which started in one part of the world and quickly spread to the rest of the world [32, 61]. Numerous investigations are being conducted to develop defences against the coronavirus because it has sadly infected millions of individuals and killed thousands of people. The use of personal masks is one of the precautions that should be followed to safeguard against the infection. Numerous issues occur in the manufacture and distribution of masks as a result of the rising demand for them. This technology is utilised to make masks, which could be a viable answer to this issue. In this approach, masks are created more quickly and are accessible worldwide. In addition, masks can be made in the same way that implants and personal prostheses can. In addition to masks, it can be used to make protective garments, gloves, goggles, face shields, and other tools that stop the disease from spreading. Any sort of mask may be designed and manufactured quickly using CAD-CAM software in only 10 minutes. Therefore, production may be made more quickly and at a lesser cost of labour than it could be using old methods. In addition, on-demand production lessens waste. Due to its participation in the fight against the pandemic and the promise of a greener, more environmentally conscious future, this technology has gained attention for its advantages during this time of crisis [32, 33, 61].

Furthermore, 3D printing techniques show promise in the treatment of cancer, the second-largest cause of death globally and one of the most pressing health challenges of our day. Every year sees an increase in cancer diagnoses, and the disease claims many lives. As a result, research into cancer treatment, early detection, and tailored medicines has become very important. As each cancer patient reacts differently to current medication treatments, individual differences pose a severe dilemma for cancer treatment. 3D models are utilised to better understand the illness and provide a more successful course of therapy. The problems experienced by cancer patients can be resolved since they permit complex therapies with models that closely mimic actual circumstances. Along with these benefits, the developed tumour model enables medical professional analysis, use in surgical planning, and more successful treatment [32, 33, 62, 63]. In addition, it is anticipated that chemotherapy used in cancer treatment will become more effective. It is a very challenging process that virtually all patients may find risky. In reality, toxic medications are used to treat chemotherapy, which has a number of side effects including vomiting and heart failure. The 3D sponge project was developed by Steve Hetts, a neuroradiologist at the University of California, San Francisco, to lessen the severity of chemotherapy side effects [62, 63]. Pigs were used in the sponge's testing, which was successful. Before the medicine enters the body, the sponge's job is to absorb it. By doing this, the medicine works where it ought to work without harming other organs. Utilizing the sponge created with this technology would lessen chemotherapy's potent negative effects and stop it from hurting various other organs [32, 61]. It has potential for the treatment of congenital diseases or birth disorders in addition to cancer studies.

Applications for organ transplantation are now not possible since current technology does not allow for the design of an organ which is identical to the patient's original organs, has a whole vascular system, and is capable of performing all of the tasks of the original organ. Although it can be modelled identically, the patient's organ is not functional. It is anticipated that this will change in the future, since it will be possible to make organs that can perform their intended tasks and to save countless lives, which will be utilise in organ transplantation. These are but a handful of the possibilities it will present in the future. A few years ago, the capabilities of 3D printers seemed like science fiction movie fantasies. However, that has changed. As a result, it is anticipated that this technology will lead to more opportunities in the future [35, 61, 62].

2.1.2. 3D Printing's Limitations. The 3D printing design process is iterative, involving multiple steps and a variety of software. Computer tomography (CT) scans of the patient's jaw, DICOM databases of fractured teeth, or already-existing tomography scan databases are used to construct dental implant models, depending on the situation [15, 64, 65]. However, additional processes are needed to get the scan ready for image reconstruction, design alterations, FEA, and printing. The unequal shape and curve of the teeth could make adjustments difficult. The entire process is time-consuming and expensive in the software licencing. Even if design issues are resolved, it may still be difficult to properly fit the manufactured implants into the bone due to poor CT scan data resolution. The produced implants and the CAD model typically differ in these surgeries. Because V and Al are absent in typical Ti-6Al-4V, it has been found in one study that the material is less hazardous than Cp Ti powder [15, 65]. It is widely acknowledged that the distribution of the particle size and implant surface chemistry may affect osteointegration. For cell growth, the biocompatibility profile of Ti-6Al-4V produced by the SLM technique is particularly crucial, and it needs to be confirmed using several tests [15, 32]. Depending on the input parameters, a wide range of implant structures, from those with perfectly precise pores to those with more than 10% of them, can be produced via 3D printing.

Overall, this can result in a 20% reduction in the strength. It is crucial to precisely select the ideal pressure, temperature, and sintering duration depending on the powder being used throughout the fabrication process. Meanwhile, even minor technological advancements during variation fabrication have a greater than two-fold negative impact on bending and tensile strength [32, 33]. It has been noted that because of the material being deposited in layers, the fatigue life of implants is insufficient, resulting in a structure that resembles plates. Each plate has a different surface finish, which could be a location for fatigue cracks. In AM, when the primary crack spreads quickly and the quick crack occurs, Ti structures exhibit brittle behaviours [15, 33, 66].

It was found that high laser energy densities can melt metal powders, making the subsequent layers of deposit rougher and more brittle. The bonding strength of the implant would be reduced by a laser with insufficient energy density, which would have a negative impact on performance of the specimen [32, 33, 65]. Due to an enlarged melt region, it has been found that excessive laser energy density can decrease surface roughness of specimen irrespective of specimen inclination angles [32, 66]. According to the majority of studies, washing the implant is a crucial step in the production process. It is anticipated that washing and sonication in various solutions will remove any loose Ti particles. Another difficulty with the 3D printing technology is the stress concentration brought on by the laser melting. One of the polished Ti implants used by the study team to solve the stress-related concentration problem has demonstrated better cell biocompatibility. For the majority of additively created specimens, it is anticipated that post-processing will improve cell adhesion and proliferation while reducing the effects of warpage.

3. Different Types of Sustainable Biomaterials

3.1. Proteins as Biocompatible Material for Biomedical Applications. Plants or animals can be used to produce proteins [67, 68]. In nature, they are abundant, biodegradable, and frequently incorporated into products using eco-friendly techniques and in a comfortable environment [69]. Due to their affordability and ability to be produced in large quantities, proteins of plant origin are an environmentally friendly and sustainable source of polymers, having low greenhouse gas emissions and reliance on renewable sources [70]. Table 1 shows protein-based materials and their explicit applications. In addition, proteins derived from plants are frequently not connected to diseases transmitted by animals and can serve as an alternative for those who refrain from consuming products derived from animals owing to personal preferences, religious or ethical convictions, or both [89]. Animal proteins can be obtained from alternative sources or as by-products of the food or agricultural industries, even though they are frequently more expensive than plant proteins. This makes animal proteins an economical and environmentally responsible alternative for biomedical applications [90]. For instance, jellyfish collagen has been used, among other materials, for bone tissue engineering, osteoinductive biocomposite scaffolds are being developed [91], and collagen from marine waste products can be used as a substitute for mammalian collagen [92]. In order to employ it as a building material for biomaterials, proteins can also be obtained from human hair or biological wastes for the poultry industry [90, 93].

A circular bioeconomy and the need for greener, safer, more environmentally friendly, and more sustainable technologies are currently being promoted [94]. To reduce the environmental footprint by 2030, the entire material life cycle, including production and raw materials, needs to be restructured [94–96]. The usage of proteins for the manufacture of biomaterials addresses numerous important principles of green chemistry due to the aforementioned properties of proteins, including the usage of renewable and biodegradable building blocks, minimum waste generation, and restricted use of scarce raw materials. Generally speaking, biomaterials based on proteins from animal sources exhibit more mechanical strength than those created from proteins from plants. In addition, only a few numbers of suitable solvents are compatible with the bulk of plant proteins, which can make it more difficult to produce biomaterials with a plant origin [97]. Animal and plant proteins can be cross-linked [98, 99], blends of polysaccharides or other proteins with synthetic or natural biopolymers [100–102], or made more versatile and applicable in a variety of applications by selecting the right solvent [101, 103, 104]. Proteins are generally considered to be biocompatible and biodegradable due to their natural origin; they are therefore perfect as secure and long-lasting building blocks for substances intended for a range of medical uses. Proteolytic enzymes break down proteins, and the rate at which they break down can have a significant impact on how well protein-based biomaterials function in vivo. Different proteases have varying degrees of affinity for specific recognition motifs depending on the primary amino acid sequence of the protein, which may make some proteins less or more vulnerable to proteolytic degradation by certain proteases [67]. Recognition motifs can be buried by protein folding, particularly secondary and tertiary structures, which makes some parts of the protein less amenable to proteolytic cleavage. A protein might be more resistant to being digested by certain proteases if it is denied access to recognizing motifs. As a result, a protein-based material's behaviour throughout the degradation process is determined by the type of protein; however, the kind of material may also influence the pace of breakdown [105].

Table 1: Protein-based materials and their explicit applications.

Protein	Material	Applications	References
Gliadin	Nanoparticles	Used for all trans retinoic acid encapsulation and possible skin disease treatment	[67]
Lactoferrin	Nanoparticles	For mucosal applications and drug carriers, curcumin and efavirenz-containing lactoferrin vaginal microbicide	[71, 72]
Serum albumin	Nanoparticles	For the administration of aspirin to treat diabetic retinopathy, and the administration of bevacizumab to treat proliferative (neovascular) eye diseases	[73, 74]
Zein	Nanoparticles	For the encapsulation of numerous medications from proteins and small molecules for topical applications	[67]
Silk	Films	For the goal of delivering ciprofloxacin using silk/gelatin sheets coated in polyethylene glycol (PEG)	[34]
Gelatin	Films	For the buccal delivery of sumatriptan succinate as well as the encapsulation of thymol/-cyclodextrin in mucoadhesive gelatin-based films to cure oromucosal infections	[75]
Collagen	Films	To maintain the release of human growth hormone with the intention of mending injuries	[67]
Silk fibroin	Hydrogels	For the administration of nanoparticles with curcumin to treat psoriasis	[76]
Gelatin	Hydrogels	As oxidised alginate hydrogels that develop in situ as wound dressings or as hyaluronic acid wound dressings	[77]
Collagen	Hydrogels	As chitosan-containing as corneal implants	[67]
Keratin	Hydrogels	As polyvinyl alcohol-based wound dressings, poly (ethylene imine) with (PVA) for faster wound healing	[78]
Gelatin	Microneedles	For the administration of insulin, they are made with calcium sulphate, sodium carboxymethyl cellulose, or cross-linked with genipin. As an insulin release mechanism with gold nanoclusters that responds to glucose (AuNC). For the distribution of the polio vaccination, in order to increase lipolysis and restrict lipogenesis in order to decrease subcutaneous adipose tissue	[79–81]
Silk	Microneedles	Levonorgestrel's prolonged release over the administration of insulin, several months in order to distribute immunizations	[82–84]
Insulin	Microneedles	In order to deliver insulin	[85]
Alpha lactalbumin	Nanofibers	For the oral delivery of nicotine as part of a nicotine replacement programme and for the encapsulation of ampicillin for topical treatment	[86]
Collagen	Nanofibers	As skin grafts	[87]
Elastin silk	Nanofibers	For tissue regeneration and to speeding up the healing of wounds	[88]

Because the materials' constituent proteins are cross-linked, it is possible to increase their sensitivity to proteolytic breakdown and customise how they behave [105]. In addition, proteins can modify their secondary structure and crystallinity when exposed to solvents like methanol or formic acid during the manufacture of a material, reducing the susceptibility of the protein-based compounds to degradation [105]. For instance, it was discovered that the ratio of silk to polyvinyl alcohol (PVA) and the number of sheets in the silk—both of these elements—had a significant role in the swelling and destruction of silk fibroin/PVA microneedles by PXIV, which was elevated by exposure to methanol during production. The rate of material degradation will be influenced by the in vivo proteolytic environment that the protein-based substance will come into contact with, and different applications may call for particular degradation kinetics. Predicting the performance of new protein-based materials in vivo requires a thorough evaluation of their degradation behaviour. Biodegradable proteins may commonly be able to substitute synthetic polymers due to their biodegradability and may occasionally be not just a greener but also a safer solution [82, 106].

For clinical consent of biomaterials based on them, peptides and proteins must first be approved as safe excipients. A few businesses have received FDA approval to market protein-based delivery devices. For the treatment of different cancer types, Abraxane is an injectable albuminbound paclitaxel delivery method. In addition, NEURONTIN brand gebapentin capsules made with gelatin are sold for the treatment of partial-onset seizures and postherpetic neuralgia [67]. By modifying the pea-derived protein, it is possible to create robust and flexible materials composed solely of plant protein, such as coatings, films, and microcapsules for a range of uses, including personal care products. In addition, a Gelatex product called GelaCellTM uses biobased and ecologically friendly cross-linked gelatin and corn-based zein to construct nanofibrous three-dimensional scaffolds that mimic the extracellular matrix for applications including wound treatment and tissue engineering.

3.2. Cellulose, Chitin, and Chitosan Composite-Based Sustainable Biomaterials. The below section covers a few biomedical uses of biocomposites made of Cel/Ch/Chs. It should not be surprising that one of the components, either chitin or chitosan, each of which is biodegradable and possesses biological activity. For example, electrostatic interactions between the positively charged amino groups of chitin and chitosan and the negatively charged microbial cell membrane are most likely what produce antibacterial activity against many bacteria and fungi [107]. As can be inferred from the discussion below, the solubility of the biopolymers is routinely increased by chemical modification, which can further enhance biological interactions. On the other side, by preventing amino group protonation, such as by adding substituents, chitin and chitosan microbial activity may be decreased [108]. Due to the Gibbs-Donnan effect, chitosan protonation greatly enhances its swelling ratio in water (by about 1500%) and solubility. However, when a composite has a high chitosan content, it can also cause significant weight loss (leaching). Because of its high pH, cellulose does not protonate in the typical application pH range (3 to 8) [109]. The same discussion, in theory, applies to modified chitin/chitosan and cellulose derivatives that are anionic or cationic. Natural polymers that are plentiful and inexpensive include polysaccharides like cellulose, chitin, and its partly diacetylated derivative, chitosan [110, 111]. They have functional groups ($^{-}NH_2$ and ^{-}OH) that contribute to their high bio- and cytocompatibility, are nontoxic, and biodegrade readily. Chitin and cellulose are two significant polysaccharides that are physically related and give plants and some animals structural stability and protection, respectively. Despite the benefits of low cost and consistency in composition, synthetic polymers have low biocompatibility, and the potential toxicity of their breakdown products typically limits their usage. Concern regarding the ecologically friendly aspects of the production and disposal of synthetic polymers, as well as their capacity for sustainable production, is also on the rise. For instance, the issue of microplastics is one manifestation of the unfavourable perseverance of artificial polymers in the environment. The current SARS-CoV-2 pandemic brought this issue to light due to the concurrent rise in the application, for example, personal protective equipment made of fossil fuels [112].

A technological method for creating new composites with custom properties is the blending of various polymers. With the use of this technique, novel tissue engineering fibres and materials with better qualities than their precursor polymers can be created. For instance, pure chitosan's restricted industrial use is a result of its poor mechanical strength; cellulose can be used as reinforcement to overcome this drawback. The fabrication of a wide variety of materials for diverse uses, including biomedical research in vitro and future uses in vivo, as well as films, foams, fibres, filters, and nanoparticles, is therefore a growing field. These composites are multifunctional and biodegradable and can be made from the blending of biopolymers. Tissue engineering, for instance, is the area of biomedical applications that is growing at the fastest speed [113]. Cellulose and cellulose acetate are being employed more and more in the food and beverage industries for ultra- and nanofiltration [114], and innovative ideas for the use of biopolymers are now being created by the requirements of the current pandemic. Where applicable, we discuss recent literature on Cel/Ch and Cel/Chs biocomposites in this review. These materials are primarily produced by solution blending, which involves dissolving both biopolymers either simultaneously or separately in compatible solvents before processing into the desired "shapes." Because it enables the creation of biocomposites, for example, one-pot method solution blending can greatly reduce processing complexity and costs, which is desirable [115]. The latest reviews on the heterogeneous synthesis of Cel/Ch and Cel/Chs composites by adding cellulose nanofibers, nanocrystals, and bacterial cellulose to chitin and chitosan matrices, or vice versa, will not be taken into account here.

3.3. Hydroxyapatite-Starch-Based Sustainable Biomaterials.

There is an urgent need for bone-replacing materials due to the rising incidence of bone disorders and longer life expectancy. This is why a primary goal of biomaterials science research is the development of artificial materials that can be further assured as a possibly practical choice for substituting bone tissues [17, 106]. The synthetic materials are offered in big batches, unlike the bone transplants currently employed in practise. In addition, these materials are easily processed and changed to meet the needs of numerous medical applications involving bone replacement. Furthermore, if proper production techniques are used, the hazards of biological contamination and immunologic incompatibility are reduced [116, 117]. As substitutes for bone, various synthetic materials are now under investigation [22, 118]. The creation of materials that closely mimic genuine bone tissue, a composite material comprised of an organic matrix including a ceramic component is one of the objectives of advanced materials. Given that bone can regenerate, any synthetic material used as a replacement must possess the bioactive and resorbable properties needed to promote host tissue regrowth and make it easier for newly generated bone tissue to replace the implanted material. If vascularization-friendly porosity was used in the creation of the material, bone regeneration would be made possible by the osteoconductive properties of bioceramics made of calcium phosphates [119].

Calcium phosphates can interact favourably with bone, although they are brittle and challenging to manufacture into intricate geometries. In composite materials made of natural polymers and calcium phosphates, the organisation of the bone is mimicked [16, 120]. Natural polymers are secure biomaterials that are now utilised independently in a variety of scientific studies [121]. Because they are freely available in nature, polymers produced from plants and animals are both biocompatible and may boost the bioactivity of ceramics [122]. In view of the present biomedical concerns and the huge potential of biomaterials, researchers are attempting to highlight prospective applications of hydroxyapatite and starch mixtures for creating sustainable materials intended for medical purposes. Polymers of both vegetable and animal origins are abundantly available in nature, are biocompatible, and some are even biodegradable. Because of this, they may boost the bioactivity of ceramics. Both chemicals can be obtained from natural sources employing rapid, simple, and economical techniques that produce substances with sustainable properties. Both substances have proven to be biocompatible [123]. Recently, a summary of the relative sustainability of starch-based materials, particularly nanocrystals, was published [124].

A calcium phosphate that is stable in aqueous conditions is commonly identified by its Ca/P ratio (Ca/P = 1.67 for stoichiometric hydroxyapatite). Hydroxyapatite is a calcium phosphate [125]. Due to its bioactive and osteoconductive properties, as well as its hydroxyapatite's ability to encourage cellular adhesion and development, it is widely recommended for use as a component in composite materials, as a coating on metal specimens, or as a bulk component in bone replacements [126]. Three-dimensional (3D) cell-laden nanohydroxyapatite/protein hydrogels were studied by Sadat-Shojai et al. for application in bone regeneration, and the findings have been reported [127]. Figure 5 depicts the design for creating 3D cell-filled HAp/hydrogel nanocomposites.

According to some studies, a certain concentration of HAp nanoparticles (0.5 mg/mL) is sufficient to provide the generated gelatin hydrogel with the needed strength and bioactivity. Furthermore, it was demonstrated that the composite production process is quite compatible with bone cells through the encapsulation of MC3T3-E1 cells. Several methods have been published that attempt to create HAp from natural precursors like coral, eggshell, or various forms of bone as an alternative to traditional chemical production. It has been discovered that certain of these processes can create nonstoichiometric hydroxyapatite, which contains ions like Na and Mg as well as carbonate groups in its lattice. In clinical investigations, hydroxyapatite demonstrated its bioactive and osteoconductive properties [128]. Its ability to absorb proteins like vitronectin and fibronectin and improve cell adhesion on its surface via integrins are the main causes of its bioactive capabilities [129]. While hydroxyapatite has several benefits, some of its biggest drawbacks, such as fragility and low tensile strength, are caused by its poor mechanical qualities. In addition to its mechanical qualities, hydroxyapatite is linked to increased postimplantation infection risks. However, this thoroughly researched bioceramic is still being taken into account as a substitute for bone starch because of ongoing improvements in the processing and production of this material, in addition to the fact that nonstoichiometric hydroxyapatite makes up about 70% of natural bone [124, 130].

Of all the important naturally occurring polymers, starch is one of the most important and is utilised in clinical uses because of its cheap rate, renewability, and ability to decompose into a range of environments without the generation of dangerous compounds. Some of its physical characteristics, including the capacity to thicken, swell, and gel, are related to the make-up of starch and to the material changes in aqueous medium at high temperatures [131]. Amylose and amylopectin are two large molecules found in starch. The latter is in charge of the crystallinity of the material. The alternate crystalline and amorphous zones generated by the molecular chains are then organised into expanding rings. The term "starch grains" refers to the group of all these useful parts that are present in plants like wheat, rice, and potatoes [132]. Depending on the source from which it was derived, different starch properties, such as composition, swelling ability, or grain interaction might exist [133]. According to the study, polymeric films tensile elongation, fracture toughness, and abrasion resistance were improved by starches with increased amylose concentrations. The way that water interacts with other substances under watery conditions is the main factor that inhibits the starch gelatinization/melting. The substance is structured into an amylose gel with granules rich in amylopectin as the water molecules permeate inside the starch granules. Smaller amounts of water will not ensure an appropriate swelling for gel formation, and too much water could separate the amylose gel from the amylopectin crystallites. The amount of water in the solution affects how quickly gelatinization occurs. Temperature and shear pressures, which improve molecular mobility and enable quicker breakdown of crystalline areas, also affect the gelatinization of starch [134]. Regardless of its benefits, starch's utilisation is constrained by a variety of factors, including difficulties in processing, poor mechanical characteristics, and water sensitivity. These are now overcome by choosing the right additions and/or chemical changes that will guarantee its stability throughout time. In addition, creating starch blends or starch composites by combining starch with other components promotes better properties control (the investigations based on starch, phyllosilicates, clays, and other polysaccharides are those that have received the greatest attention).

3.3.1. Comparison of Natural and Synthesized Hydroxyapatites. Among the hard tissues such as the teeth is a mineral called hydroxyapatite [22, 118], the skull, and the spine [135, 136]. The hydrothermal approach, solid-state process, sol-gel process, emulsion, microemulsion, and principally chemical precipitation are all workable ways to create commercial synthetic hydroxyapatite powders since they are straightforward and affordable [82]. But a number of crucial ions, including magnesium, natrium, potassium, silicon, strontium, and iron may not be present in the final product [137, 138]. Table 2 lists the biological impacts of various trace elements.

According to different studies, Xenograft is an improved osteogenic differentiation option for biomedical applications due to the readily available essential ions in it, such as from human bone or fish bone and scale [146–149]. Due to their great availability and practicality from an economic standpoint, shells are also recognised as excellent calcium supplies that can be supplemented with a phosphate precursor to create hydroxyapatite [150]. High crystallinity, purity, and environmental friendliness are all characteristics of natural hydroxyapatite [151]. Tricalcium phosphate and natural hydroxyapatite are both far more biodegradable than synthesized hydroxyapatite, according to a prior study [152]. For biomedical applications, hydroxyapatite from natural sources is preferred due to its superiority. The differences between hydroxyapatite produced chemically and that obtained from natural sources are shown in Figure 6 in terms of price, ca/p ratio, source, trace elements, and process time. An overview of the history and production process of natural hydroxyapatite derived from animal sources is shown in Figure 7.

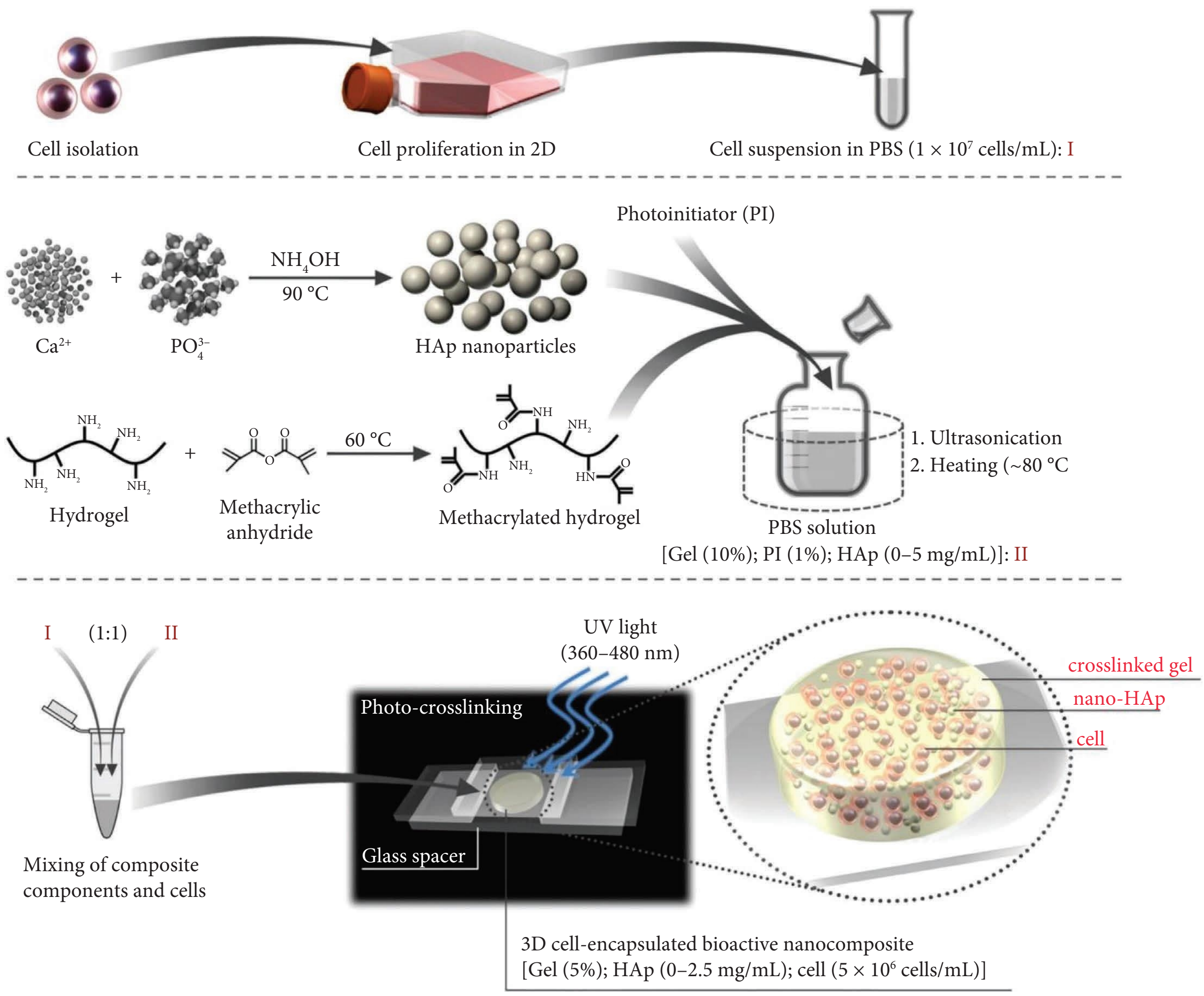


Figure 5: Diagram illustrating the process needed to create 3D cell-loaded HAp/hydrogel nanocomposites [127].

Table 2: Overview of trace element biological effects.

Trace elements	Biological effects	References
Si	Enhance cell differentiation, improve osteogenic differentiation, and enhance mechanical property	[139–141]
Mg	Increased bioactivity and cell adhesion and encourage the differentiation of cells	[142]
Sr	Increased osteoblast activities and proliferation, lack of cytotoxicity, and promotion of cell attachment, multiplication, and alkaline phosphatase activity	[143–145]
Zn	Reduce the production of osteoclast cells, prevent osteoporosis, promote angiogenesis, and improve the development of osteogenic cells	[146, 147]
F	Boost osteoblast activity to prevent osteoporosis. Restrict the growth of osteoclasts and improve their strength and resistance to corrosion	[123, 124]

3.4. Carbonaceous Materials for Sustainable Biomaterials. The most prevalent element in the biosphere in terms of sustainable biomaterial development is carbon. There are several uses for biomaterials made from renewable carbon sources, including catalysis, electrochemistry, photochemistry, energy generation, polyester manufacturing, etc. Several renewable materials, including cellulosic fibres and agricultural biomass (such as pomelo skins and maize stalks), appear to have been used to make them [153]. According to findings that have already been published, carbon resources can be divided into a number of categories, including (i) carbonaceous material made from an eutectic solvents such as choline chloride, urea, mixtures of sugar, and salt; (ii) carbon materials made from graphitic nanostructures such as carbon nanotube, graphene, carbon nanofiber, carbon nanohorns, graphene oxide, and graphene dots; and (iii) a variety of carbonaceous gels and biomaterials based on cellulose fibres and carbon nanotube. Zhao et al.'s recent study on the pyrolysis-based synthesis of cellulose carbon fibres containing branched carbon nanotubes serves

Figure 6: Natural hydroxyapatite vs synthetic hydroxyapatite [142].

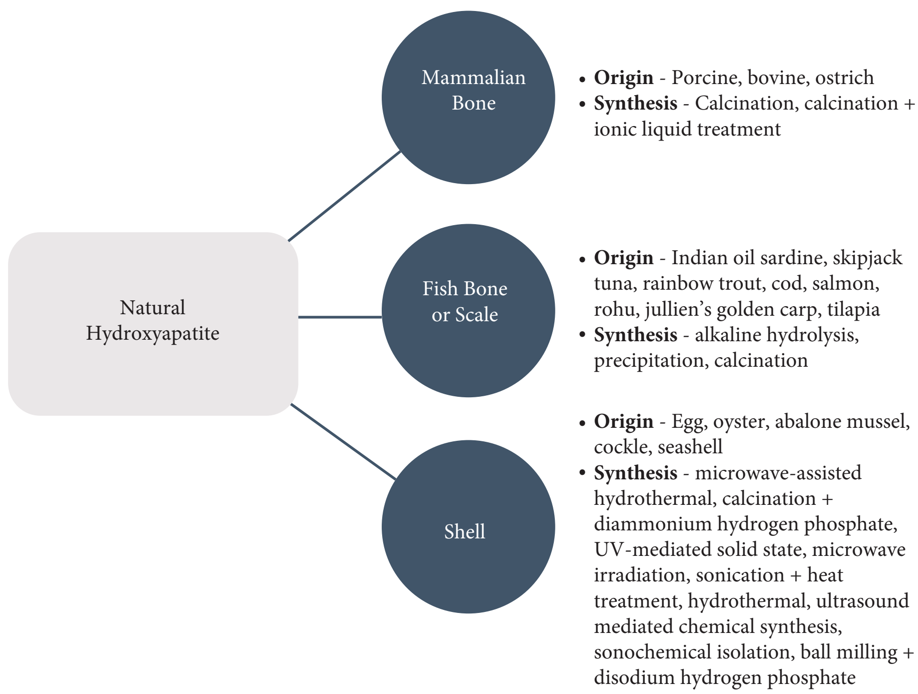


Figure 7: Origins and synthesis methodology of natural hydroxyapatite [142].

as evidence for this claim. A salt solution containing metal was added to the surface prior to carbonization to create branching, which significantly increased the specific surface area of the carbon fibres and decreased the possibility for biological redox reactions [154]. Wang et al. also looked into the use of multiwalled carbon nanotubes integrated with 243Am (III) for the elimination of heavy metal ions from industrial effluents with a view to managing nuclear waste [155]. Along with these investigations, in order to remove Cd (II) or Co (II) ions, naphthalene, and 1-naphthol, respectively, Zhao et al. showed how graphene oxide nanosheets and their sulphonated version work as biosorbents [156, 157], laying a solid foundation for the application of graphene nanomaterials for environmental clean-up. The manufacture of carbonaceous gels via hydrothermal treatment has received a lot of attention among the listed methods for making biomaterials because it is a cheap and environmentally friendly process. By substituting air for the liquid solvent present in hydrogels or other wet gels, aerogels can be created without causing the network assemblies to collapse. Supercritical drying, costly chemicals, and templates either hard or soft are frequently used in conventional procedures to create aerogels. Furthermore, poorly mechanical and/or thermally stable aerogels are also linked to problems. In order to overcome these difficulties, for the purpose of producing affordable 3D carbonaceous flexible hydrogel and aerogel, a quick and effective template-free hydrothermal method was developed by Wu et al. Their production process includes crude biomass like watermelon as a carbon source and inserting Fe_3O_4 nanoparticles into the networks [158]. These 3D gels showed exceptional potential as a scaffold for the creation of 3D composite materials beneficial for electrochemical uses because of their excellent mechanical qualities and strong chemical activity (better ion and electron movement in the electrolyte). The implementation of this technology has made a variety of products conceivable, including catalyst supports, adsorbents, supercapacitors, sensor supports, electrode materials for batteries, and biomedical materials. They are chemically inert, possess substantial specific surface areas, substantial pore volumes, and superior mechanical durability. Porous carbons have also been shown to be extremely effective at removing dyes and decolorizing materials. As sorption materials, biochemicals, and other products, carbon compounds made from waste biomass have also demonstrated interesting applications. A prime example is the hazardous dye component malachite green, which when released into water could harm aquatic life. Recent research has demonstrated that sulphuric acid-stimulated carbon generated from naturally existing waste biomass palm flowers can successfully absorb malachite green [159]. In a different study, banana peels were employed to create highly porous functional carbons with excellent methylene blue removal performance [160].

In a different study, banana peels were used to create very porous functional carbons that were highly effective at removing methylene blue. In a similar vein, nitrogen-doped carbon nanosheets that are porous and resemble graphene made from biomass and waste feedstocks (such as chitosan and urea) have been identified as one of the viable options for enhanced energy storage[161]. By adding a variety of elements via doping into porous carbon to produce donor states at the Fermi level and increasing the link between the carbon and adsorbents by including more active sites, a well-bonded random element can significantly alter the electrical and electrochemical performances. Aceous materials can produce n-type conductive materials, and these materials can be used to make electronic and electrochemical devices. For example, a simple two-step procedure that involves carbonization and then chemical synthesis, or a one-step carbonization can be used to create organic-inorganic hybrid nanocomposites (such as various metal NPs-macroporous carbon systems) [162–165]. Such composite systems can work efficiently as electrocatalysts for the oxidation of amino acids and glucose as well as the oxidation of H_2O_2 and glucose. The main contributors to the electrochemical activity were discovered to be the heteroatom content, larger porosity, increased surface area, and electrical conductivity. Fermented rice is another easily accessible and inexpensive material that is used as a first step in the synthesis of porous carbons [166].

Quick and scalable hydrothermal carbonization can be used to produce nitrogen-doped carbon compounds having high porosity and huge specific surface areas. These nanocomposites exhibit good electrocatalytic activities as compared to a commercially available Pt/C catalyst, respond to the great stability, and oxygen reduction reaction (ORR) tolerates methanol, pointing to a promising potential metal-free substitute for Pt-based cathode catalysts in alkaline fuel cells. Despite having certain benefits, most parts of conventional synthesis at the industrial scale were detrimental to cost, environment, time, and complex routes. Many efforts were taken to use an absorption process with alkanolamine solvent in connection with the creation of cutting-edge CO_2 collection and storage and H_2 generation technologies. A high energy need, solvent regeneration, equipment corrosion, and toxicity were some of the disadvantages of this approach. A significant amount of focus has been paid to the creation of ecologically friendly techniques that offer an alternative to using trash as a source to create new engineering materials. These techniques use sawdust, birch wood xylan, biomass, polysaccharides, and grasses as catalyst supports. In addition, to being employed as electrode materials and as adsorbents for pollutants including harmful chemicals and odours, these inexpensive carbon compounds have other uses [167].

4. Future Scope, Opportunities, and Challenges

One of the issues the 21st century will face is the creation of technological solutions that are both economically feasible and ecologically responsible for the increase in the manufacturing of materials, chemicals, and fuels. The instances for bio(nano) material designs that have been chosen in light of their prospective applications successfully demonstrate the usage of such bioderived materials, such as carbonaceous materials and biocompatible nanocomposites from natural sources, in a wide range of applications. The future of this discipline depends on the ability to create predictable, well-defined nanostructures utilising affordable, environmentally friendly alternative precursors (such as biomass and trash). Because of the original material's complexity, contaminants, etc., can be difficult to accurately regulate the properties of synthesized biomaterials, but these issues have occasionally been solved dependent on the biomaterial synthetic protocol and/or the chosen usage. Heteroatoms like nitrogen or boron are capable of enhancing the electrochemical efficiency. In other situations, the development of nanocomposites or the availability of a different substrate or base material (such as graphene) can result in the development of advanced materials with high-end applications, such as electrodes in energy storage devices (batteries, fuel cells, etc.), where physical characteristics like conductivity, adaptability, accountability, and mechanical strength are strictly required. These biomaterials with individualised compositions and porosities may work effectively as CO_2 adsorbents as well as electrodes in supercapacitor cells. My research experience suggests that an in-depth knowledge of the structure and make-up of the starting material (such as lignocellulosic fractions) is necessary to produce novel sustainable biomaterials for a variety of applications.

The search for benign design protocols that can function similarly to traditional methods is another topic of focus in the future. The morphology, mechanical stability, etc., of the biomaterials were affected by unresolved or unanticipated mechanistic effects of temperature, pressure, and pH using a number of conventional approaches, which included challenging, drawn-out processes with limited control over ending particle size. The sustainable design of biomaterials still faces numerous obstacles to be solved, such as repeatability, high porosity, controlled characteristics, stability, and other issues. But the creation of nanomaterials and nanocomposites from polysaccharides like starch, alginic acid, and exopolysaccharides derived from natural items like tobacco or macroalgae amply demonstrates the promise of such benign design ideas. More study is now being done in this area, and new discoveries will be made in due course. This research is being done in order to address the massive problems of shortages of resources and energy needs for generations to come.

Along with the 3D printing technique, a brand-new branch of research named 4D printing was created. The 3D printing technique is still being developed. 4D printing has a number of limitations and challenges that must be promptly overcome because it is still a young field of research. The three main obstacles to 4D printing are those related to technology, materials, and design. One of the technological challenges is the absence of 3D printing. Only a small number of research institutions worldwide have access to four-dimensional 3D printers. The PolyJet and SLM printing methods are now used in 4D printing to produce metallic and multimaterial components, respectively. The creation of intelligent structures is a difficulty that 4D printing faces. Smart materials are able to adapt to their surroundings and make the necessary adjustments; thus they must be built correctly to get the intended outcomes. When developed during the prestrain phase, smart structures perform better as actuators. However, there are not many works that have been documented that have achieved this prestrain phase. Furthermore, the prestrain membrane cannot be printed using a 3D printing method. As a result, attention must be paid to creating intelligent structures for 4D printing. They may function in accordance with user demands and adapt to their surroundings. In addition, several intelligent materials that may develop 4D printing and expand its potential uses have not yet been fully investigated. New materials such as personalised textile composites, carbon fibres, and printed wood grain would expand 4D printing's capabilities. The primary purpose of 4D printing now is for its capacity to change shapes, but in the future, many new uses for 4D-printed structures may be found that will make them multifunctional. Future research on the varied responses that 4D-printed materials have to stimuli will further its many uses. By the year 2025, 4D printing will reportedly have a global market worth of $537.8 million. Despite the fact that 4D printing is a multidisciplinary area, increased cooperation across its constituent sectors will provide these structures greater control over how they evolve in shape. Future developments in 4D printing will have a significant impact on how we live now.

Despite the tremendous advancement, researchers are still having trouble creating soft robotics, dynamically created tissues, and implants that may be employed in minimally invasive operations or patient-specific controlled drug delivery systems. The constraints can be divided into manufacturing- and design-based constraints. The lack of 3D technologies and biocompatible smart materials, as well as the extrusion-based technique's slow print speed and poor print resolution, are design-based constraints, while the dearth of 3D technologies and biocompatible smart materials is a manufacturing-based constraint. Design-based restrictions were ignorance of biological systems' complexity and feedback processes, 3D structures' reaction times, and the controllability of SMMs' stimuli and responses.

Material permeability, which refers to the capacity to permit gases to travel through them, might also play a significant role in 4D printing. It is important in many applications, especially in ones like medication delivery and biomedical engineering. SMPs do not have enough permeability, but hydrogels behave more permeably. This drawback prevents SMPs from fully replacing hydrophilic gel materials. It may have an impact on how quickly medications are released from printed structures used in drug delivery applications. Controlling permeability can improve the therapeutic results and medication release rates. Engineered living materials (ELMs) may be used to address the discovery of novel biocompatible-stimuli-responsive materials.

In order to create novel materials with functional qualities akin to those of natural biomaterials, engineered biological cells are used in the production of ELMs. Furthermore, these sophisticated materials are particularly alluring for a variety of biomedical applications due to their ability to respond to various biosignals with adjustable sensitivity under various physiological conditions. Despite ELMs' enormous promise for 4D printing, scaling up manufacturing methods and meeting high-cost requirements are currently the biggest obstacles. The deterioration of the 4D printed constructs, biocompatibility, magnitude, and duration of the stimuli, as well as the activation/deactivation of the transformations or elimination, represent additional significant hurdles.

The energy transfer and shape-morphing behaviour of the materials may be predicted using computational predictions, which may be a useful source of information. The biomedical industry's use of 4D technology will advance if these issues are resolved. Although data-driven techniques have shown computational predictions to be helpful in forecasting the behaviour of linear, inflexible materials, stimuli-responsive materials remain a challenging issue due to their nonlinear locomotion properties. In the near future, it is anticipated that the outcomes of these hypotheses, together with the collection of experimental data, will produce a sizable database that artificial intelligence systems may use to discover and create new smart materials.

Due to their numerous therapeutic uses in a variety of fields, such as medication administration, gastrointestinal surgery, dentistry, and periodontal devices, bioabsorbable materials can also be regarded as an active area of study. Despite being a relatively new technology, 4D printing has already had an influence on the biomedical industry. With continued and rapid expansion, it is anticipated that 4D printing will soon realise its full potential. To do this, new biocompatible dynamic materials must be discovered, and high-resolution, low-cost printers must be created. In addition, the field of 4D printing may undergo a revolution thanks to the development of 5D printing. The ability to produce items with twisted surfaces using 5D printing eliminates the requirement for a support system and improves printing speed and output strength by combining print head movement with the printed build. Innovative medical research and exploration are now possible because of this cutting-edge technology.

5. Conclusion

By utilising the idea of production-on-demand (POD), 3D printing has the potential to decrease material waste, slash transportation costs, optimise manufacturing costs, streamline the supply chain in supply chain management (SCM), and improve environmental sustainability. Due to their additive nature, 3D printing technologies are able to include the ideas of sustainability and circularity by enabling circular production systems across a variety of industries by using recycled and recovered materials as raw materials only when necessary.

Proteins are derived from either plants or animals. They are plentiful, biodegradable, and usually incorporated into products in nature utilising eco-friendly methods in a comfortable environment. Proteins of plant origin are a sustainable and affordable source of polymers with low greenhouse gas emissions and a reliance on renewable resources because of their low cost and capacity for mass production. Furthermore, plant-based proteins are typically not linked to animal-transmitted diseases and can be a suitable substitute for those who avoid ingesting animal-derived goods due to personal preferences, religious or ethical convictions, or both. Animal proteins are sometimes more expensive than plant proteins, although they can also be found in alternate sources or as by-products of the food or agricultural industries. Animal proteins are therefore a cost-effective and ethical substitute for human proteins in biological applications.

The field of biomedical applications with the quickest growth is tissue engineering. Numerous applications of tissue engineering involve biopolymers. The demands of the current pandemic are now inspiring creative concepts for the usage of biopolymers. Biocomposites made of chitin, chitosan, and cellulose may be used when appropriate. The procedure used to create these materials is known as solution blending, which entails dissolving both biopolymers concurrently or separately in compatible solvents before processing them into the appropriate "shapes." Solution blending is advantageous because it permits the production of biocomposites using one-pot techniques that significantly lower processing complexity and costs.

Researchers are working to highlight possible uses of hydroxyapatite and starch combinations for developing sustainable medicinal materials in light of the current biomedical problems and the enormous potential of biomaterials. There are several biocompatible and even biodegradable polymers in nature, both with the plant and animal origins. They might thereby increase the bioactivity of ceramics. Both chemicals can be produced using quick, easy, and affordable methods that result in materials with sustainable qualities from natural sources. Both compounds have demonstrated biocompatibility. According to research that has already been published, there are various subcategories of carbon resources, such as (i) carbonaceous materials made from eutectic solvents like choline chloride, urea, and mixtures of sugar and salt; (ii) carbon materials made from graphitic nanostructures like carbon nanotube, graphene, carbon nanofiber, carbon nanohorns, graphene oxide, and graphene dots; and (iii) a variety of carbonaceous gels and biomaterials based on cellulose fibres and carbon nanotube. Carbon is the most pervasive element in the biosphere. Among the stated techniques for producing biomaterials, the hydrothermal treatment of carbonaceous gels has drawn the most attention due to its low cost and environmentally beneficial nature.

Abbreviations

SCM:	Supply chain management
POD:	Production-on-demand
PMMA:	Polymethyl methacrylate
HA:	Hydroxyapatite
HDPE:	High-density polyethylene
PTFE:	Polytetrafluoroethylene
UHMWPE:	Ultrahigh-molecular-weight polyethylene
FDM:	Fuse deposition modelling
SLS:	Selective laser sintering
SLM:	Selective laser melting
SLA:	Stereolithography
CE:	Circular economy
PLA:	Polylactic acid
ABS:	Acrylonitrile butadiene styrene
OM:	Operation management
CT:	Computed tomography
FEA:	Finite element analysis
PVA:	Polyvinyl alcohol
NPs:	Nanoparticles
ORR:	Oxygen reduction reaction
BNC:	Bacterial nanocellulose
NFC:	Nanofibrillated cellulose
CNC:	Cellulose nanocrystals
PSI:	Patient-specific instrument
BJ:	Binder jetting
TE:	Tissue engineering
BTE:	Bone tissue engineering
ELM:	Engineered living material
SMP:	Shape memory polymer
SMM:	Shape memory material.

Data Availability

No underlying data were collected or produced in this study.

Disclosure

The authors have not conducted any activity that requires animal or human subject.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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