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RESEARCH PROGRESS OF 4D PRINTING TECHNOLOGY

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ABSTRACT

4D printing technology represents a major advance in additive manufacturing, in which materials can dynamically change shape or properties over time in response to external stimuli. Recent years have seen phenomenal advances in the field of 4D printing technology, which has revolutionized production and design. This review provides a concise overview of the research progress in 4D printing technology, focusing on its principles, applications, and challenges. Researchers have looked into a variety of materials, such as composites and smart polymers that may change programmably in response to light, humidity, or temperature. Applications for 4D printing are found in a wide range of industries, from aerospace parts to biomedical equipment. The creation of self-assembling and adaptable structures has enormous potential for the development of materials that are useful and responsive. Significant developments in the creation of cutting-edge 4D printing methods, like multi-material printing and exact control over shape-changing processes, are highlighted in this review. Challenges, material constraints, and scalability problems are also addressed, with a focus on continuous efforts to overcome them. The revolutionary effect of 4D printing on manufacturing, design, and many other industries is becoming more and more evident as it develops, opening up previously unimaginable opportunities and creative solutions. Finally, challenges and future directions in the field are discussed, aiming to inspire further research and innovation in the dynamic field of 4D printing technology.

KEYWORDS

4D Printing, Smart Polymers, Responsive Design, Multi-material Printing, Dynamic Structures.

1. INTRODUCTION

3D printing, known as additive manufacturing, is a method for fabricating 3D structures by layering materials depending on a predetermined design (Choi et al., 2015). A lot of remarkable efforts have been made after the idea of Chuck Hull (the father of 3D printing technology) in 1983, which proposed that 3D printing technology can be applied to achieve the goal of stereolithography (SLA) (Hossian et al., 2023). 3D printing technology has been used in many fields, such as the fabrication of fashion jewelry (Yap et al., 2014), polymer printed textiles (Pei et al., 2015), super capacitors, mechanical metamaterials and sensors, bio-hybrid robotics (Stanton et al., 2015), and tissue scaffolds because of its highly customizable nature. Although 3D Printing technology increases the quality of the traditional manufacturing process by decreasing its manufacturing steps, it still cannot gain satisfactory results in the case of conventional manufacturing processes because of several demerits (Ali et al,. 2019). The drawbacks are slow fabrication speed (Wu et al., 2018), the roughness of inclined edges (Gebhardt et al., 2014), and printed mechanically weak objects. To solve this problem, Skylar Tibbits introduced a new concept in 2013 (Singholi et al., 2020), 4D printing, which means the printed configuration changes over time depending on environmental stimuli (Nkomo et al., 2018), i.e., heat, light, water, voltage, pH, etc. 4D printing incorporates additive manufacturing through sensitive innovative materials for acquiring programmable substances (Ji et al., 2022). Shape change and shape memory are the two main properties of intelligent materials. Shape-changing materials are related to two states under specific stimuli (Kirillova et al., 2019) when innovative material is not under any permanent shape or state stimuli. On the other hand, when it is under any external stimuli known as a temporary shape and state. After withdrawing external stimuli, innovative material turns into a state. Shape memory materials can be transformed into transient shapes, preserving a fixed shape or form. Under the external stimulus, the materials are mechanically wrapped into a quick shape and become static when the stimulus is withdrawn. The shape memory materials reshape their permanent shape when it is under stimulus again (Subeshan et al., 2021). The basic principle of 4D printing is to accumulate the structural design of shape change to the material components and 3D printing processes that can simplify the design strategy and manufacturing processes and help to achieve the goal of desirable 4D properties (Ding et al., 2018; Zhou et al., 2015; Kuang et al., 2019). As a result, 4D printing has multiple advantages over traditional manufacturing processes and 3D printing technology. For example, manufacturing cost savings by printing different parts of a whole object collectively, and assembly cost is reduced because of shape-changing self-assembly properties. Again, the simplification of manufacturing processes is another advantage of 4D printing. Whereas traditional manufacturing requires different equipment to print other parts of an object, 4D printing technology requires only one printer to print other parts. For this reason, various materials such as polymers, metals, or nanomaterials can be mixed and printed by the same printing equipment (Ma et al., 2020). Based on these advantages, 4D printing can be applied in a variety of fields, including medicine, electronic devices, robotic systems and engineering, and, more recently, food. (Ghazal et al., 2023)

This review paper provides an in-depth analysis of the changing state of 4D printing technology research. The examination dives into the revolutionary developments that have changed traditional manufacturing and design paradigms, emphasizing the dynamic character of this industry. The paper delves into the concepts and uses of 4D printing by carefully analyzing the literature. It does this by revealing the complex web of intelligent polymers and composites that allow materials to change according to a computer program. The story develops to highlight the adaptability of 4D printing and its uses in a variety of industries, including aerospace and biomedical engineering. As the article progresses, it becomes clear that 4D printing is a paradigm shift with significant ramifications for the future of manufacturing and design rather than just a technological improvement. The story ends with a summary of current initiatives and potential directions for the future, establishing 4D printing as a disruptive force that keeps pushing the envelope of innovation and possibilities. The purpose of this study is to comprehensively review and analyze the current research progress of 4D printing technology. This review intends to get an in-depth understanding of recent developments and emerging trends in this field by reviewing recent advancements in materials, technology, and applications. Additionally, this review aims to identify challenges and potential future techniques for 4D printing technology, ultimately fostering creativity and directing more study into this dynamic and growing area of additive manufacturing.

2. 3D AND 4D PRINTING TECHNOLOGIES

3D printing technique produces a 3D part by using 3D printers. The seven techniques that make up the ASTM standard for 3D printing are sheet lamination (SL), powder bed fusion (PBF), vat photopolymerization (VP), direct energy deposition (DED), material jetting (MJ), binder jetting (BJ), and material extrusion (ME) (Hossain et al,. 2024; Ngo et al,. 2018; Guo et al., 2019; Yao et al., 2019). The binder-jetting method joins powder particles together to make the desired three-dimensional parts by selectively applying a liquid bonding agent to them. MIT first created the method, and ExOne Company patented it (Ziaee et al., 2019). Large build volumes, quick print times, and simple post-processing are benefits of the binder jetting technique;

nevertheless, the mechanical qualities of the printed items are compromised. The fused filament fabrication (FFF) material extrusion technique involves heating thermoplastic material in the filament. Extrusion tip diameter and layer thickness are important processing parameters. The most common method of generating digital models is with computer-aided design software (CAD). Unlike traditional manufacturing methods, a critical stage in the 3D printing process requires the conversion of digital model files into STL (stereolithography) files. STL uses triangles (polygons) to describe the three-dimensional parameter information of objects. 3D printers are often made up of many small, complex parts, so proper maintenance and calibration are crucial to producing accurate prints. At this stage, printing materials are also loaded into the 3D printer.

Above the temperature at which glass transition occurs, the filament is heated, forced through a nozzle, solidified, and then applied to the layer that has solidified. Layered production is produced as the filament cools and solidifies (Hossain et al., 2023). Layers may become evident on the surface during printing, and post-processing is necessary. In the biomedical sector, extrusion-based printing shows great promise for applications ranging from cell-loaded connections to accurate tissue imitation (Sireesha et al., 2018; Wang et al., 2001; Konta et al., 2017). The technique known as "directed energy deposition" uses thermal energy sources, such as laser beams and plasma arcs, to break down the materials so that a nozzle may deposit the powdered or wired material on a substrate (Kamran et al., 2016). In sheet lamination, thick sections of material are cut and then bonded together layer by layer to create the desired component (Khosravani et al. 2020). One of the earliest commercial 3D printing techniques was called "Powder Bed Fusion" (Gibson et al., 2021), in which powder particles are fused to the preceding layer through the introduction of a heat source Fig. 1 (Brandt et al., 2016; Snow et al., 2019). The powder substance is spread over the top layer using a roller or a blade. Binding the powder material to the preceding layer is mainly accomplished by sintering and melting. The benefits of this approach include low cost, inexpensive design, self-supporting construction, and prototype applicability. The drawbacks, on the other hand, include the limited size, high power consumption, and comparatively slow printing pace. Vat photopolymerization is a type of 3D printing that uses light-curing resin materials and light-selective hardening polymerization molding to create complicated devices with functional pieces like fluidic interconnects, valves, and lenses. In order to create the required architectures, resin ingredients are brought under a laser or light control beam and then polymerized after being exposed positionally (Hossain et al., 2023). A variety of nozzles are used in material jetting, an advanced 3D printing technique, to selectively deposit material that a broad area energy source has cured.

Supporting resources are needed in this case in order to print. Low waste, high resolution, different materials, high-quality surfaces, and multiple print heads are benefits of material jetting. This technique has several drawbacks, including high cost, sluggish printing, poor mechanical characteristics, and high dimensional accuracy.

The evolution of 3D printed products into 4D printing technology. Rather than being immobile, 4D-printed things can reshape themselves over time in an active, preprogrammed manner (Wu et al., 2018). The ability to change shape over time is a remarkable advancement of 4D printing over 3D printing. 4D printed materials are similar to 3D printed materials; the primary distinction is that 4D printing technology uses sophisticated and programmable materials, like novel materials. There are many different kinds of intelligent materials that are available, including temperature-responsive, photo-responsive, magnetic form memory alloys, shape memory polymers, electro-responsive polymers, smart inorganic polymers, and electro-active polymers (Haleem et al., 2021). Among the critical characteristics of 4D printing technology are self-assembly, self-repair, and multifunctionality. Time-dependent, printer-independent, and programmable printing are required (Momeni et al. 2017). Single-material and multi-material 4D printing are the two main categories into which 4D printing techniques fall. Extrusion and photopolymerization are two techniques that can be used for single-material 4D printing. Shape memory polymer (SMP) and hydrogel technologies can be used for multi-material 4D printing. (Kumar et al., 2021)

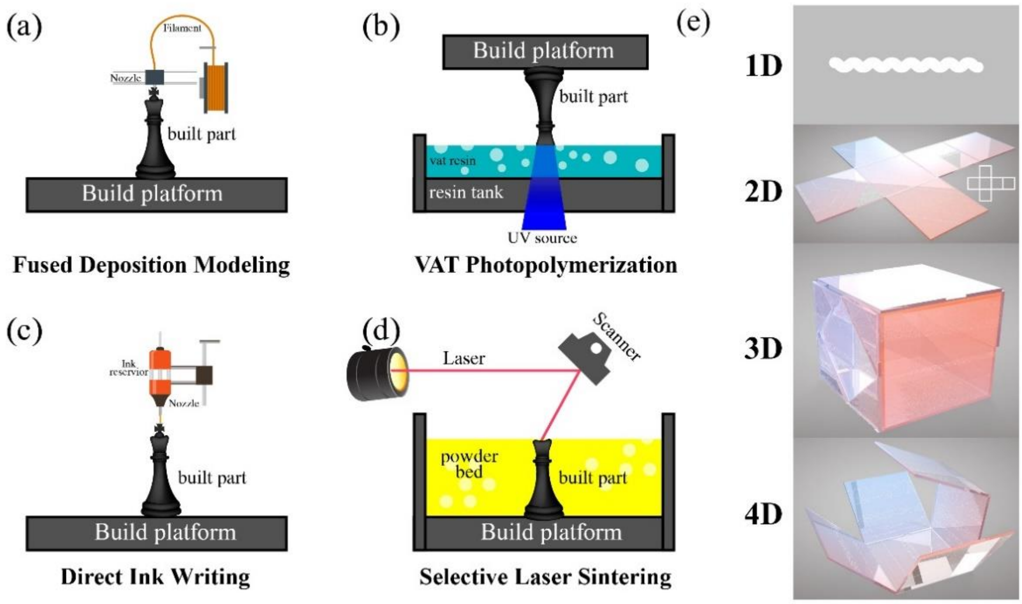

Fig. 1. (a) The most widely used polymer-based 3D printing techniques are shown as follows: a combination of Fused Deposition Modeling (FDM), Vat photopolymerization (also known as Stereolithography (SLA)/DLP), Direct Ink Writing (DIW), and Selective Laser Sintering (SLS/SLM) are the four processes that are presented here (Hossain et al., 2023), and (b) Illustration showing the progression from 1D to 4D printing over time. Integrating a dimension of time to 3D printing is known as 4D printing.

2.1. Characterizations of 4D printing technology

The intelligent materials used in 4D printing determine the properties of the items produced. These materials have characteristics that allow them to self-assemble, repair, remember their shape, and become capable of responding to stimuli over time (Leist et al., 2016). In 4D printing, time is the most essential component to take into account. It differs from 3D printing in that printer independence and time dependence are involved. The five components of additive manufacturing (AM)—materials for printing, stimuli, interaction mechanism, and modeling—are what make 4D printing possible. (Chu et al., 2020)

(Jeong et al., 2020) illustrated the three laws in 2018 to provide a more precise grasp of the features of 4D printing technology. The "relative expansion" between active and passive materials, according to the first law of 4D printing technology, is a fundamental phenomenon that underlies almost all shape-shifting behaviors (such as solvent, pH, moisture, electrochemical, electrothermal, ultrasound, enzyme, hydro, thermos, etc.-responsiveness) that lead to the twisting, coiling, curling, etc. of multi-material 4D printed structures Fig. 2. Nearly all multi-material 4D printed structures feature four different types of physics, including mass diffusion, thermal expansion/contraction, molecular transformation, and organic development for shape-shifting behavior under stimuli, according to the second law of 4D printing. The absorption or adsorption of stimuli (such as iron or water) might cause a change in the mass of the structure. Mass diffusion can also happen when other stimuli are utilized, including electrical, thermal, chemical, and light ones. Thermal expansion, the process that produces changes in the average distance between atoms and molecules as a result of temperature fluctuations, results in structural deformations. The application of an electric or magnetic field can cause a molecular change because the dipoles in the material will align in the direction of the field. Once more, a photosensitive substance may exhibit geometrical isomerism when exposed to UV radiation. Organic growth refers to the way that living things, including cells, tissues, scaffolds, stents, organs, etc., change shape in response to electrical stimulation. This leads to the development of 4D bioprinting. The shape-shifting behavior of nearly all multi-material 4D printed structures is dependent on time. It is controlled by two different kinds of time constants, according to the third law of 4D printing. The stimulus and the variety of printing materials are what determine these constants. (Ahmed et al., 2021)

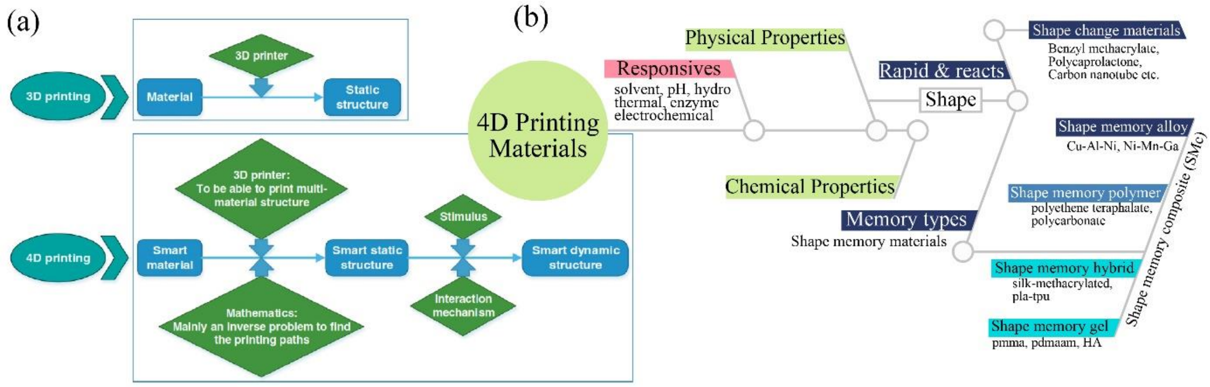

Fig. 2. Diagram of (a) The fundamental distinctions between 3D and 4D printing (Momeni et al., 2017), and (b) Stimulus-responsive materials can be categorized into various subgroups.

2.2. Diversity of 4D printing

The diversity of 4D printing involves a wide range of technological specifics, making it possible to create dynamic structures that are beyond the constraints of conventional production. Fundamentally, 4D printing represents a shift away from rigid, static shapes and toward a dynamic evolution over time, giving additive manufacturing a previously unheard-of degree of diversity. This variety takes on multiple forms, including materials, uses, and the complex relationship between form and function. The materials used in 4D printing represent one aspect of diversity (Vatanparast et al,. 2023). Scholars have explored the domain of advanced composites and intelligent polymers, which are materials that react to environmental stimuli. These materials alter transformative in response to stimuli such as changes in humidity, temperature, or exposure to particular light wavelengths. These materials' dynamic properties provide a plethora of opportunities for designing structures that can precisely change shape, self-assemble, or adapt to their surroundings. The astonishing range of uses for 4D printing shows another aspect of its versatility. For example, 4D printing has the potential to transform the medical field by enabling the production of patient-specific implants that are dynamically adjusted to the body (Ramezani et al., 2023). Technology in aerospace presents chances for the creation of adaptable structures that can react to shifting circumstances while in flight. The construction sector is investigating self-assembling materials that adjust to the surroundings to maximize building energy efficiency. This wide range of uses highlights how 4D printing is revolutionizing a number of industries, including architecture and biomedical engineering. (Kantaros et al., 2023)

Furthermore, the variety of 4D printing encompasses the methods used during production. One significant advancement that makes it possible to combine various materials with unique qualities into a single, well-designed structure is multi-material printing. This technology improves the printed products' utility and adaptability. The shape-changing processes are controlled by precise control mechanisms, which allow for fine-grained customization and programmability throughout the design stage. This degree of control offers a refined method for building intricate, flexible structures, which adds to the diversity of 4D printing. But diversity also brings with it a set of difficulties. Researchers are attempting to utilize 4D printing fully, and among the issues they face are material compatibility, scalability, and reproducibility assurance. However, these difficulties are essential to the iterative process of technical development. As they are resolved, 4D printing's range of applications will only grow, pushing the bounds of what is practical in the field of additive manufacturing. Fundamentally, the versatility of 4D printing bears witness to its revolutionary potential, indicating a future in which the ever-changing interactions between materials, applications, and procedures will redefine the boundaries of design and manufacturing. (Sajjad et al., 2023; Kouka et al., 2023)

2.3. 3D Printed smart materials and bioinspired designing

Innovative materials are those that possess adaptive capabilities to external stimuli, such as load or environment, with profound intelligence. The concept of 4D printing is based on intelligent materials. The most prominent features of 4D printing are an arbitrary combination of materials, homogeneous or hybrid materials, patterned at the liquid, solid, or gas station, low material consumption, and dynamic materials that respond to the printing process (Kamila et al., 2013). Based on the distinct roles that materials play in printing processes, two types of intelligent materials may be identified: sensing materials and actuating materials. A variety of sensors that can excite the outside world or gather data can be created using sensing materials that affect external stimuli. Actuating materials can produce mechanical output or displacement reactions in response to external stimuli. In order to solve complex human challenges, bioinspired engineering refers to the application of biological systems and techniques from nature to the research and design of engineering systems and contemporary technology (Su et al., 2021). In reality, intelligent material-manufactured actuators power bioinspired 4D printing. One controlling factor that can be used to modify the mechanical properties of bioinspired structures is the usage of actuators. In 4D printing, an actuator stimulates a bio-inspired structure to transform it from 2D to 3D. The primary stages of this printing are the preparation of the intelligent material configuration, the stimulation of the innovative materials, and the programming of the printing process (Morega et al., 2020). Bio-inspiration comes mainly from plant and animal movement. Naturally, plants have some phytomimetic and movement characteristics, which are initiated by sunlight, touch, gravity, and water. These properties enhance the various biological actions, such as the blooming of flowers, curling of tendrils, and expansion or contraction of cells due to osmosis. This actuation is distinct from manufactured actuation, such as utilizing thermal gradients and the understanding of materials properties, but it is an inspiration for bioinspired 4D printing (Zeng et al., 2022). The inspiration of animals is more complex according to locomotion, so that it can be considered as a single action for bioinspired 4D printing. Here, locomotion includes complex muscle tension and contracts. The complex bioinspired design can be achieved by improving printing processes and the discovery of new intelligent materials in the near future. For example, the robotic finger is inspired by the human finger. As a result of the tendon and muscle working together, it has a varied stiffness (Tee et al., 2021). The metacarpophalangeal (MCP) joint, proximal interphalangeal (PIP) joint, and distal interphalangeal (DIP) joint are the three joints that make up this group. The muscle acts on the tendon to move the finger. Four components make up the soft actuator: an air chamber, reinforcing fiber, silicon matrix, and strain limiting layer. Similar to a tendon or muscle, this gives the finger the ability to bend Fig. 3. (Yang et al., 2017; Cheng et al., 2021)

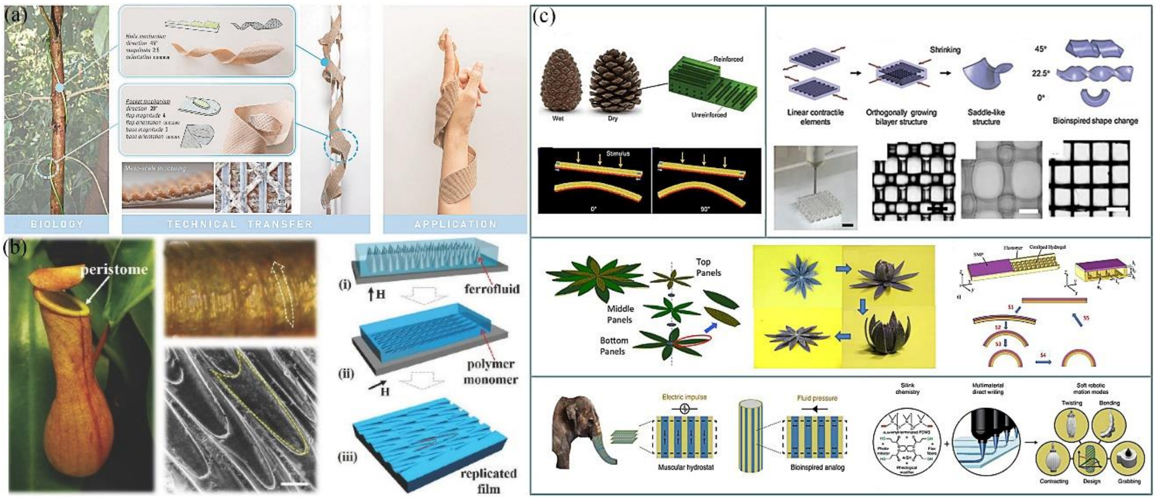

Fig. 3. (a) Using the biomechanics of *Dioscorea bulbifera* as inspiration, wearable materials are designed using biomimetic techniques. A multifunctional 4D-printed material system is the result of bioinspired motion mechanisms made possible by computational approaches (Cheng et al., 2021), (b) the anisotropic wettability surface of the Nepenthes alata plant using ferrofluid-assembled templates demonstrates unidirectional water flow. Selected UV irradiation molding is used to construct an artificial peristome modeled after biological systems (Hossain et al., 2023), and (c) Illustrations of natural-inspired 3D printing shapes are pine cone structure and shape change, hydrogel bilayer motions, reversible petal-like structures, and soft actuators modeled after elephant trunks. (Yan et al., 2021)

3. APPLICATIONS

With the addition of time, 4D printing technology expands on 3D printing by enabling printed things to change, self-assemble, or display dynamic behaviors over time in reaction to outside stimuli. The numerous industries in which 4D printing has found use serve as evidence of its potential to transform conventional production processes. Below are a few noteworthy applications:

3.1. Biomedical

4D bio-printing technology comes from 3D bio-printing by integrating time with this technology. The technology improves the capabilities in the medical field. It will offer great promise for biological scaffolds as well as other vital uses. An intelligent stent, organ printing, creative multi-material printing, tissue engineering, intelligent medical implants, dyspnea (breathing difficulty), and skin transplants are among the fields' potential uses (Javaid et al., 2019). With the patient's heart as support, the 4D-printed stent can grow and take on the necessary shape. In complex surgeries, it might save a patient's life (Zarek et al., 2017). 4D printing is the next milestone in organ printing. The heart, kidney, and liver can be printed with this technology. It also helps to overcome organ shortage, thus saving human lives (Yi et al., 2017; Gosnell et al., 2016). The feature of multi-material printing can help to print multipart of the human body (Ge et al., 2016). The dyspnea problem can be solved by creating a medical implant in 4D printing, which helps to breathe easily. The technology can give revolution in implant and tissue engineering. Muscle, bone, and cardiovascular tissue are among the tissues that can renew because their mechanical qualities change dynamically when our bodies become active Fig.4 (Hendrikson et al., 2017). By using this technology's shape-changing ability, skin grafting can assist a patient who has been burned by fire to grow their body more like the original. (He et al., 2018)

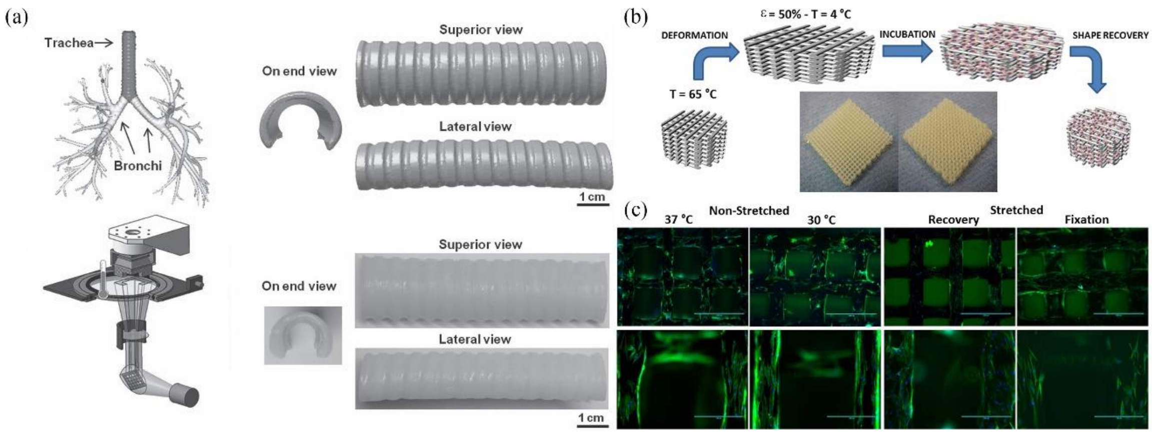

Fig. 4. (a) CAD and digital models based on MRI data can be used to create shape-memory airway stents. Construct a heated bath specifically for the melting of resin using an SLA printer (Zarek et al., 2017), (b) a diagram of the 4D scaffolding procedure is shown. Shape memory polymers are added to a polyurethane SMP scaffold that is shaped at 65 °C with 50% strain, kept in place at 4 °C, cultured at 30 °C to help cells grow, and then fixed permanently at 37 °C, and (c) used phalloidin (green) to show actin fibers and DAPI (blue) to show nuclei on 0/90° scaffolds that were stretched or non-stretched. The cells moved and were colored. The scaffolds were kept at 30 °C after seeding, at 37 °C, flexed (non-shape recovery, and after shape recovery). (Hendrikson et al., 2017)

3.2. Aerospace

The diversified property of 4D printing has given to develop the desired structure for the aerospace industry. Shape memory alloys (SMAs) and shape memory polymers (SMPs) are the two groups of commercially available intelligent materials (Melocchi et al., 2021). The austenite phase (high temperature) and the martensite phase (low temperature) are balanced during SMAs (Brinson et al., 1996). When SMP is exposed to external stimuli like temperature, it transforms bidirectionally into a transient shape (Zarek et al., 2015). A 4D-printed material has previously been produced by the Naval Ordinance Lab in collaboration with SMPs and SMAs (Shishkovsky et al., 2018). With 4D printing, lightweight structures that can collapse and regenerate in space, like solar panels, could be produced. It could be used in drones and aircraft wings. (Liu et al., 2021)

3.3. Soft robotics

Soft robotics can benefit from the use of 4D printing. Transformative shape-memory materials' programmable features have demonstrated the material's actuation possibilities through 4D printing (Ryan et al., 2021). Conventional robots are composed of rigid materials such as metal and complex polymers. Conventional robots have the drawback of being unable to tolerate significant deformations without experiencing adverse effects. This issue can be solved with the creation of soft robots. Since the soft robots are composed of soft materials, intelligent materials, and 4D printing need to be able to support them. Soft actuators, sensors, and controllers are the three categories under which soft robotics falls. Soft robots are adaptable to their surroundings, can change their stiffness when needed, and are flexible (Chen et al., 2017). The field of soft robotics has seen a great deal of activity. Hydrogel material was used by (Nikkanen et al., 2022), to create grippers that could capture and release a fish swimming in a water tank Fig. 5. According to (Truby et al. 2018), embedded 3D printing can be used to create soft somatosensitive actuators that allow for thermosensitive, proprioceptive, and haptic sensing. Nowadays, traditional rigid electronics are embedded into flexible substrates to create soft sensors (Luo et al., 2017). (Breger et al., 2015), reported on 4D printed soft robotics, wherein photo patterning was used to create tiny grippers composed of thermomagnetically responsive polymer. A soft robotic system resembling a spider's movement was developed by (Gul et al., 2016), using an epoxy, urethane body, and SMA wire.

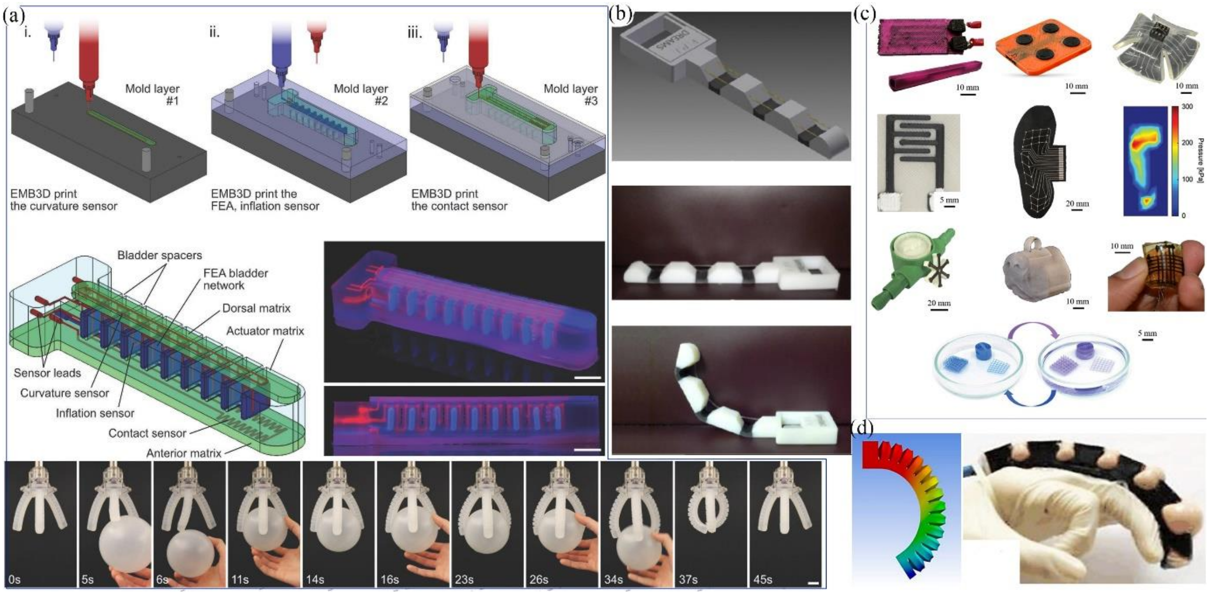

Fig. 5. (a) Multiple sensors are used in the fabrication of a soft somatosensitive actuator (SSA): curvature is located in Layer 1, an inflation sensor and actuator features are located in Layer 2, and a touch sensor is positioned in Layer 3. Soft robotic graspers that provide tactile feedback. Pictures depicting a sequence of events involving a ball and a soft robotic gripper made of SSAs (Nikkanen et al., 2022), (b) Computer aided design (CAD) representation, the design and manufacturing of a robotic finger using an AM method in-situ finger as built with embedded monofilament fiber, and finger actuated via a sliding joint (Li et al., 2017), (c) 4D-printed soft robots are used in a variety of fields, utilizing a wide range of 3D-printed sensors, such as pressure, piezoelectric, e-tongue, strain, and sEMG electrodes, and (d) Applications of Finite element methods (FEM) and topology optimization (TO) in data-driven modeling of 4D-printed soft robotics, and optimization of topology for a multi-material 3D-printed soft robot. (Zolfagharian et al., 2020)

Additionally, 4D printing has applications in many fields. In the automotive business, the technology is used to create driver-comfortable seats and other components that can adjust to the surroundings (Raina et al., 2021). Using 4D printed items that can self-assemble and self-repair can likewise be used to create military gear (Bird et al., 2021). Additionally, 4D printing technology may be able to address issues facing the textile industry, including reducing the physiological load, minimizing membrane deterioration, restricting the impact of liquid, biological, or chemical agents, and removing dirt from an extensive membrane's textile surface. The creation of a flexible, self-cleaning membrane can resolve the issue (Gugliuzza et al., 2013). The ability of 4D printing to self-assemble can also be applied to the creation of architectural buildings. (Ding et al., 2019)

3.4. Architecture

4D-printed building materials can modify their form or characteristics in response to environmental changes, improving sustainability and energy efficiency. Innovations in technology have made it possible to design self-assembling structures that may be customized to meet specific needs and streamline the construction process (Tahouni et al., 2021). By using 4D-printed materials in construction, elements that react to variations in humidity, temperature, or seismic activity can be created, increasing the structural robustness of buildings (Yi et al., 2021). Using 4D printing technology can help create building materials that can heal cracks or other damage over time Fig. 6. (Li et al., 2019)

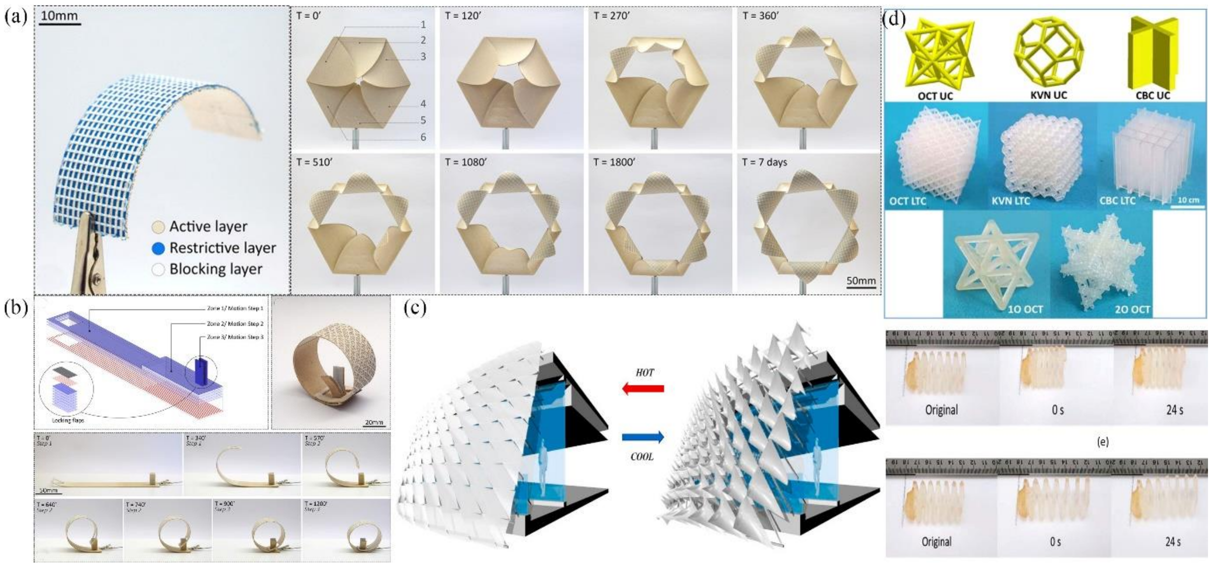

Fig. 6. (a) 4D-printed hygromorphs with architected mesostructure, including test samples with active, restrictive, and blocking layers. Time-lapse images showcase a prototype's sequential motion and successful aperture opening in 40% RH, (b) Diagram showing various zones with parameters indicated: a prototype that locks itself together after self-shaping. To "lock" and secure the mechanism in place, the locking flaps are put into the slot and bent outward. Time-lapse photos demonstrate the self-locking prototype's three stages of motion (Tahouni et al., 2021), (c) Architecture concept of biomimetic self-shaping skin: prototyping of 4D-printed self-shaping building skin, and (d) Used high-recovery stress-shaped memory polymers to print Octet micro lattice structures, Kelvin micro lattices, cubic micro lattices, multi-length scale micro lattices, and Octet truss in the 4D printing of lightweight, recyclable structures, and (e) Shape memory behavior and recovery stress of cubic microlattices and 3D-RSMPs. After heating, a 3D-printed spring with compression programming regains its original shape. (Li et al., 2019)

3.5. Textiles and Fashion

The use of 4D printing in textiles has made it possible to create clothes that can alter their characteristics in response to outside factors like wetness or temperature (Koch et al., 2021). With 4D printing, designers may produce elaborate, movable garments that react to the wearer's actions and environments Fig. 7. (Biswas et al., 2021)

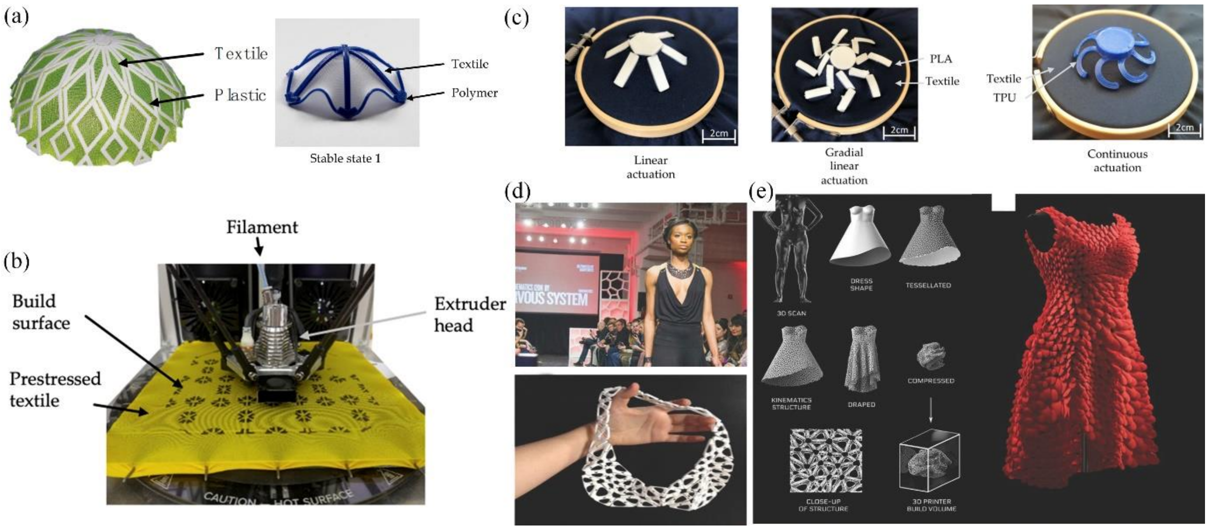

Fig. 7. (a) 4D textiles' spatial forms and bistability synclastic dome form; illustration of stable states of a single 4D textile structure, (b) 3D printing in the manufacturing of textiles Layers of plastic created with 3D printing onto textiles, (c) clamping printed buttons in embroidery hoops to use as 4D textile actuators: There are three types of actuation: linear, progressive, and continuous (Koch et al., 2021), (d) Adaptable jewelry and camouflage apparel are two new 4DP application areas, and (e) Clothes without assembly using a hinged mechanism are one application for 4D-printed textiles. Outfit created using a 4D printer and 1600 stiff nylon components. (Biswas et al., 2021)

3.6. Final Products

By using 4D printing, it is possible to make packaging that changes its shape or qualities in response to environmental factors, protecting and preserving its contents. With 4D printing, consumer items like shoes and furniture may be made to have any shape, color, or function that the user desires (Chen et al., 2022). Using 4D printing in education may help create dynamic, interactive models that help explain difficult scientific, engineering, and biology subjects. By using 4D printing to create dynamic models quickly, engineers and designers can test ideas and make iterations more quickly. Research and development are leading to the expansion of 4D printing technology's adaptability, which offers creative solutions for a variety of industries Fig. 8. (Chong et al., 2018)

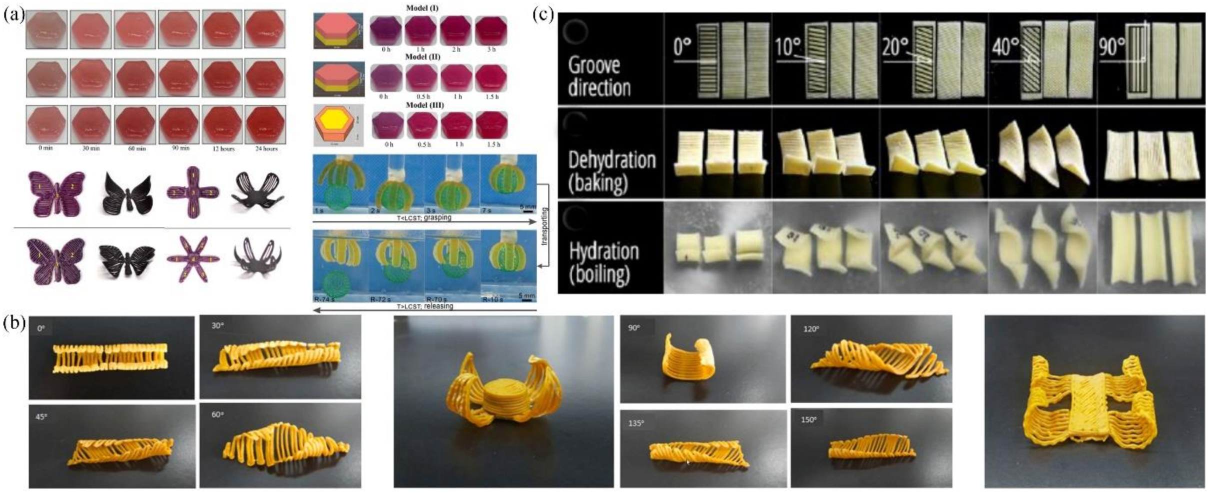

Fig. 8. (a) 4D models, created by 3D printing with various anthocyanin concentrations, exhibit predetermined color and shape variations. Adhesion, design, and microwave dehydration are taken into account during the process. A heat-responsive gripper that is holding a hollowed-out ball serves as an example of how various geometric models facilitate the creation of 4D designs, (b) Deformation process of the paper/pumpkin double-layer construction. Straightforward models with several filling angles and intricate models, and (c) Characteristics of printed pasta, including unique groove configurations. A collection of parallel grooves positioned at different angles relative to the rectangular samples' edge. The samples bend in the groove's direction as they undergo either dehydration or hydration. (Chen et al., 2022)

4. OUTLOOK AND FUTURE OF 4D PRINTING TECHNOLOGY

The outlook and prospects of 4D printing revolutionize a compelling and intriguing story of transformative innovation, promising to redefine the landscape of manufacturing and design. Looking further into the horizon of this rapidly developing technology, we can see that 4D printing is still in its early phases of development and has a great deal of untapped potential. The development of 4D printing as a commonplace industrial technique is a crucial aspect of its future. The frontiers of materials, methods, and applications are currently being pushed by research and development initiatives. We may expect a wider industry usage of 4D printing as these technologies advance. The versatility of 4D printing is poised to alter the way we imagine and produce products, structures, and even complex gadgets, with applications ranging from healthcare to construction (Yan et al., 2021). In particular, the healthcare industry has an excellent future. New avenues in personalized medicine are being opened by the development of patient-specific implants and dynamic medical devices that adjust to the dynamics of the body. Imagine therapeutic gadgets that react to changing bodily conditions or implants that change in response to the patient's motions. There is a tremendous amount of opportunity to improve patient outcomes and treatment effectiveness. (Zarek et al., 2017)

Additionally, there are plans to combine 4D printing with other cutting-edge technologies like robotics and artificial intelligence (AI). Autonomous systems that can self-assemble or instantly adapt to their environment may result from this convergence. The potential of such integration is best illustrated by applications in space exploration, where the ability to adapt to unfamiliar and unpredictable surroundings is essential (Yi et al., 2017). Future developments will also need to take 4D printing's environmental sustainability into account. A more sustainable approach to manufacturing can be achieved by investigating eco-friendly materials and procedures as technology develops. The capacity to design items with environmental adaptation and performance optimization in mind fits in with the global movement towards greener technologies (Gosnell et al., 2016). Still, there are challenges in the way of 4D printing's broad use. The necessity for standards, material constraints, and scalability concerns are topics that researchers and industry pioneers are still working to resolve. In order to realize the full potential of 4D printing and bring in a new era when dynamic, shape-changing buildings are easily incorporated into our daily lives, it will be essential to overcome these obstacles. (Ge et al., 2016)

The next generation of printing technology, known as 4D printing, is derived from 3D printing and holds enormous promise for overcoming the drawbacks of the conventional printing process. It is currently in the early stages and is hampered by the creation of stimuli-responsive materials, the modeling and design of intelligent structures, and the study and development of manufacturing methods and techniques (Falahati et al., 2020). These domains, which include the hardware of 3D printing processes, material science of intelligent material, novel design, and modeling tools, require interdisciplinary study and technical advancements (Peng et al., 2022). The requirement for additional specialized software for 4D printing technology presents another design challenge. Because it is built on 3D printing, the current design and slicing software is unable to satisfy the demands of 4D printing's diversity. For instance, Cura and Simplify3D were created to be compatible with filament-based materials and FDM 3D printers. Therefore, the objective is to create new, influential software that can regulate the rate and timing of a stimulus's response (Sahafnejad et al., 2022). There are now just a few 3D printing technologies that can be used with 4D printing. The most popular 4D printing technologies are extrusion and polyjet printing, yet both have drawbacks. While digital materials with highly adjustable mechanical properties for SMPs and composites are a well-known benefit of polyjet printing, their limitations include expensive equipment, a limited selection of resins, and a narrow range of material options. Similar to this, extrusion-based printing techniques are popular for 4D printing of hydrogels and polymeric composites on a large scale and with multiple materials. However, they have several disadvantages, including low production rates, slow printing speeds, limited structural fidelity, anisotropic mechanical properties, and occasionally poor interfaces. Other 3D printing technologies can leverage 4D printing in the future. Although photo-polymerization methods can produce high-resolution structures quickly and efficiently, they are limited by the materials they can use and can only produce lower print volumes. The following is a potential future outlook for 4D printing technology. The use of additive manufacturing may help uncover limitless opportunities in uncharted territory. Create new, cutting-edge materials with cutting-edge characteristics. Research on self-controllable functions like self-growing and self-reacting. Apply to implantable medical applications as a mature technology. Improve its stimulus-responsive performance. Increase printed product lifespan, recycle cycle times, and preprogrammed cycle capability. Investigate printed product structural complexity. The 4D printing market is currently growing for its diverse characteristics. In the future, 4D printing can be used in aerospace and automotive, biomedical, soft robotics, electronics, and intelligent device manufacturing applications. To sum up, the perspective and prospects for 4D printing have endless possibilities. With the ongoing growth of research and technology developments, 4D printing is a critical component of the upcoming industrial revolution. Its capacity to unite the dynamic and physical domains creates previously unimaginable opportunities, paving the way for a time when the things in our environment are not only manufactured but are sentient, living things that can intelligently adapt to the changing needs of our intricately designed environment. (Wang et al., 2023)

5. CONCLUSION

In overview, 4D printing has an opportunity with indefinite innovation and revolutionary possibilities. Observing the incredible progress that has been made so far, it is evident that 4D printing is a paradigm change that will have a significant impact on how we conceptualize, design, and produce products. It is more than just a technological improvement. The way materials, processes, and applications interact dynamically is paving the way for a time when fabrication itself will be redefined. One of the most important directions for 4D printing going forward is its assimilation into standard production practices. We studied a more comprehensive integration of 4D printing across industries as continuous research and development activities push the boundaries. In the future, the combination of robotics and artificial intelligence with 4D printing creates opportunities for the development of intelligent, self-adjusting systems. Potential uses in space exploration and other dynamic environments point to a future in which self-adjusting, intelligent structures will be able to navigate and react to their surroundings with ease.

Furthermore, the potential of environmentally friendly production is present in the future of 4D printing as environmental sustainability gains prominence. Experts in the industry and researchers are increasingly looking into materials and procedures that support international initiatives to develop greener technologies. The capacity of 4D printing to produce items that not only fulfill a function but also adjust and operate better in response to changing environmental conditions highlights the technology's potential to contribute to a more sustainable future. Unquestionably, 4D printing has an opportunity for growth, but difficulties still exist. The need for standardization, material constraints, and scalability concerns are some of the topics that require ongoing research and development. Unlocking the full potential of 4D printing and guaranteeing its smooth incorporation into our daily lives will depend on addressing these issues. The prognosis and potential applications of 4D printing ultimately point to a future filled with excitement and anticipation. This is a dynamic and ever-evolving journey where every step forward pushes the envelope of what is possible. As 4D printing develops into a critical component of the upcoming industrial revolution, its transformative potential offers hope for a day when the things around us are no longer just inanimate artifacts but rather living, breathing things that can intelligently respond to the intricate and constantly shifting needs of our environment.

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Declaration of Competing Interests

The study's findings, according to the authors, would not have been impacted by any financial or personal conflicts that they are aware of.

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