STM JOURNALS

Journal of
Polymer & Composites

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 13, Special Issue 3, 2025
DOI (Journal): 10.37591/JoPC

https://journals.stmjournals.com/jopc

Review JoPC

Current Developments In 4D Printing Technology

D. Saritha[1,*], R. Sujithra[2]

Abstract

The perception of four-dimensional (4D) printing expertise was prompted through the time dimension inclusion in three-dimensional (3D) printing. Many other industries, including engineering, health, and the arts, have revealed a great deal of attention it. Recently, innovations in bioscience have been established that can be implemented using 4D printing. The ability to integrate time with situational variations has many benefits, but perceptibility and adaptability are merely two. Smart material, stimulus, and 3D printing applications are the essential components of operative 4D printing expertise because they may be employed in 4D printing to create dynamic structures. Smart materials' flexible qualities allow them to vary in shape, colour, or function in response to both internal and external inputs. Thus, the medical sector has a bright future thanks to the 4D printing technique and intelligent materials. This study aims to illustrate the current smart materials applications and 4D printing expertise in the health field, which can help to paint a clearer image of potential future 4D printing uses. The existing difficulties and benefits of 4D printing were also emphasized. This work offers a thorough analysis of the current developments, opportunities, and difficulties in the 4D printing of materials, with an emphasis on the uses of these materials in bionics and soft robotics.

Keywords: 4D printing, Review, 3D Printing, Smart Materials, Polymers, Shape Memory Materials.

INTRODUCTION

The 3D printing concept was first conceived by Charles Hull and then categorized under additive manufacturing. In current ages, interest in fast prototyping and AM also recognized as 3D printing, has increased [1]. Today, numerous applications influence additive manufacturing (AM) and rapid prototyping (RP) technology [2]. Technological advancements have made it possible to use a diversity of techniques in 3D printing procedures, which can be considered into the subsequent groups: fused deposition modeling (FDM), digital light processing (DLP), stereolithography (SL/SLA), electron beam melting (EBM), selective laser sintering (SLS), selective laser melting (SLM). It is significant to highlight that the materials utilized by the 3D printing method are diverse and include metals, polymers, alloys, ceramics, composites, and concrete. Today, 3D printing expertise is employed in various operations, including those in the automotive, textile, construction, aerospace, medical, biomedical engineering, and military sectors [3].

Smart materials are those that can adapt their structure or physical characteristics to the surrounding environment. 4D printing is possible via the usage of smart materials in 3D printing technology. Professor Tibbits first presented the 4D printing concept in 2013 [4]. The "4D printing = 3D printing + time" was initially used to explain 4D printing and relates to variations made to 3D printing's form, structure, or usefulness over time [5,6]. Smart materials can be used to make 3D microstructures that are dependent on their properties and that can undergo intentional varies over time. The distinction among 3D printing and 4D printing is that the prior includes "pre-modeling + printing of the completed product," whereas the latter requires

***Author for Correspondence**
D. Saritha

[1]Associate Professor, Department of Chemistry, Chaitanya Bharathi Institute of Technology, Gandipet, Hyderabad, Telangana, India
[2]Assistant Professor, Department of Applied Mechanics, Motilal Nehru National Institute of Technology Allahabad, Prayagraj, Uttar Pradesh, India

Received Date: November 12, 2024
Accepted Date: February 17, 2025
Published Date: April 08, 2025

Citation: D. Saritha, R. Sujithra. Current Developments in 4D Printing Technology. Journal of Polymer & Composites. 2025; 13(Special Issue 3): S108–S120p.

the product's design integration into an adaptable smart material founded on that technology. Microstructures can thus deform under the track that was previously built under particular time and activation circumstances. Nevertheless, 4D printing can generate various products that are now impractical with 3D printing. These objects can vary their color, volume, and shape in response to their environment as well as external stimuli, such as water.

A 3D-printed object's form, structure, and functionality are purposefully changing to achieve self-gathering, deformation, and self-repair. Zhong et al. categorize 4D printing as an AM method by incorporating smart materials into the printed material's primary form for 3D printed assemblies. 4D printing has recently been expanded by scientists to refer to 3D-printed assemblies that modify their intended shape or other characteristics in response to environmental factors. 4D printing is described as "AM of objects that can alter their functionality in response to an external stimulus, including current, heat, light, or other energy sources. The three geometric axes of x, y, and z are used to manufacture objects when using 3D printing techniques, but 4D printing adds a fourth dimension known as the "time" dimension. This does not accurately signify how long it took to print something. Instead, it is referred to as the significant contrast among 3D and 4D printing and reflects the passage of time when things experience shape modification. Alternatively, 4D printing is defined as "3D printing and time" by Momeni et al [7]. There must be a precise trigger to start the change before 4D printing can be done. This can comprise things like heat, light, electricity, and humidity. Unique materials are utilized in this instance to react to various stimuli. These materials can develop programmable characteristics at times determined by the stimuli. The capability to construct dynamic structures out of intelligent materials is one of the vital benefits of 4D printing.

The smart materials usage in 4D printing may result in the following product qualities: self-detecting, self-folding, self-gathering, self-disassembly, self-repairing, and self-flexibility. For instance, employing stimuli-responsive materials, this state-of-the-art technology might be able to produce a bone that will eventually develop inside the human body. Because flexible parts can be created employing smart materials and 4D printing, it satisfies a variety of criteria. Currently, most studies focus on the 4D-printed construction's capability to change shape, including bending, extending, corrugating, and twisting. These actions could be configured further to create toys, robots, microtubes, lifters, lockers, and more. Material anisotropy will be used in the 4D printed structure to produce directed shape change. A combination of various materials must be printed in tandem for this to work. Some of the presently used 4D printing approaches comprise direct inkjet cure, stereolithography, selective laser melting, fused deposition modeling, and laser-assisted bioprinting. Because 4D printing produces greater assistance than 3D printing, it can demonstrate the requisite abilities and expand deployment. More specifically, 4D printing allows the incorporation of micro/nano-actuators and/or smart devices by providing actuation, identifying, and programmability built into a material without the need for cables, motors, batteries, or other external electromechanical systems. Additionally, these systems have the benefit of requiring less manual labor, money, space, flaws, and components per archetype or system [8]. A few applications for 4D printing include the creation of multidirectional structures, soft actuators, biomedical devices, safety, and finely patterned optics surface and electronic devices. Soft robotics, which tries to mimic biology by creating programmable, flexible devices in both soft and stiff forms, has observed a major rise in admiration in current years, especially in the medical sector. Research initiatives that concentrate on soft robotics and the biomedical sector are becoming more and more popular. As a result, it is anticipated that many new opportunities and prospects will materialize in the future as a consequence of the growth of 4D printing expertise.

4D printing has an edge over conventional production techniques in terms of material flexibility, which makes it easier to precisely configure material responsiveness. Using 4D printing has proved successful in various fields. The capability to produce 3D constructions of living things including cells, tissues, organs, and nutrition is one of the greatest advantages of the new technology known as bioprinting [9,10,11]. The next generation of bioprinting technology is 4D printing, which has numerous applications in various fields. The capability to modify the functionality of manufactured bio-structures is one of 4D bioprinting's primary benefits [12]. Finally, some 4D printing applications are discussed, along with the 4D printing trend and future prospects for this fascinating novel industry. This review offers the numerous smart material types utilized in 4D printing and their applications. Finally, we'll discuss 4D printing's challenges and prospective applications.

FOUR-DIMENSIONAL PRINTING STIMULI

The materials utilized to create particular objects are the crucial difference among 3D and 4D printing methods. An external stimulus causes the material's mechanical condition to change from static to dynamic. Several stimuli that are useful to 3D objects to change their behavior and function have been studied. The following stimuli have been studied the most in the literature: temperature, electric, light, pH, electric, magnetic, water and humidity.

Thermo-Responsive

The stimulus that is most frequently utilized for 4D-printed objects is temperature. Numerous researchers have looked into employing temperature as a stimulus because of its potential. The capacity to manipulate mechanically, the ease of operation, and the ability to manage the adjustment in a manufactured object are benefits of employing temperature as a stimulus. The majority of experiments focused on employing temperature as an external trigger to produce shape-deforming bio-printed objects. Both tissue engineering and in vitro drug release applications have exploited temperature as a trigger. Applications for bio-4D printing can leverage temperature stimulation, which is primarily employed for smart materials. For example, an object can be positioned under pressure and at a high temperature to create a transient position. It is possible to return an object to its initial state by cooling it and exerting enough effort. For tiny bone defect implant replacements, this shape recovery capability is utilized. Thermo-responsive materials can reshape and alter their geometric configuration in response to temperature stimuli. The 4D printing process is utilized for engineering and medicinal applications that require temperature-responsive materials [13].

Moisture-Responsive

Moisture-responsive materials are more significant as a result of their many applications and global stimulation. The most common use of water and moisture-sensitive materials is due to their numerous uses and widespread stimulation. Hydrogels are remarkable moisture-approachable materials due to their hydrophilicity, which permits them to have 200% expansion compared to their original volume. In addition, the hydrogel sort of polymer materials has excellent printability. Hydrogel usage has the advantage that direct ink writing (DIW) and biocompatibility make them simple to print. Hydrogels are employed in the DIW method since they are easy to produce and biocompatible [14]. The scientists essential to delay longer for the hydrogels to dry and shrink in this case due to the delayed reverse reaction. To understand how hydrogels behave in this situation, anisotropy would be used for swelling. Thin hydrophobic films formed of cellulose stearoyl esters (CSEs), which react more quickly and accurately, were developed by Zhang et al. after describing the rapid reactions [15]. When hydrogels are mixed in the typical aquatic environment, they begin to absorb water and continue to do so until they reach their moisture saturation point, which confines their capacity to be regulated in the interim. The temperature of the aquatic environment can be changed to affect the capacity of hydrogels to swell. Gladman et al. mixed hydrogel ink with cellulose fibrils in a study. So that the cellulose could be controlled by shear forces created through contact among the ink and print bed [16]. The 4D-printed assembly programming is made possible by this alignment, which raises the transverse swelling strain to four times the longitudinal strain.

Photo-Responsive

Light is the frequent stimulus mentioned in the literature, and scientists are starting to focus on it [17]. Rapid switching, accurate focusing, biocompatibility, renewable sources, wireless, and remote control are a few benefits of employing single light as a stimulus (Figure 1.). A photo-responsive material's exposed surface warms up in response to light, an indirect stimulation as opposite to heat and moisture. Liu et al. have demonstrated a self-folding structure that is sequentially controlled [18]. The colour of the light source and the joint itself both affect how rapidly light energy is transformed into heat through the joints. Kuksenok et al. utilized light differently as a catalyst for deformation [19]. A polymer gel block is infiltrated with a specific quantity of photo-responsive chromophores to make some regions only swell when exposed to light. In optical devices and microcantilevers, light-sensitive materials can also be employed.

Electro-Responsive

Current can be utilized in 4D printing as an indirect stimulus, similar to light. Okuzaki et al. employed PPy films on an origami microrobot with distinctive foot forms to lessen resistance while moving. A voltage in a humid atmosphere induces moisture absorption, which moves the head forward, and moisture desorption, which is ignited by voltage absence. Silicone elastomer and ethanol can be utilized to print easy artificial muscles, as demonstrated by Miriyev et al. The ethanol evaporates as a current is provided because heat is produced by resistive heating. The volume of the ethanol is significantly increased during this transition from liquid to gas, which extends the entire matrix [21]. To regulate the absorption or desorption of water, polypyrrole (PPy) films are also subjected to a current.

Magneto -Responsive

Magneto-responsive materials are used to create 4D-printed objects that respond to magnetic fields. Breger et al. created magnetic fields for remote control using a hydrogel-printed microgripper that was filled with magnetic nanoparticles [22]. (Figure 2). By combining ferric oxide particles with the material solution during the pre-processing, the embedding is accomplished. Another application for this technology is printing on polymers and metal. The print's size constraint and requirement that it be magnetic field-sensitive are both problems. With this technology, printing on metal and polymers is conceivable. The fundamental limitation is the print size, which must be adequately lightweight and magnetic field-resistant.

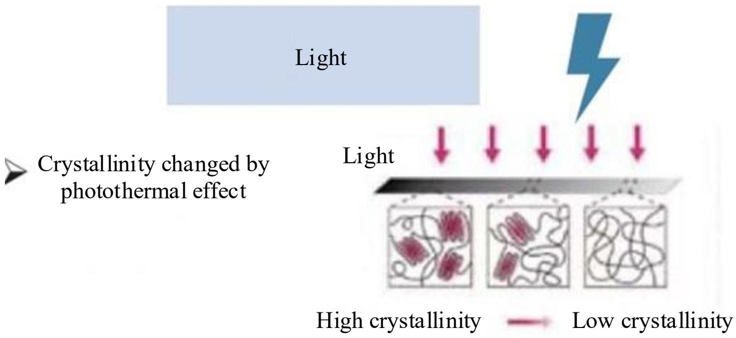

Figure 1. Light stimuli [20].

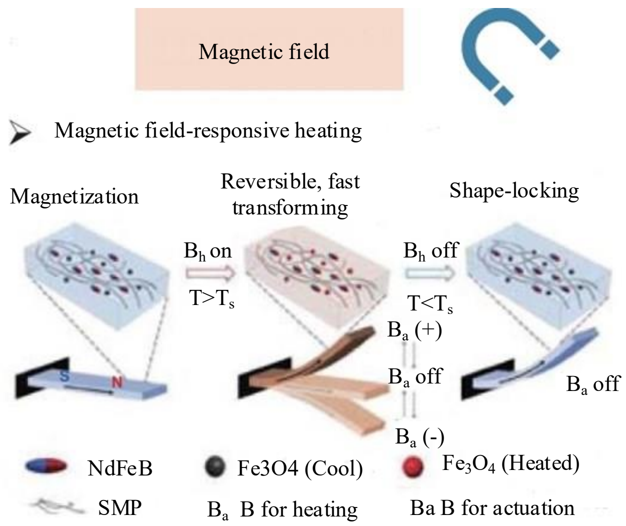

Figure 2. Magnet stimuli[23].

STIMULI- RESPONSIVE MATERIALS

Materials that react to particular stimuli are a subset of "smart materials," which can respond and vary. Shape-memory and shape-changing materials are the two types of smart materials. Two sorts of smart materials comprise shape-memory and shape-altering materials.

Shape Changing Materials (SCMs)

These materials can alter shape in react to stimulus, and the kind of shape change depends on the material's underlying structure. The materials are reversible because they go back to their initial location after the stimulation is discontinued.

Shape Memory Materials (SMMs)

SMM was founded in 1962 by Buehler and Wang. There are various types of shape memory materials. SMMs should be programmed with information that knows what the item will become following stimulation, even though no planned transformations need to be prepared for them. The next phase, recognized as the recovery phase, involves the object receiving a specific stimulus to return to its initial state [24]. The shape memory effect (SME) characteristics of these materials allow them to "memorize" long-lasting shapes.The key change among SCMs and SMMs is that the material returns to its early place after the stimulus is eliminated. When the material is stimulated in the case of shape memory, transformation takes place. For the second memory feature, the content needs to be programmed. One-way and two-way SMMs can be characterized into two groups. The temporary shape in one-way shape-memory materials must be changed using a new programming stage on a period-by-period basis. After recovering from the temporary posture, the initial shape is restored. However, the reprogramming phase is not necessary for two-way shape memory materials to recover their temporary shape [25]. SMMs also come in a variety of forms that can change depending on the circumstances when they are actuated externally. SMAs, SMHs, and SMPs are frequently used in medical engineering. Scientists favour employing shape-memory materials because they are proficient than shape-changing materials. Therefore, many shape-memory material types are discussed in the section that follows.

Shape Memory Polymers (SMPs)

Actively moving polymers (AMPs) are a type of smart materials that have memory-enhancing properties. Despite the diversity of these materials, epoxy-based polymers, polynorbornene, and cross-linked polycyclooctene are the most often used. SMPs can alter their structure once exposed to environmental stimuli including moisture, light, pH, and temperature. SMPs are more cost-effective than SMAs, more flexible, more resistant to chemicals, biodegradable, and able to respond to light stimuli but are less stiff and have lower tensile strengths than SMAs. SMAs are still less useful in the biomedical engineering field than SMPs.

SMP is a pair of entities with the ability to actively change from form I to shape II, with shape II serving as the permanent shape while shape I serves as an interim structure owing to mechanical contortion that results in shape modification [26]. As was already noted, these smart material varieties can react to a variety of physical stimuli. These substances can change shape when heated and have shaped memory effects. These material groups have so far been employed in various industries, particularly in the manufacture of medical devices including vascular stents, splint airways, and surgical sutures. For instance, 280,000 persons experience heart disease annually, according to a study [27]. Therefore, there is a pressing need to create cardiovascular stents. It is believed that there is a need to]create new stents with superior features since metal stents of today have several drawbacks, including a growing capacity that lags and the ability to induce hyperplasia. Therefore, 3D printing was employed for the stent's quick and improved creation.

The detail that 3D printing for manufacturing can produce static assemblies, however, means that the products cannot be moulded as necessary. This is one of the difficulties of 3D printing for construction. These implants cannot develop simultaneously with the implant, for example, when a 3D-printed implantable stent is produced. Smart implants, on the other hand, can provide this expanding capability with 4D printing. As exposed in Figure 3, Qi Ge et al. created a cardiovascular stent with shape memory polymers employing 3D printing [28]. This stent could be a lot more effective than metal stents since it utilizes shape memory polymers. Consequently, under the necessary circumstances, this stent's morphology changes and it can respond to heat stimulus.

Shape Memory Hydrogels (SMHs)

Hydrogel is another sort of shape-memory substance. The fabrication of 4D bioconstruction or living tissue hydrogel scaffolds could enable them to self-fold or unfold in response to stimuli by exploiting the 3D printing capabilities to produce constructions using smart hydrogels. It is a vital topic since it greatly influences the bioprinting 3D tissues field [29]. These intelligent material sorts can react to stimuli from water or other liquids, making them useful when there is a connection with water or other fluids. These intelligent material sorts can respond to stimuli from liquids, making them useful for applications where there is interaction with water or other fluids. Li et al. were successful in creating a micro-robot utilizing a hydrogel layer and a substance that is pH sensitive that injects medications into the tumor and causes the tumor to die as commerce with a cancerous tumor. High water content substances known as "smart hydrogels" can respond to numerous ecological features, including pressure, ionic, pH, temperature, electric, magnetic field, and light. In addition to the memory effect, self-healing, and programmable sol-gel alteration, they have a variety of other distinctive qualities. It is possible to create structures for 4D printing or bio-origami hydrogel scaffolds that may self-fold or unfold in response to an external signal by utilizing AM technologies' capacity to assemble structures made of intelligent hydrogels. In the realm of bioprinting usable 3D tissues, this will significantly advance the science.

Shape Memory Alloys (SMAs)

A sort of stimuli-responsive material called shape memory alloys (SMAs) can transform thermal energy into mechanical force. SMAs come in a variety of forms, but those made of nickel-titanium (Ni-Ti) have uses in the aerospace, mechanical, and electrical industries among others. SMAs also exhibit helpful qualities such as a super-elasticity effect (SE), are highly corrosion-resistant, and are biocompatible. Ni-Ti is manufactured in various geometries for specific purposes to achieve and take advantage of these properties [30]. These materials have significant potential for biomedical engineering because they can respond to thermal stimuli. SMAs are therefore applicable to medical engineering applications including orthodontic wires, catheters, implantable devices, vascular surgery, cardiology, medication delivery, closure devices, radiography, surgical instruments, and neurology [31]. Selective laser melting (SLM) technology is frequently associated with the SMAs for printing. For instance, Habijan et al. looked at the feasibility of delivering substances to human mesenchymal stem cells (hMSCs) [32]. Their work established a connection between SMAs and SLM methods to create implants for cranial, pelvic, and face repairs.

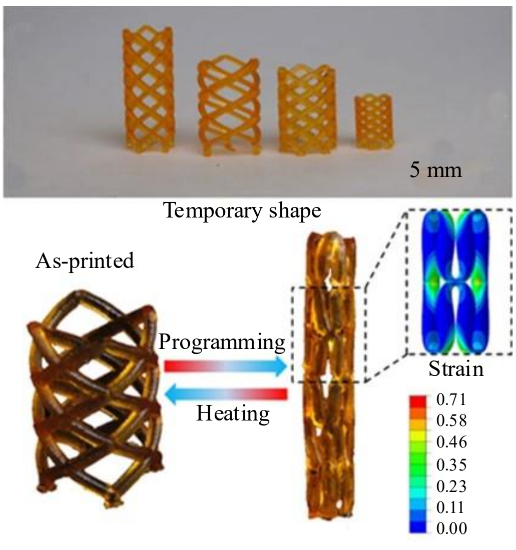

Figure 3. Graphic representation of a cardiovascular stent made up by 4D printing expertise[28].

Nevertheless, the usage of these sorts of smart materials is constrained by their slow rate of degradation. For example, native tissues must be absorbed by artificial implants that are essential for tissue regeneration (such as bone scaffolds) at the appropriate time, atomically over time. Due to alloys' limited biodegradability, the implant persist in the body for ages, which could consequence in a stress-shielding phenomenon or demand another surgery. Before using shape memory alloys in 4D printing, it would appear that more research is necessary to address the current limitations and issues.

Shape Memory Composite/ Ceramics (SMC)

Ceramics display the shape memory effect (SME), and in 2013, shape memory ingestions jointly led the ceramics announcement pack manufacture with MIT. Similar [33]. martensitic growth affects the monoclinical structure of the tetragonal system in shape memory ceramics (SMC). As an antiferroelectric shape memory (AFE) composite material, lead zirconate titanate (Pb (ZR, Ti) O_3, PZT) ceramic production has established notable isotropic volumetric shape memory capability.

Shape Memory Hybrid (SMH)

SMH can be produced for both the elastic wipe and cupric sulphate pentahydrate. It can show how quickly a reservoir can acquire a desirable shape in response to water. The SMP can currently output a shape memory hybrid and is intended to be the current literature of natural, metal, and anonymous processes [34]. SMH and SMPS, despite the impression that the composition is contesting several factors, including forgeries and protections. They offer chemical data and solid aptitudes in addition to solid aptitudes, unlike shape memory alloys which demand both.

APPLICATIONS OF 4D PRINTING

Drug Delivery Systems (DDS)

The essential application of 4D printing for drug delivery has drawn consideration. Localized drug release within the body can be accomplished by bringing thermos-responsive materials' SME transition point near physiological temperature and attaining a comprehensive transition temperature range [35]. It is employed as a medication carrier due to the porous polymers' high surface area and low weight. A directly triggered medicine delivery system is produced by Mirani et al. using 4D bioprinting. PCL has been employed for numerous years in biomedical applications owing to its small melting point, mild in vivo degradation amount, and good drug penetrability. Biological applications typically use hydrogels due to their exceptional biocompatibility and flexibility. However, it is challenging to precisely deliver the medication at the injury site. The "perfect drug delivery scheme" is a procedure used to release medications at the disease site under controlled circumstances and through changes in the environment.

Akbari et al. created a straightly activated medication delivery scheme using 4D bioprinting [36]. They began by printing different kinds of permeable sensors, made of alginate fibers and pH-reactive materials. Concurrently, the gentamicin-encumbered alginate fibers were working to print the drug-eluting stent. The procedure for working is as follows: The sensor can record a change in pH, and the drug-eluting stent can then release the medication at the location of the change in pH to kill the bacteria.

Infrared light (IR) is used to shape-memorize a thermally responsive hydrogel (pluronic F127 diacrylic macromolecule-founded), according to a new technique proposed by Dai et al [37]. The composite materials become photo-responsive once graphene oxide is added. The folded hydrogel needs to be exposed to near IR light for 240 seconds to be completely transformed back into its original shape. The structure's surface area changing shape is the key feature inducing the drug release rate. The surface area shrinks and the drug issue proportion reduces as the temporary shape is twisted. The 4D bioprinting used for the delivery of medication has become feasible with the growth of intelligent materials that can respond to biological signals and extreme situations in the body. Scientists require certain information in pathophysiology, bioengineering, and medicinal chemistry to create an operative pharmaceutical delivery scheme. Research on effectiveness and safety must be done in-depth to support widespread clinical usage.

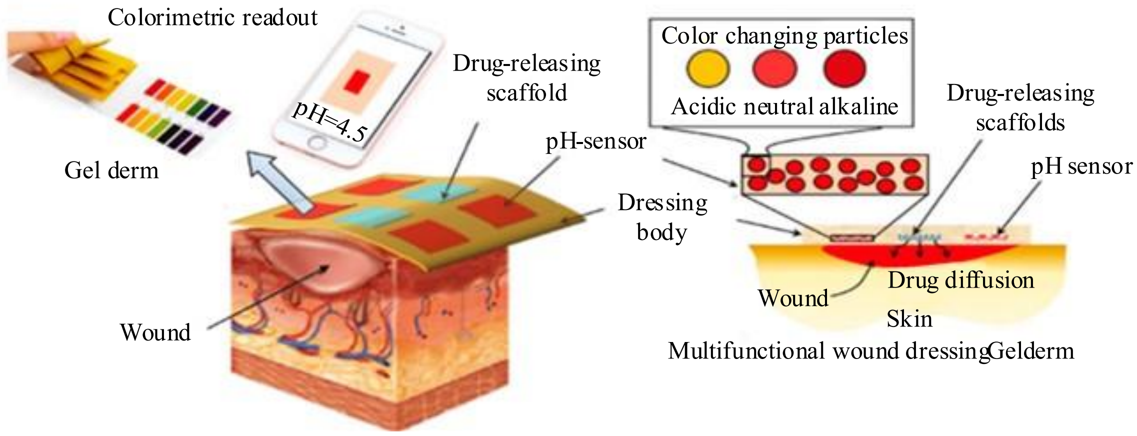

Figure 4. Graphic illustration of GelDerm treatment of epidermal wounds, with pH-sensitive and drug-eluting components expertise[39].

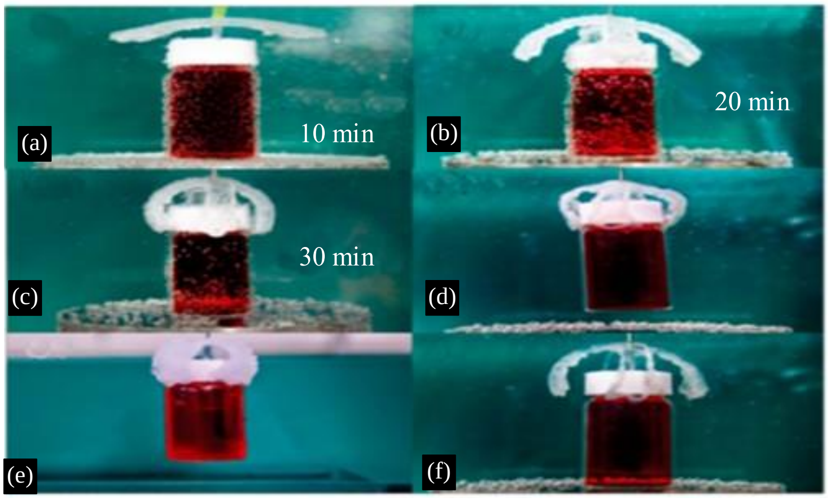

Figure 5. 3D macroscopic gripper assembled utilizing shape-memory hydrogels at diverse bending sites expertise[39].

Soft Robotics

4D printing expertise provides flexible processing of complicated structural components as well as the merging of structure and intelligence by imbuing the material structure with specialized intelligence [38]. Numerous works on soft robots formed with 4D printing expertise have been published recently (Figure 5). Advancements in engineering design, soft programmable materials, and other technical areas have also contributed to the quick progress of soft robots. Soft robots are more adaptable and portable compared to conventional robots comprised of motors, joints, pistons and hinges. They can be included in more intricate procedures and can alter their size and shape as needed. Additionally, they are more environmentally friendly and safer. Thus, there are numerous potential uses for soft robots in the bionic and medical fields. The hydrogel software robots can be powered by local circulation or oscillating chemical processes thanks to the advanced movement developed by some researchers.

Stents

The need for surgery to implant the stent into the patient's body after it was mass-produced in the past knowingly elevated the risk to the patient's protection. Scaffolds are now being formed utilizing smaller stimuli-responsive materials thanks to the growth of 4D bioprinting. The stent will naturally deform to a correct size and shape after transplantation with the right stimulation, considerably reducing the danger of surgery. There are now several different materials and 4D bioprinting techniques that can be used to create stents. The ability to maintain the stent's temporary shape at a small diameter is the first of several technical requirements that the stent must meet. After the stent is inserted, the blood vessel's width may be increased, and the stent may then be heated to take on its original shape. Lonov et al. combined 4D printing and hydrogel to produce a hollow structure self-folding stent and a minimum diameter of 20 m [40]. The polymer may experience a reversible shape change when the Ca^{2+} ion concentration changes. The cell survival rate for stents manufactured from these biocompatible hydrogels is comparatively high.

Ge et al. produced a stent utilizing micro-stereolithography (SL) to establish the viability of shape memory polymers for the manufacture of stents and to demonstrate the effectiveness of stent fabrication utilizing 4D printing [41]. The process is founded on SL and employs a range of photo-curable methacrylate-founded copolymer networks. They developed the components and compositions to demonstrate the required thermomechanical characteristics to allow controlled shape memory behaviour. This work used a high-resolution, digital microdisplay to demonstrate the excellent resolution of methacrylate-founded SMPs, which require more exposure energy than acrylate-founded polymers, which are more frequently used. Multiple photo-curable SMPs can be used to create 3D composite constructions using an automated material exchange mechanism. We do high-fidelity computer simulations of the 3D composite microarchitectures' complicated nonlinear, time-dependent behavior to understand how they behave. We also take a close look at important design elements including free recovery rate, shape fixity, and local deformation. Simulations, which for a variety of single and multi-material components are in good accord with experiments, can enable the SMP 3D structures design.

Microfluidics

Microfluidics has several applications in biomolecular, high-quantity screening, cell examination, analysis, and treatment. Microfluidic devices must be operated and controlled with minimal expense, power consumption, and restrained miniaturization. These demands are fulfilled through some micro and smart components. As a result, incorporating soft and stimulus-approachable hydrogels into microfluidic devices is a tendency for the future. It can precisely regulate the fluid through form change when there are external stimuli. By altering the pH to control microfluidics, Beebe et al. created a smart hydrogel actuator [42]. They created several pH-responsive hydrogel forms using photolithography, and the response time needed was smaller than 10 s. According to its chemical makeup, each hydrogel gate will react to a particular pH value and then automatically identify the fluid.

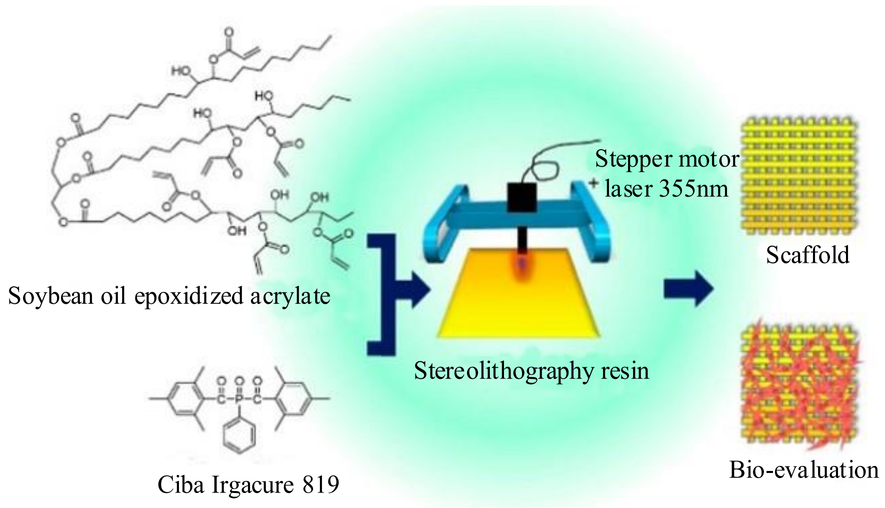

Figure 6. Smart biomedical scaffold fabrication using 4D printing expertise[43].

Tissue Engineering

The significant rise in the global population and the frequency of age-related problems are driving up the need for medications and organs. The method of 4D bioprinting requires the realization of dynamic operations to produce complex and dynamic tissues in vitro. Current studies have shown that shape memory scaffolds have the possible to be employed in functional tissue delivery with the least amount of invasiveness. 4D printing enables the astonishing potential of the shape-shifting substance. Potential uses contain tissue engineering along with medical implants that can change the shape of the body inside. The best illustration of this is the preparation and use of scaffolds for tissue engineering or bone reconstruction. It can be characterized as a three-dimensional biomaterial assembly that is utilized in the healing, regeneration, and repair of bone wounds. When tissues like muscle, bone, and cardiovascular tissues need to regenerate, scaffolds are frequently used since these tissues' mechanical properties vary dynamically with physical activity. The shape memory scaffolds can control the transmission process wirelessly and precisely by integrating with bioelectronics and biodegradation machinery. The direct implantation of stem cells into biological scaffolds utilizing 4D bioprinting expertise is another significant development in organ transplantation and tissue regeneration fields.

For bioprinting using 3D stereolithography, photocurable, biocompatible liquid resins are very anticipated. In this study, Miao et al solidified a new sustainable soybean oil epoxidized acrylate utilizing a 3D laser printing technology to generate intelligent, highly biocompatible scaffolds that can support the development of multipotent human bone marrow mesenchymal stem cells (hMSCs) (Figure 6). Simple adjustments to the printer's infill density made it easy to create porous scaffolds, and the frequency and speed of the laser had a big impact on the surface structure of the polymerized soybean oil epoxidized acrylate. Shape memory studies showed that the scaffold maintained a momentary structure at 18°C and recovered its initial shape at 37°C, demonstrating the scaffold's immense potential for 4D printing applications. The printed scaffolds significantly outperformed conventional polyethylene glycol diacrylate (PEGDA) in terms of hMSC adhesion and proliferation, according to cytotoxicity studies, and did not statistically vary from poly lactic acid (PLA) and polycaprolactone (PCL). This study is expected to make substantial progress in the creation of biomedical scaffolds using cutting-edge 3D printing technology and renewable plant oils.

FUTURE PROSPECTS AND CHALLENGES

The 4D printing concept has grown quickly and shows promise, especially for uses in the medical engineering field. This quick development may be just the start of what 4D printing technologies will supposedly be able to accomplish. Researchers in the biomedical area have mixed feelings about the idea that 4D printing can be employed to produce dynamically created structures like soft actuators, systems that are specifically drug-loaded, and implants that are smart for each patient. The three main challenge zones are technology-based, materials-based, and design-based.4D printing has the potential to address numerous issues while being a relatively new invention. But there are still many issues with this topic that need to be resolved. One of the biggest challenges is that present 3D printers are unable to solve essential 3D printing topics like avoiding support assemblies, particularly for internal constructions that are hard to access, printing multiple materials, the deficiency of readily available printable materials, and extended print times. Either new printing machinery must be created or must be significantly enhanced. 3D printing is presently quite common and helps to solve some of these 3D printing issues. Another significant issue is that the anticipated shape or property transformation imposes limitations on the mechanical qualities of 4D-printed constructions.

Regarding technological obstacles, printing techniques are the main constraint. There are now just a few 3D printing processes that are employed in 4D printing. Therefore, it appears that 3D printing methods must be improved in light of the usage of 4D printing expertise to realize the goals of 4D printing and the production of smart products. The lack of specialized 4D printing software is one of the major limitations in terms of design-related difficulties. Most of the software now in use, including slicing software and design, has been developed for use with earlier fabrication techniques like 3D printing. The requirements of 4D printing expertise have not yet been met by any prospective program. The third issue that researchers are confronting with this new technology is material-based difficulties. Since most 3D printing materials don't respond to stimuli, they can't be used in 4D printing. In other words, traditional materials are incapable of varying their shape or form in response to ecological factors. Future introduction of intelligent materials with the capacity to react to a variety of stimuli is advised to achieve this. Additionally, the development of intelligent materials that can concurrently alter their shape and colour or their size and function may give scientists more options and tools to design biological structures and drug delivery systems. Fourth, 4D printing technology demands the synthesis of several academic fields' knowledge. It is necessary to incorporate design considerations and restrictions into a methodical design framework to build functional, shape-altering materials and structures depending on detailed applications.

CONCLUSIONS

Over the past ten years, 4D printing technology has progressed significantly. Meanwhile, its commencement has increased its impact in numerous manufacturing areas. In 4D printing, a shape-altering mechanism is frequently induced over time using additive manufacturing processes and stimuli-responsive materials. One printed object can support numerous operations, increasing flexibility and adaptability. Stimuli-responsive materials are required for smart materials, and 3D printing knowledge makes it probable to generate dynamic structures with this technology. The idea of 4D printing emerged as an outcome of the quick development of 3D printing equipment, ideas, and printers. Interest in 4D printing has recently increased due to the capacity of printed assemblies to change over time in reaction to ecological issues including temperature, pressure, water, wind, and light. The use of 4D printing, which makes use of intelligent materials, designs that account for change processes, and intelligent printing, varies from little alterations to the bioprinting of animals.

REFERENCES

1. Guzmangonzalez JV, Saldanamartinez MI, Barajasgonzalez OG, et al. Multifunctional cube-like system for biomedical applications featuring 3D printing by dual deposition, scanner, and UV engraving. *Proc. SPIE*. 2017; 10095: 1009511.
2. González-Henríquez CM, Sarabia-Vallejos MA, Rodriguez Hernandez. J Polymers for additive manufacturing and 4D-printing: Materials, methodologies, and biomedical applications. *Prog Polym Sci.* 2019; 94: 57–116.
3. Raina A, Haq M, Javaid M, et al. 4D Printing for Automotive Industry Applications. *J Institute Eng India: Series D.* 2021;102(2): 521-529.
4. Tibbits. S 4D Printing: Multi-Material Shape Change, Architecture and Design. *Architectural Design*. 2014; 84: 116-121.
5. Gladman AS, Matsumoto EA, Nuzzo RG et al. Biomimetic 4D printing. *Nat.Mater*. 2016; 15: 413-418.
6. Momeni F, Liu X, Ni. J A review of 4D printing. *Mater. Des.* 2017;122: 42-79.
7. Choi J, Kwon OC, Jo W et al. 4D printing technology: A review. *3D Print. Addit. Manuf.* 2015;2 (4): 159-167.
8. Zolfagharian, A. Kouzani , Khoo SY, et al. Evolution of 3D printed soft actuators**.** *Sens. Actuators.* 2016; 250: 258-272.
9. Tofail SAM, Koumoulos EP, Bandyopadhyay A, et al. Additive manufacturing: scientific and technological challenges, market uptake and opportunities. *Mater. Today.* 2017; 21: 22–37.
10. Murphy SV, Atala. 3D bioprinting of tissues and organs. Nat. Biotechnol. 2014; 32: 773–785.
11. Jessop ZM, Alsabah A, Gardiner MD, et al. 3D bioprinting for reconstructive surgery: principles, applications and challenges. *J. Plast. Reconstr. Aesthet.Surg.* 2017; 70:1155-1170.
12. An J, Chua CK, Mironov V. A Perspective on 4D Bioprinting. Int. J. Bioprint. 2016; 2: 3-5.
13. Ma SQ, Jiang ZY, Wang M, et al. 4D printing of PLA/PCL shape memory composites with controllable sequential deformation. *Bio-Des. Manuf.* 2021; 4: 867-878.
14. Zhang YS, Yue K , Aleman J, et al. 3D bioprinting for tissue and organ fabrication. *Ann Biomed Eng.* 2017; 45(1): 148–63.

15. Zhang K , Geissler A , Standhardt M, et al. Moisture-responsive films of cellulose stearoyl esters showing reversible shape transitions. *Sci Rep.* 2015; 8: 11011.
16. Sydney Gladman A, Matsumoto EA, Nuzzo RG, et al. Biomimetic 4D printing. *Nat. Mater*.2016; 15 (4): 413–418.
17. Roppolo I, Chiappone A, Angelini A, et al. 3D printable light-responsive polymers.*Mater. Horiz*. 2017; 4: 396-401.
18. Liu Y, Shaw B, Dickey MD, et al. Sequential self-folding of polymer sheets. *Sci. Adv.* 2017; 3: e1602417.
19. Kuksenok O, Balazs AC, Stimuli-responsive behavior of composites integrating thermo-responsive gels with photo-responsive fibers. *Mater. Horizons.* 2016; 3: 53-62.
20. Peng W , Zhang G, Liu J et.al. Light-coded digital crystallinity patterns toward bioinspired 4D transformation of shape-memory polymers. *Adv. Funct. Mater.* 2020; 30 (19): 2000522.
21. Miriyev A, Stack K, Lipson. H Soft Material for Soft Actuators. *Nat. Commun.* 2017;8 (1):1-8.
22. Breger JC, Yoon C, Xiao R, et al. Self-Folding Thermo-Magnetically Responsive Soft Microgrippers. *ACS Appl. Mater. Interfaces*. 2015; 7 (5): 3398-3405.
23. Ze Q, Kuang X, Wu S, et al. Magnetic Shape Memory Polymers with Integrated Multifunctional Shape Manipulation. *Adv. Mater.* 2020; 32(4): 1906657.
24. Jamróz W, Szafraniec J, Kurek M, et al. 3D printing in pharmaceutical and medical applications. *Pharm Res.* 2018; 35(9):176.
25. Ding H, Zhang X, Liu Y et al. Review of. mechanisms and deformation behaviors in 4D printing. *Int J Adv Manuf Tech.* 2019; 105(11): 4633–4649.
26. Korde JM, Kanda Subramanian. B Naturally biomimicked smart shape memory hydrogels for biomedical functions. *Chem. Eng. J.* 2020; 379: 122430.
27. Sun JC, Davidson MJ, Lamy A, et al. Anti thrombotic management of patients with prosthetic heart valves: current evidence and future trends. *Lancet.* 2009; 374(9689): 565-576.
28. Ge Q, Sakhaei AH, Lee H, et al. Multimaterial 4D printing with tailorable shape memory polymers. Sci Rep. 2016; 6: 31110.
29. Khoo ZX, Teoh JEM, Liu Y, et al. 3D printing of smart materials: a review on recent progress in 4D printing. *Virt Phys Prototyp.* 2015; 10(3):103–122.
30. Khoo ZX, Liu Y, An J, et al. A review of selective laser melted NiTi shape memory alloy. Materials. 2018;11(4): 519.
31. Bogue. R Shape-memory materials: a review of technology and applications. *Assembly Automation*. 2009; 29(3):214-219.
32. Habijan T, Haberland C, Meier H et al. The biocompatibility of dense and porous Nickel–Titanium produced by selective laser melting. *Mater Sci Eng C.* 2013;3(1): 419-426.
33. Bogue. R Smart Materials A Review of Capabilities and Applications. *Assembly Automation.* 2014; 34:16-22.
34. Weiss RA, Izzo E, Mandelbaum. S New design of shape memory polymers: mixtures of an elastomeric ionomer and low molar mass fatty acids and their salts. *Macromolecules.* 2018; 41(9):2978–80.
35. Behl M, Razzaq MY, Lendlein. A Multifunctional shape-memory polymers. Advanced Materials. 2010; 22: 3388–410.
36. Mirani B, Pagan E, Currie B, et al. An Advanced Multifunctional Hydrogel-Based Dressing for Wound Monitoring and Drug Delivery, *Adv. Healthc. Mater* 2017; 6(19): 1700718.
37. Malekmohammadi S , Sedghi Aminabad N, Sabzi A, et al. Smart and Biomimetic 3D and 4D Printed Composite Hydrogels: Opportunities for Different Biomedical Applications. *Biomedicines.* 2021;9(11):1537.
38. Zhou X, Yu X, You T , et al. 3D Printing Based Hydrogel dressings for wound Healing. Adv Sci (Weinh). 2024; 11(47): e2404580.
39. Shiblee NI, Ahmed K, Kawakami M, et al. 4D Printing of Shape-Memory Hydrogels for Soft-Robotic Functions. *Adv. Mater. Technol*. 2019; 4: 1900071.

40. Kirillova A, Maxson R, Stoychev G, et al. 4D Biofabrication Using Shape-Morphing Hydrogels.*Adv. Mater.* 2017; 29: 1703443.
41. Ge Q, Sakhaei AH, Lee H, et al. Multimaterial 4D Printing with Tailorable Shape Memory Polymers. *Sci. Rep.* 2016; 6 (1): 31110.
42. Beebe DJ, Moore JS, Bauer JM, et al. Functional hydrogel structures for autonomous flow control inside microfluidic channels. *Nature*. 2000; 404: 588-590.
43. S. Miao, W. Zhu, N. Castro, N. et al. 4D printing smart biomedical scaffolds with novel soybean oil epoxidized acrylate. *Sci Rep.* 2016; 6: 27226.

