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RESEARCH PAPER

Transforming Medical Manufacturing: Groundbreaking Innovations Redefining Healthcare

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Abstract

This paper presents a thorough examination of recent progressions in additive manufacturing (AM) methodologies utilized within the biomedical realm, with particular attention to tissue engineering. Additive manufacturing provides exceptional precision in producing intricate three-dimensional objects using a variety of materials. Techniques such as Jetting, Material Extrusion, Material Jetting, Powder Bed Fusion, Sheet Lamination, and Vat Polymerization are strategically employed in biomedical applications to fulfill specific component requirements. Our focus is on polymer materials, encompassing both natural and synthetic variants, exploring the use of hydrogels for scaffold fabrication. We critically analyze the mechanical properties of these polymer scaffolds to enhance personalized patient care and mitigate implantation risks. Through careful adjustment of process parameters, this study illustrates the feasibility of achieving improved mechanical properties in manufactured components. This comprehensive review contributes to the ongoing discussion on advanced manufacturing methods for polymeric scaffolds in medical contexts, offering valuable insights for researchers, practitioners, and industry experts.

Keywords: Additive manufacturing; Polymeric scaffold; Material Jetting; Powder Bed Fusion; Manufactured components; Tissue engineering

1. Introduction

Additive manufacturing (AM) or rapid prototyping (RP) is an innovative technology that enables the creation of three-dimensional structures by adding material in a layer-by-layer fashion, using digital data (3D model) as a blueprint [1, 2]. In order to manufacture tangible 3D objects using AM technology, it is essential to utilize CAD 3D software or scanning devices such as computerized tomography (CT), micro-CT, or magnetic resonance imaging

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(MRI) [3]. These tools allow for the creation of a digital design file in a CAD format [4]. Unlike subtractive manufacturing technology, which involves removing material to produce an object, AM technology relies on the sequential addition of material layers [5, 6]. This distinction highlights the unique advantages ofadditive manufacturing compared to traditional manufacturing methods [7]. The advancements in this field of technology have effectively eliminated several manufacturing limitations, enabling the creation of products with greater precision, controlled dimensions, and intricate geometries— all without relying on traditional tools [8-12]. These advancements also contribute to lower manufacturing costs, faster production times, and reduced human intervention [13-15]. The aforementioned advantages highlight the considerable potential of AM technologies in offering a cost-effective solution for enhancing or transforming the supply chain of complex and personalized medical products [16]. Furthermore, the healthcare industry is experiencing notable growth driven by factors such as population aging, a rise in chronic diseases, and the dynamic development of emerging markets[17]. In 2018, the global healthcare segment of AM was valued at approximately USD 951.2 million, and it is projected to experience a compound annual growth rate (CAGR) of 20.8% [18]. The term '3D printing' encompasses various manufacturing methods, including Binder Jetting (e.g., Powder Bed Inkjet printing, S-printing, M-printing, ZipDose®), Directed Energy Deposition (e.g., Be Additive Manufacturing (BeAM), Direct Metal Tooling (DTM), Electron Beam Direct Manufacturing), Material Extrusion (e.g., Fused Deposition Modelling, gel or paste extrusion), Material Jetting (e.g., Inkjet printing, Polyjet), and Powder Bed Fusion [19]. In general, these mentioned methods vary in terms of device construction, material selection specific to each method, layer bonding techniques, production efficiency, and the characteristics of the resulting object, such as geometric accuracy, surface finish, structure, and mechanical properties. Based on the specific method employed, the manufactured components can be utilized in diverse sectors of industry, including aerospace, automotive, art, construction, cosmetics, food, medicine, textiles, toys, and sports accessories. Moreover, a wide range of materials can be used, such as polymers (both natural and synthetic), metals, ceramics, resins, and even living cells [20]. Additionally, the incorporation of advanced materials, such as nanomaterials (e.g., carbon nanofibers, carbon nanotubes, graphene), further expands the possibilities of additive manufacturing [21]. 3D printing applications, particularly in the field of bioengineering, offer the advantage of manufacturing intricate structures while ensuring precise dimensions [22]. Ongoing advancements and research in material engineering present opportunities to utilize enhanced biomaterials in the medical domain [23]. The recent growth of AM technologies has enabled personalized patient care, such as the ability to administer precise doses of medication [24]. The field of medicine extensively utilizes 3D printing for various applications, including anatomical models for surgical planning, dental applications such as braces, bridges, dentures, crowns, and surgical guides, medical devices like implants, prostheses, orthoses, and surgical instruments, pharmaceuticals including controlled-release drugs and personalized medicines, as well as the creation of organs, tissues, and disease models for drug testing [25]. In the field of biomedical and tissue engineering, scaffolds are extensively utilized as highly porous 3D structures [26]. These scaffolds serve the purpose of functionally and structurally replacing or regenerating native tissues in the human body [26]. The primary objective of scaffolds is to facilitate essential cell activities, including migration, proliferation, attachment, and differentiation [27]. Additionally, they enable the transportation of oxygen and nutrients to support cellular functions [28, 29]. The materials employed in the production of scaffolds need to possess qualities such as biocompatibility, easy sterilization, and non-toxicity. Among the commonly utilized materials are natural or synthetic polymers like hydrogels, proteins, thermoplastics, and thermoplastic elastomers [30]. Additionally, metallic materials such as titanium and magnesium alloys, bioactive ceramics, glasses, and composite materials combining polymers and ceramics are also frequently used in scaffolds production [31]. The purpose of this article is to provide an overview of the manufacturing methods currently employed for polymeric scaffolds, along with a discussion of the materials utilized[32]. The utilization of additive manufacturing (AM) technologies in scaffold fabrication allows for a diverse selection of polymeric materials, particularly in the form of hydrogels[33]. In order to assess the potential application of scaffolds in the biomedical field, it is crucial to evaluate their mechanical properties, especially when considering implantation in the human body.

2. The application of additive manufacturing (AM) technologies in the biomedical field

The utilization of additive manufacturing (AM) in medicine enables personalized patient care. An exciting area

of development is the creation of novel drug delivery systems, where the precise dosage of medication (such as tablets, pills, or capsules) can be tailored to individual patient characteristics, disease condition, age, gender, lifestyle, genetic profile, and more. Furthermore, additive manufacturing enables the construction of intricate geometries and structures, such as implants, prostheses, and porous scaffolds, that traditional production methods struggle to achieve with the same level of precision. With the aid of computer-aided design (CAD) software, itbecomes possible to design shapes and geometries that can be accurately and consistently produced, all while retaining the ability to customize as needed. Furthermore, there is an opportunity to combine multiple components in pharmaceuticals and medication carriers, where the controlled release of the drug is dependent on the materials used, such as in the case of tablets[34]. In the biomedical field, various additive manufacturing techniques are utilized. Each of the additive manufacturing technology methods employs distinct materials and bonding techniques, utilizing various energy sources and considering the physical state of the material. This enables the production of desirable pharmaceuticals and medical devices. In the early stages of additive manufacturing technology, it became possible to rapidly create prototypes at a reduced manufacturing time and cost-effectively. In modern times, when compared to traditional manufacturing methods, additive manufacturing technology often offers the advantage of reduced material costs, achieved through material savings. Additionally, it serves as an example of how large-scale manufacturing systems can be replaced by compact devices used in additive manufacturing technology. Due to advancements in technology, numerous additive manufacturing methods have been developed. However, only a limited number of these methods are currently utilized in the biomedical field, primarily due to the more stringent material requirements and process conditions. Some manufacturing methods involve high temperatures that could potentially damage the materials or additives, such as drugs, being used. Every additive manufacturing technique has its own advantages and disadvantages, and not all types of materials can be utilized with each method, particularly in the biomedical field where materials must meet strict criteria for biocompatibility and bio functionality [6, 35-37].

2.1. Fused deposition modelling

Thermoplastic polymer in the form of a filament is melted and extruded cthrough a narrow nozzle. The processed material, in a semi-liquid state, is added layer by layer. Each cross-section is formed by the movement of the print-head in the X and Y axes. The iterative process entails constructing a geometry based on a three-dimensional computer-aided design (3D CAD) model. The method is illustrated in Figure 1 [38]. Fused Deposition Modeling (FDM) offers numerous advantages, including high efficiency, ease of material replacement, and low operational and implementation costs. Additionally, the building process is automated and doesn't necessitate the use of any tooling. However, FDM does have certain limitations, such as a limited selection of suitable biomedical materials for processing[39]. The mechanical properties of thermoplastics processed through Fused Deposition Modeling (FDM) generally exhibit lower parameters when compared to traditional manufacturing technologies. Consequently, this can lead to a shorter lifespan of products produced using FDM [39-42].

Because of its suboptimal surface finish, the use of this method for biomedical implants is not preferred. To enhance surface smoothness and improve mechanical properties, one approach is to reduce the layer thickness. Achieving a smooth surface finish for manufactured parts may require additional processes, such as mechanical and chemical finishing. To broaden the range of applications for FDM technology, it is crucial to enhance the properties of the processed material, improve processability, reliability, and enhance the functionality of the produced components. The primary materials utilized in Fused Deposition Modeling (FDM) include acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polycaprolactone (PCL), polyethylene terephthalate glycol (PET-G), tricalcium phosphate (TCP), and nylon. However, incorporating cells or bioactive molecules into the filament during production is often challenging and inefficient [43].

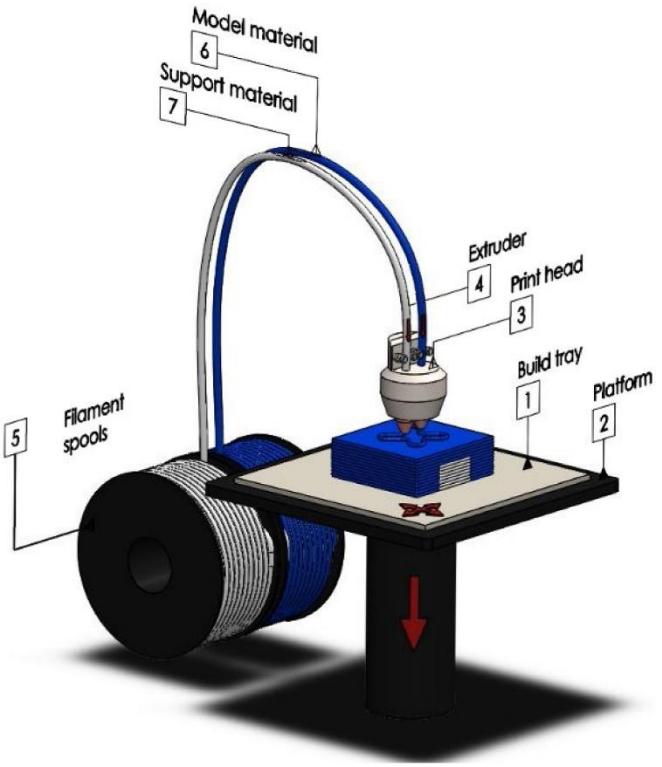

Fig. 1 Illustration of the Fused Deposition Modeling (FDM) system [33]

2.2. Selective laser sintering refers to the process and equipment used for this additive manufacturing technique

SLS, which stands for selective laser sintering, is a form of additive manufacturing process known as powder bed fusion. It was one of the earliest commercially developed techniques for creating intricate 3D parts. This technology originated in the mid-1980s at the University of Texas at Austin and reached a significant milestone in 1989 with the establishment of DTM Corporation. The early years of selective laser sintering (SLS) revealed its potential in producing biomedical devices and its significant role in medical applications. SLS has been regarded as the standard for describing powder bed fusion additive manufacturing processes due to its ability to process a diverse range of materials, including wax, various polymers, ceramics, elastomers, and metal-polymers in powder form. The system can create prototypes of biomedical devices using not only 3D CAD models but also data from CT and MRI scans, as these anatomical scanning techniques also operate on layer-based methodologies. In this section, we will provide a concise yet comprehensive exploration of the working principles, process modeling, materials suitable for SLS processing, as well as the advantages and limitations of SLS technology in the realm of manufacturing biomedical devices. Similar to other additive manufacturing (AM) processes, in selective laser sintering (SLS), the part is incrementally constructed by selectively fusing ultrathin cross-sectional layers of powder, one on top of the other, to gradually build up the desired shape. The initial layer is deposited onto a platform or substrate, and subsequent layers of sintered powder are added and solidified to create the volume of the part. Additional reinforcement of the constructed structure occurs through the sintering effect, which involves focusing intense thermal energy from the laser beam onto a small area of the powder bed, leading to rapid solidification. Figure 2 [44] illustrates the working principle of the SLS system. In the SLS process, the creation of the part starts with a CAD model that is first converted into an STL file. Then, the model is computationally sliced into consecutive two-dimensional layers for proper processing on the SLS machine [45-48].

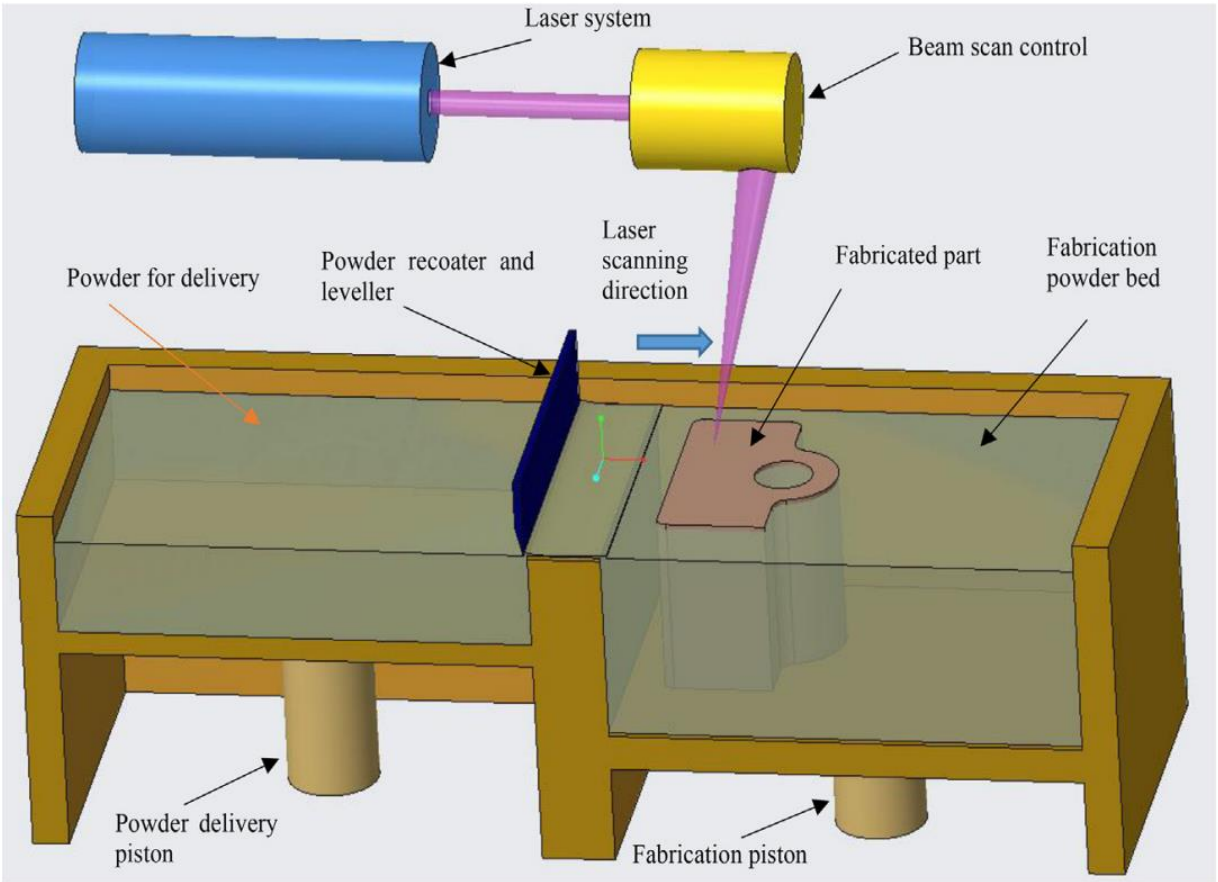

Fig. 2 Schematic illustrating the setup and process of selective laser sintering [38]

The laser is directed onto the powder bed using a scanning system, which follows the contours of each cross-sectional layer with a thickness ranging from 0.08 to 0.15 mm. After completing a layer, the bed is lowered by the thickness of one layer, and fresh powder is spread over the previously sintered layer. This process repeats until the 3D part is fully formed.

2.3. Stereolithography

Stereolithography, like many other solid freeform fabrication methods, is an additive manufacturing process that enables the creation of parts based on a computer-aided design (CAD) file. The desired external and internal (pore) geometries of the structure to be fabricated can be designed using 3D drawing software, described through mathematical equations, or derived from scanning data obtained from imaging technologies like magnetic resonance imaging (MRI) or tomography techniques. The ability to utilize scan data makes these manufacturing technologies highly valuable for numerous biomedical engineering applications, as it allows for the fabrication of patient-specific models or implants. The geometry and dimensions of the parts to be constructed are described in a CAD file. To facilitate this, the STL file format was created, which contains a list of triangle coordinates that collectively form the surface of the intended 3D structure. The designed structure is digitally divided into layers with a thickness that corresponds to the layer-bylayer fabrication process, typically ranging from 25 to 100 μm. These sliced data are then transferred to the stereolithography apparatus (SLA) for the fabrication of the structure (Fig. 3) [49]. The accuracy of the process can be evaluated by performing computed tomography (CT) scans of the built structures and comparing the scan data to the original design [50-52].

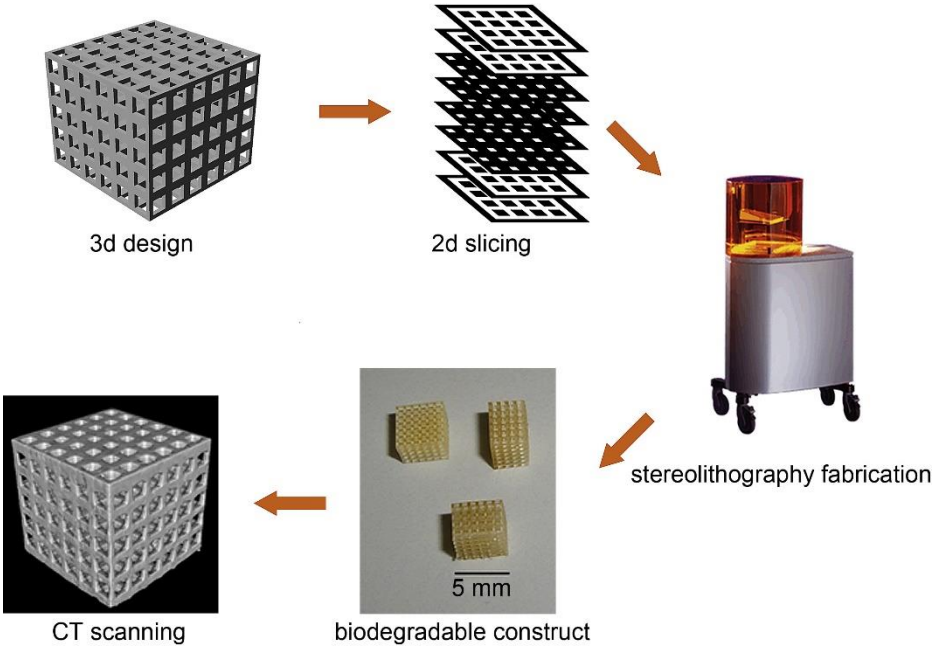

Fig. 3 An overview of the steps involved in the design and fabrication of structures using stereolithography [49]

2.4. Binder Jetting (BJ3DP)

BJ3DP as shown in Fig. 4 [53], also known as binder jetting 3D printing, is a powder-based additive manufacturing process that involves jetting a binder solution onto a powder bed to create a 3D printed structure. A typical BJ3DP system consists of a reservoir for storing the binder/ink solution, a powder reservoir, and a build platform where the printing process takes place. During the printing process, the powder is released from the powder reservoir onto the build platform. Following this step, the discharged powder is evenly spread into a thin layer using a roller. Then, a binder solution is jetted onto the powder layer based on the image design file that represents the desired geometry of the object. This layering and jetting process continues in a sequential fashion, with the powder being spread and the binder solution jetted layer by layer until the desired object is fully printed. Subsequently, Z corporation introduced a commercialized version of the technology with added color capability, branding it as '3D printing.' BJ3DP has found widespread use in various fields such as rapid prototyping, including applications in electro-chemical, plastic surgery, bone scaffolds, and the cosmetic industry. The pharmaceutical industry recognized the potential of BJ3DP in 2015 when the FDA approved the first 3D printed tablet manufactured using BJ3DP [54-57].

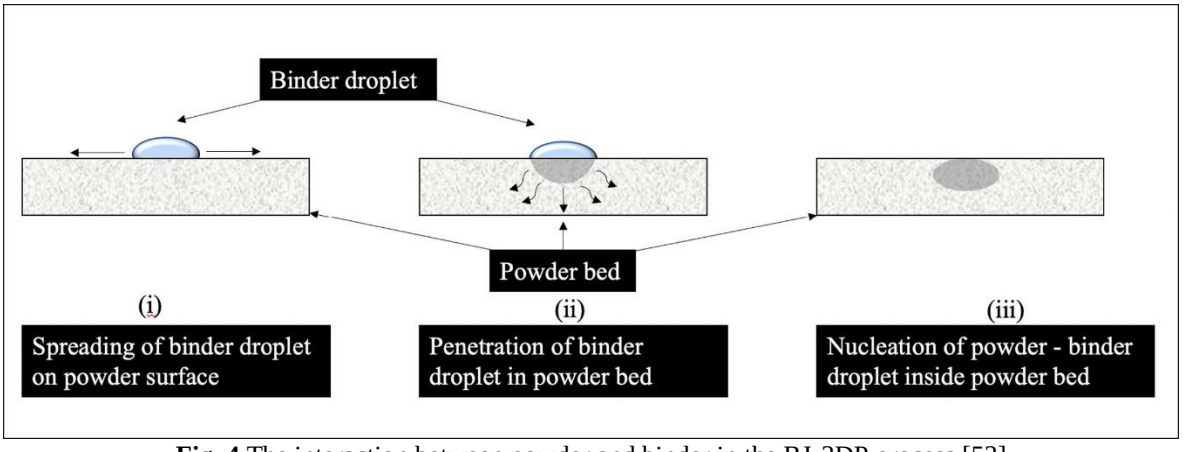

Fig. 4 The interaction between powder and binder in the BJ-3DP process [53]

3. The fabrication of polymer scaffolds using additive manufacturing techniques

Scaffolds are three-dimensional structures primarily used in tissue engineering and regeneration. The porosity and pore size of scaffolds are crucial factors in biomedical applications. The maximum porosity values typically range from 50% to 65%, while the minimum pore size requirement is usually 100 μm to accommodate cell size, migration needs, and transport. For improved new bone formation and capillary development, pore sizes larger than 300 μm are recommended. Scaffold structures find application in various clinical uses, including bone grafts, bone material substitutes, growth factor delivery, fibrous transplantation, and the incorporation of metalwork to enhance bone stability, restoration, regeneration, or replacement of damaged living tissue, cartilage, and organs. Open porosity is a critical factor in scaffold design and production as it facilitates the flow of culture medium or blood, ensuring a continuous supply of nutrients and metabolites. Furthermore, porous scaffolds facilitate tissue growth and provide the necessary mechanical strength for transplantation and implantation within the human body, thereby aiding in the healing of complex tissues. By producing biocompatible and biodegradable scaffolds, it becomes possible to create implants using cells obtained from cell cultures. These implants can later be replaced by natural tissue as the scaffold gradually dissolves. By incorporating scaffolds into the design of biomaterials, tissue engineers have the potential to unlock cellular mechanisms, enhance the reaction and regeneration of native tissues, and contribute to the healing process. In the field of tissue engineering and regenerative medicine, biomaterial-based 3D structures are frequently used across a wide range of human tissues, including blood vessels, bones, and ears. These structures also hold promises for the manufacturing of complete organs. Early methods for producing scaffolds relied on conventional manufacturing techniques, including electrospinning, fiber-bonding, melt molding, membrane lamination, particulate leaching, solvent casting and particulate leaching, thermally induced phase separation, and gas foaming. However, these methods often resulted in diverse architectural structures in the scaffolds due to limited control over the geometry of the pores. In modern times, complex and porous 3D structures are primarily manufactured using additive manufacturing techniques, which offer the ability to overcome the limitations of traditional production methods. Specifically, by controlling the geometry, connectivity, and size of the pores, it becomes possible to enhance repeatability, achieve finer detail reproduction, and enable more effective customization of the fabricated scaffolds. When manufacturing polymer scaffolds for tissue engineering applications, it is crucial to carefully select a suitable material that will degrade and resorb in a controlled manner, allowing room for the formation of new cells. The physical properties of the bioresorbable scaffold should remain intact until the ingrown tissue becomes sufficiently strong and stiff, closely matching the properties of the surrounding host tissue. As the scaffold matrix gradually dissolves, it should lose its mechanical properties and be absorbed by the body without causing any foreign body reaction within a predefined timeframe. The material used for scaffolds needs to be biocompatible, meaning it should not cause inflammatory reactions, exhibit immunogenicity, or be cytotoxic when inContact with human tissue. Additionally, it should be biodegradable, allowing for the development and growth of a natural support structure after degradation. Furthermore, scaffold materials should be readily available and easy to manufacture. In addition, it is important for tissue scaffolds to be easily sterilizable in order to prevent infection Scaffolds used in the biomedical field, particularly in tissue engineering, can be made from a variety of materials including natural or synthetic polymers (such as hydrogels, proteins, thermoplastic elastomers, and chemically cross-linked elastomers), bioactive ceramics (such as bioactive glasses, glass ceramics, and calcium phosphates), ceramic and polymer composites, as well as metallic. The biomaterials mentioned above have certain drawbacks: natural polymers may have limited mechanical properties, not all synthetic polymers are biodegradable, and ceramics can be too rigid. Unfortunately, there are only a few biomaterials that meet all the requirements for scaffolds. To achieve optimal functionality and develop the ideal biomaterial for bioengineering applications, it is necessary to explore and find the most suitable combination of materials from different sources. The careful choice of a suitable biomaterial in the production of scaffolds is crucial, as it involves the incorporation of bioactive molecules and living cells into the biomaterial during certain processes. The design of scaffolds necessitates consideration of mechanical properties as a key requirement. The mechanical functionality and stability of the structure should be sufficient to prevent structural damage during the early postoperative period, accommodating physiological loading conditions and the patient's normal activities. Additionally, it is essential to maintain the shape of the scaffold pores during cell growth, which requires a certain level of mechanical strength for the structure. Scaffolds can be categorized into soft and hard tissues based on their mechanical strength. Soft tissues, such as hydrogels, have a high water content, are flexible, and allow for the

incorporation of cells. On the other hand, hard tissues, like bones and teeth, are mineralized and possess a sturdy intercellular matrix. These types of tissues are often referred to as calcified tissues [58-62].

3.1. Materials based on hydrogels for scaffolds

Hydrogels are a type of materials widely utilized in various biomedical applications, such as tissue engineering (for repairing, regenerating, or replacing bone, cartilage, nerve, muscle, pancreas, and liver), pharmaceutical applications (for delivering bioactive agents like drugs or proteins), wound healing (for dressings), and in vitro cell culture. Hydrogels are gel-like materials composed of cross-linked polymer chains with hydrophilic properties, enabling them to absorb significant. amounts of water without dissolving. A wide variety of natural, biodegradable polymers and their derivatives have been employed to create hydrogels, offering a diverse range of options. The primary benefits of hydrogels include: (1) their ability to hold a high water content, allowing for cell encapsulation and growth along with the protection of cells and delicate drugs within an aqueous environment; (2) the crosslinking feature that enables the tuning of mechanical properties; (3) their capacity for efficient transport of nutrients to cells and removal of cellular waste products; (4) controlled release of drugs or growth factors; and (5) the ability to be injected as a liquid that forms a gel at body temperature when used in vivo. Possible limitations in the application of hydrogels include: (1) challenges in the physical handling of constructs, (2) typically having weak mechanical properties that may restrict their use in load-bearing structures, (3) the time-consuming process of optimizing printing conditions for specific hydrogels, (4) difficulties in achieving even cell loading, and (5) potential challenges in the sterilization of hydrogels. Alginate hydrogels find primary applications in drug delivery, wound healing, and tissue engineering. These applications are made possible by their advantageous properties, such as easy gelation upon the addition of calcium cations, biocompatibility, and low toxicity. The concentration of Ca(II) ions and sodium alginate within a hydrogel play a role in determining its swelling and mechanical properties. Among the mentioned applications, tissue engineering garners significant interest from scientists as it offers the ability to fabricate scaffolds for tissues and organs. One technique that is employed is 3D bioprinting, which utilizes innovative biomaterials such as alginate hydrogels. The key benefits of 3D bioprinting include customized production, rapid fabrication, and high precision. The utilization of alginate hydrogels in 3D bioprinting is an innovative method for creating intricate 3D tissue structures that closely resemble real ones. Alginate-based hydrogels offer the advantage of adjustable mechanical properties, such as strength and stiffness, allowing them to be customized for improved printability and geometric precision. The viscosity and density of alginate-based bioink are two crucial characteristics that impact its printability. The categorization of hydrogels can impact the choice of biomaterials for specific applications. Hydrogels can be classified based on various factors, such as their source, ionic charges, polymerization process, physical properties, origin, triggers, or cross-linkers, as depicted in Figure 5 [63-69].

3.2. The mechanical characteristics of scaffolds produced through additive manufacturing (AM)

AM-generated structures are assessed based on various factors, including their mechanical properties such as tensile strength, flexural strength, and impact resistance. Other considerations include dimensional accuracy, shape precision, and economic indicators such as production time and material consumption. The mechanical properties of components produced through additive technologies are significantly influenced by the specific method employed and its associated process parameters. To achieve the desired mechanical properties and ensure high-quality outcomes, it is crucial to possess comprehensive knowledge of the relationships between process parameters and mechanical performance. The verification of the mechanical properties of objects manufactured using AM is important, especially in relation to the specific application's requirements, such as resistance to deformations, dynamic stress, and vibrations. The mechanical properties of 3D printed samples can be influenced by various factors, including layer thickness, fill pattern, air gap between adjacent filaments in the same layer, structural orientation, scan speed, and, in certain methods, the geometry, temperature, and laser power of the model. Additionally, the presence of defects during the manufacturing processes can also impact the mechanical response. These characteristics indicate that the mechanical response should exhibit anisotropy, with tension and compression displaying asymmetry. The size and arrangement of pores significantly impact the mechanical properties of scaffolds. Compression tests are conducted to evaluate the strength of fabricated bone scaffolds. For instance, a scaffold created from sintered $CaCO_3$ and SiO_2 with a porosity of up to 71% exhibited a maximum compressive

strength of 28.1 MPa. A composite scaffold was constructed using selective laser sintering (SLS) and composed of akermanite ($Ca_2MgSi_2O_7$) with nano-titania particles. The scaffold achieved a porosity of up to 58% and displayed a maximum compressive strength of 23 MPa. Controlling multiple parameters is necessary to achieve desired effects as mechanical properties cannot be solely controlled by altering a single factor. However, it is important to note that biodegradable materials often exhibit mechanical instability, which creates a contradiction between mechanical strength and biodegradability. However, the search for suitable materials remains an ongoing challenge that researchers aim to address in the future. The combination of increased porosity with enhanced mechanical properties not only leads to improve in vitro cell growth, proliferation, and mineralization of the scaffold, but also poses a promising avenue for future advancements [70-75].

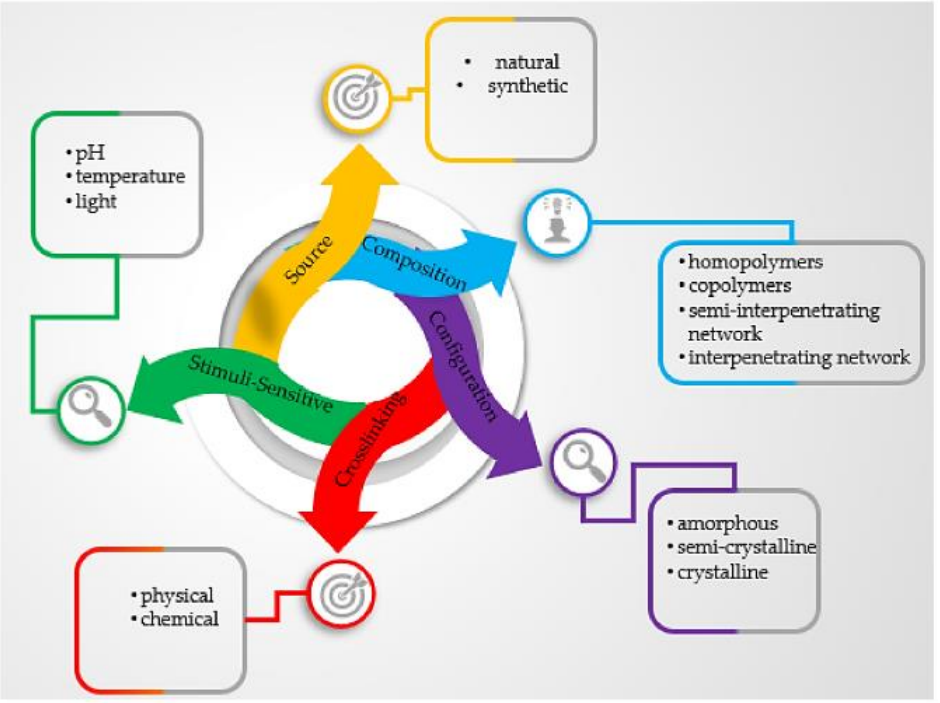

Fig. 5 The primary categories of hydrogels [63]

4. Bioprinting

Bioactive materials refer to natural or synthetically engineered substances that engage with living tissues without causing any negative effects, ensuring the effective treatment, enhancement, or replacement of organs. Put differently, the progress in 3D printing technology has led to the creation of commercial 3D bioprinters such as BioBots, Aether, Regenhu, and Cellink. 3D bioprinting, an emerging and inventive technology, is an extension of additive manufacturing (AM) technology. It involves the iterative incorporation of viable cells with bioactive materials to produce biomedical components, as illustrated in Figure 6. This transformative approach has revolutionized the fields of tissue engineering (TE), bone regeneration, and the pharmaceutical industry[76].

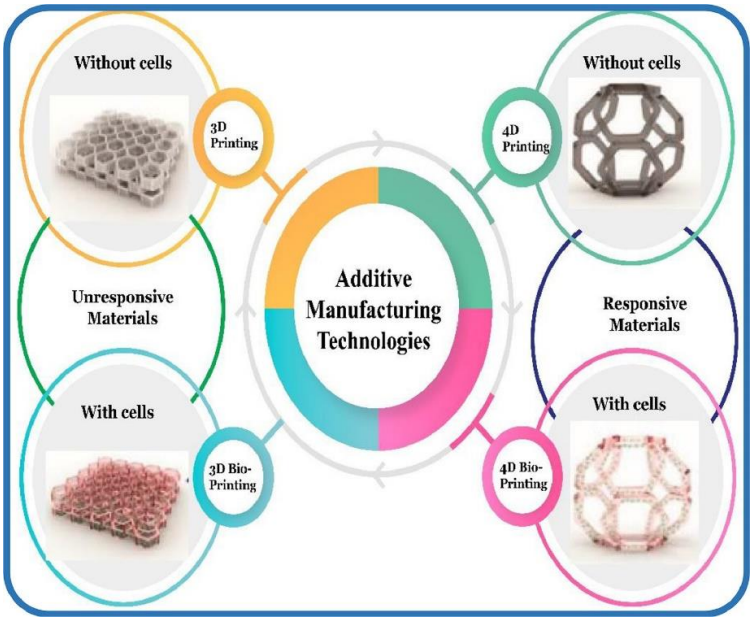

Fig. 6 Schematic depicting the distinction between 3D/4D bioprinting and 3D/4D printing [76]

4. Conclusion

Additive Manufacturing (AM) has revolutionized various industries, particularly the biomedical field. Unlike conventional methods, AM technologies have great significance in bioengineering due to their ability to produce customized implants, fabricate scaffolds with exceptional precision, resolution, complex matrix structures, and intricate geometries. The utilization of multiple biomaterials concurrently not only reduces production time but also facilitates personalized drug dosage within a single medication. Furthermore, AM technology allows for the accurate fabrication of a crucial scaffold characteristic: open porosity. This characteristic enables the flow of nutrients and metabolites, facilitates tissue growth, and ensures the attainment of suitable mechanical properties. "In the realm of tissue engineering, biomaterials utilized in AM technology should possess biocompatibility, easy biodegradability, and sterilizability. Natural and synthetic polymers are commonly employed in tissue engineering as they offer favorable properties. However, it is crucial to note that not all materials exhibit suitable characteristics for human body applications. In the field of 3D printing, numerous challenges exist in achieving optimized tissue architecture and biomaterials with desired properties, including biocompatibility, biodegradability, mechanical properties, and printability, while minimizing defects. The primary objectives of modern tissue engineering research involve the development of new materials with relevant characteristics and compatible mechanical properties.

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