Human-Material Interaction Enabled by FFF 4D Printing

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Abstract

This review delves into four-dimensional printing (4DP) through fused filament fabrication (FFF) and its implications for human-material interaction (HMI). FFF 4DP's emergence in HMI represents a nascent and evolving concept worthy of deeper exploration. The article introduces FFF 4DP's fundamental principles, methodologies, materials, and associated benefits and challenges. Its primary focus is the intersection between FFF 4DP and HMI, investigating the potential of employing FFF 4D printed objects as interactive interfaces. Various HMI scenarios are examined, including applications in soft actuators, smart toys, household devices, smart consumer products, 4D textiles, and customizable wood-based items. Moreover, the article discusses the current state-of-art and development in the field, highlighting notable projects that integrate FFF 4DP into HMI to advance environmental sustainability. It also identifies key challenges/limitations requiring attention for the widespread adoption of 4DP in HMI applications. This work offers an in-depth analysis of FFF 4DP within the HMI context, underscoring its potential to transform human interactions with machines and smart devices. It introduces innovative features for dynamic and adaptable interfaces, promising to revolutionize user experiences. The article serves as a valuable resource for researchers, practitioners, and designers interested in exploring the exciting possibilities of FFF 4DP in the realm of HMI.

TOC: This review explores 4D printing using fused filament fabrication and its impact on human-material interaction. It covers fundamental principles, methodologies, materials, and applications in soft actuators, smart toys, household devices, textiles, and wood-based items. It highlights current advancements, emphasising environmental sustainability. Serving as a valuable resource, it addresses challenges for widespread adoption, making it essential for researchers, practitioners, and designers.

Keywords: 4D printing; Human-material interaction; Fused filament fabrication; Soft actuators; Shape memory polymer

1. Introduction

1.1. *Overview*

The development of four-dimensional (4D) printing (4DP) can be attributed to the progress made in three-dimensional (3D) printing (3DP) techniques [1,2]. The process of layer-by-layer

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printing involves utilizing computer-aided design (CAD) to fabricate various structures, ranging from simple to intricate, with precise control under the supervision of a computer [3]. Integrating active materials with 3DP techniques and utilizing suitable mathematical modeling and sequential energy stimulation makes it possible to alter the structure of the printed objects, transitioning them into different shapes [4-6]. Compared to 3DP, 4DP offers numerous advantages, including the rapid development of smart and multi-materials, multifunctional objects and structures that better fit with their surrounding environment [7,8].

At present, 4DP has the capacity to produce a diverse array of objects that surpass the capabilities of traditional 3DP [9]. This innovative technology enables the transformation of a material's shape by utilizing 3DP tools and external stimuli from the environment [10]. The demonstrated evidence showcases that when smart materials are combined with 3DP techniques, along with external stimuli and/or environmental factors, a straightforward 3D structure has the capability to evolve into a more intricate structure over time [11]. The incorporation of these functional components directly into the materials eliminates the need for complex mechanical drive parts within actuation systems. Consequently, this approach reduces the number of required components, simplifies assembly processes, and minimizes production costs [12]. The procedures include single-step printing, cost-effectiveness (especially for small production lots), high-definition print surfaces, minimal material wastage through recycling of excess feed material, elimination of solvent interference, and reduced post-processing steps compared to conventional manufacturing techniques [13].

This technology integrates key features such as repeatability, reproducibility, and controllability of 3DP [14]. It also supports technical advancements in areas such as modeling novel 3D structures. The advantages have positioned 4DP as a highly sought-after technology in engineering [15]. Its capabilities have continuously expanded the boundaries of the design world, making it an increasingly popular choice. Recent demonstrations have shown that self-folding techniques can greatly expedite 3D object prototyping by reducing printing time and material consumption by approximately 60% to 87% [16,17]. Furthermore, shape-changing characteristics enabled by stimuli-responsive materials can be utilized to conserve space during storage and transportation [18].

Presently, the predominant focus of 4DP research and review revolve around biomedical and medical applications [19-21], soft robotics [22,23], electronic devices [24], wearable devices [25], construction [26], dentistry [27], and agriculture [28]. While there is a significant body of literature on 4DP, a dearth of research and review focused specifically on fused filament fabrication (FFF) 4DP of human-material interaction (HMI) for end-use products remains. The interaction between humans and 4DP in the realm of household devices, fashion design, daily construction, toys, gadgets, and wearable devices has the potential to revolutionize everyday living. With the integration of 4DP, domestic gadgets can become more adaptive, responsive, and personalized to individual needs. Imagine a kitchen appliance that adjusts its shape and functionality based on the specific culinary preferences of each family member. 4DP enables the creation of domestic tools that can morph, transform, deploy, and reconfigure themselves to optimize space, enhance usability, and improve efficiency [29]. Whether it's furniture that adjusts to provide optimal comfort, smart storage solutions that adapt to changing needs, or home automation systems that seamlessly integrate into our daily routines, the HMI in household devices paves the way for a more intuitive, personalized, and convenient living environment.

This review article underscores the significance of design principles that facilitate the development of eco-friendly 4D-printed products, emphasizing reduced material consumption and waste. The authors specifically focus on the qualitative approaches 4DP of HMI and explore FFF features and capabilities. FFF 4DP holds great potential for devices related to humans due to several advantageous features [30,31]. Firstly, FFF 4DP enables the production of customized and personalized objects that can be tailored to specific products. This flexibility allows for the creation of unique devices that perfectly fit individual requirements, promoting enhanced user experience and satisfaction. Additionally, FFF 4DP offers cost-effective manufacturing as it eliminates the need for complex tooling and moulds typically associated with traditional manufacturing processes [32]. This affordability makes it accessible to a wider range of households, democratizing the production of tailored devices. Moreover, FFF 4DP allows for the integration of multiple functionalities within a single printed object. This enables the creation of smart devices that combine various features and capabilities, enhancing convenience and efficiency in everyday tasks. With its ability to rapidly prototype and iterate designs, FFF 4DP empowers households to quickly adapt and respond to changing needs, ensuring continuous innovation and improvement in household devices.

Figure 1 provides a summary of the focus of this review article, highlighting the utilization of FFF 4DP for creating consumer goods. The article begins by introducing the concept of 4DP and delving into the properties of shape memory polymer (SMP) materials. These SMPs exhibit a thermal and mechanical response when subjected to repeated cycles of heating and cooling, a topic that will be further explored in subsequent sections. The diagram of the FFF printer, the primary tool for producing 4D-printed items, is also presented. These printed objects can be activated by various stimuli, as depicted in the illustration. Finally, the review article showcases the practical applications of these products, which represent the main objective of the study.

Furthermore, the materials utilized in FFF, such as polylactic acid (PLA), offer the advantage of being non-toxic [33]. This characteristic ensures that devices created through FFF 4DP are safe to use and handle in domestic environments. The non-toxic nature of PLA makes it suitable for a wide range of applications [34] This feature not only promotes user safety but also adds convenience, as household members can easily handle and interact with 4D-printed objects without concerns about potential harm. The accessibility and user-friendly nature of non-toxic materials in FFF 4DP contribute to the overall suitability and practicality of 4D-printed devices created through this technology. The paper initiates by addressing the significance of 4DP in the context of advancing consumer product development. It then delves into the exploration of 4D-printed products in daily life based on specific applications. Specific examples highlight the suitability of smart products, and their future growth potential is assessed. Notably, the evaluation of 4DP in smart devices is highlighted. Furthermore, the article explores the potential of 4DP techniques for end-used products, which can help minimize waste production.

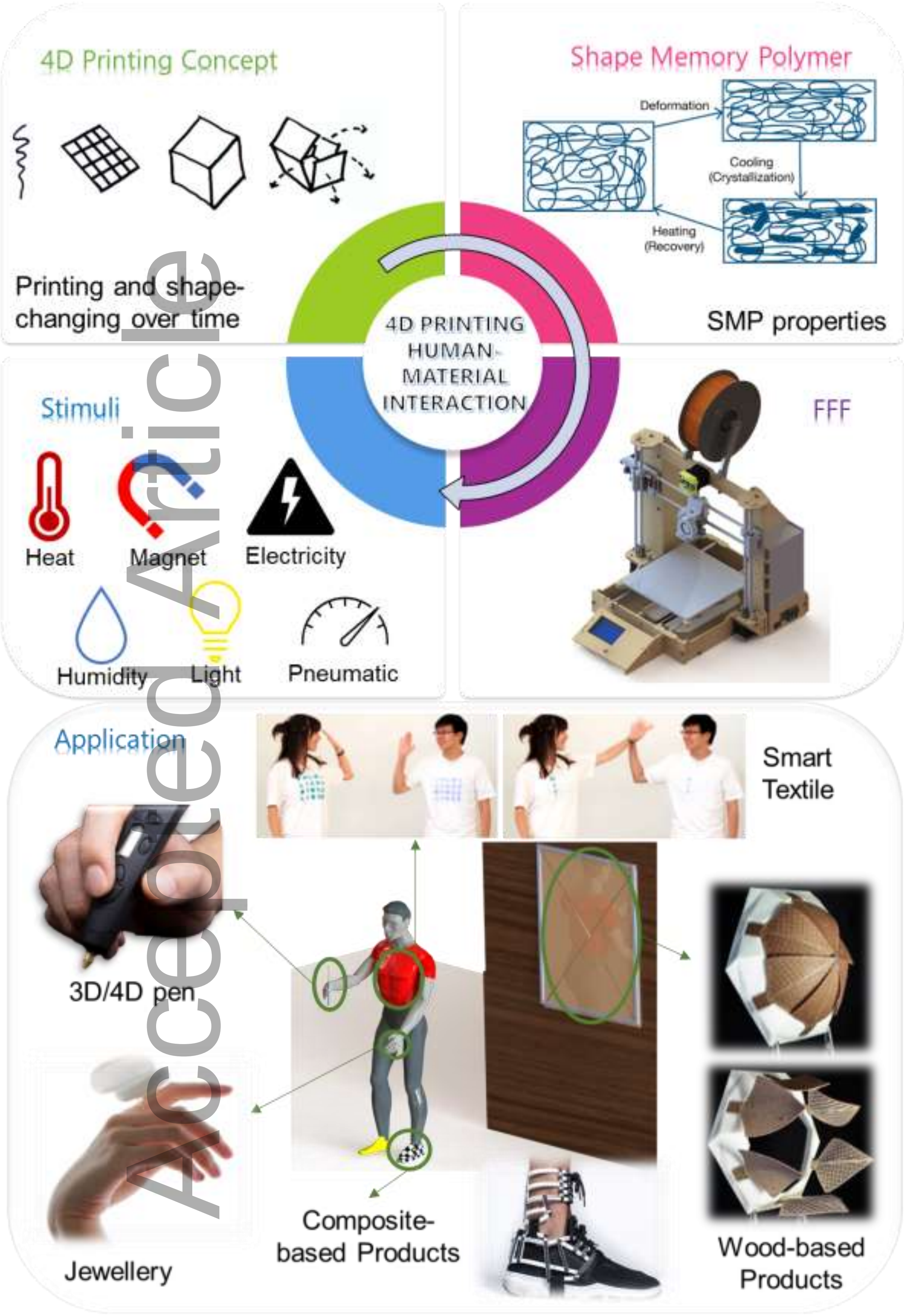

Figure 1. *An overview of the process of utilizing FFF 4DP and SMP to produce final products. The goal is to leverage the concept of 4DP, along with SMP material, and an FFF printer, incorporating diverse stimuli, to manufacture consumer products tailored for various applications. (Images in applications are obtained from [35-39]).*

1.2. Why 4D printing?

Despite living in a modern era, traditional manufacturing methods are still employed to create products for various industrial purposes [40]. However, these methods suffer from notable drawbacks such as material waste and high energy consumption rates. Consequently, there is a constant quest for innovative technologies to advance the field of 3DP and other intelligent manufacturing techniques [41,42]. Researchers have dedicated substantial attention to the field of 4DP in recent decades due to its widespread adoption across various industries and research fields [43]. **Figure 2a** illustrates the growth of publications on 4DP from 2012 to 2022, retrieved from the Scopus database. The trend of slight increases continues, and there is a significant surge in publications from 2018 to 2022, indicating substantial growth in this area. Also, **Figure 2b** presents the top 10 most productive authors based on the article frequency data retrieved from the Scopus database in the field of 4DP from 2012 to 2022. **Figure 2c** presents the expanded subject categories in which 4DP research is conducted. This analysis reveals the percentage of 4DP in various domains. Materials Science and engineering emerge as the most prominent subjects with significant contributions to 4DP research. Further, **Figure 2d** depicts the contributions of different countries in the field of 4DP, with China leading in terms of the highest share of research contributions.

The information provided offers valuable insights into the growth of 4DP technology, which is driven by its distinctive characteristics that contribute to the reduction of material waste [44]. The field of 4DP has garnered significant interest from various sectors. It has been projected that the market value of 4DP will reach USD 62.02 million in 2019 and is expected to grow to USD 488.02 million by 2025 [45-47]. The self-actuation and self-folding capabilities of 4DP offer advantages such as accelerated prototyping and reduced material consumption for 3D objects. This technology holds great promise for enhancing manufacturing processes, enabling faster production cycles, and optimizing material usage in various industries. The data highlights the increasing adoption and research efforts dedicated to 4DP, emphasizing its potential to revolutionize manufacturing processes and address sustainability challenges. The findings suggest that 4DP has gained significant attention as a viable alternative to conventional manufacturing techniques, sparking interest and investment in its development and application like soft and/or locomotion robots. As this technology continues to advance, it has the potential to reshape industries, promote environmental sustainability, and pave the way for innovative design and manufacturing approaches [48].

Moreover, the ability of 4D-printed objects to undergo self-shape-morphing in dynamic configuration areas has significantly reduced the need for external intervention, such as human involvement and the use of mechanical setups [49]. This advancement allows for the controlled transformation of shapes, including self-actuation, self-folding, self-assembling, self-decision-making, and self-responsiveness to external stimuli [50,51]. The continuous advancements in manufacturing processes have propelled the evolution of 4DP from a design-focused approach to a manufacturing perspective. This shift has paved the way for successful applications in stimulus-responsive systems. The reusability of 4D-printed objects has the potential to enhance the circular economy cycle of polymers, alloys, and composites by minimizing material waste [52,53]. Through the mutual integration of topology optimization techniques in 3DP, the material utilization rate can be reduced by up to 70%. This means that a significant portion of the materials used in 4DP can be recycled and reused, contributing to a more sustainable and resource-efficient approach to manufacturing [54]. This review aims to examine the existing research conducted in areas related to household products, focusing on identifying the challenges, gaps, and potential applications of

4DP in these domains. By exploring the current body of work, we seek to shed light on the opportunities and limitations of integrating 4DP technology into household-related contexts. This analysis will provide insights into how 4DP can be effectively utilized in new areas, contributing to the development of innovative solutions for domestic environments.

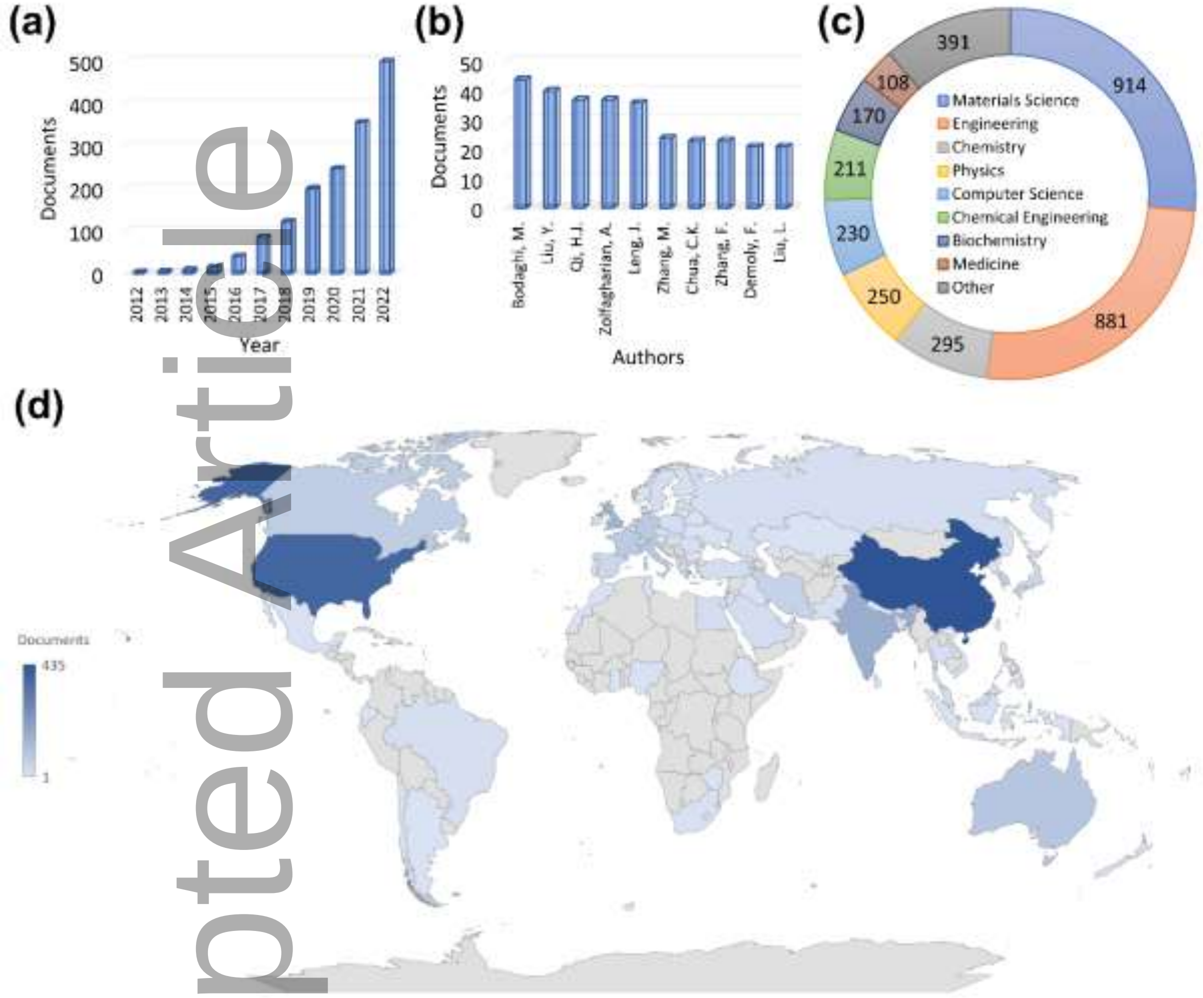

__Figure 2.__ Images illustrate various aspects of the 4DP field: (a) the increasing number of publications, (b) the most prolific authors, (c) the application areas where 4DP has been employed, and (d) the countries contributing to published articles in the 4DP field.

1.3. 4D Printing Concept

The objective of this paper is to explore the synergy between humans and the 4DP structure, starting with fundamental principles and advancing towards practical applications. The significance of this research lies in identifying components that have the potential to minimize material waste and can be utilized in diverse applications as end-user products like the fashion industry, wearable devices, and aesthetic products [55]. This review centres around FFF printers and the subsequent steps involved after acquiring one's first 3D printer. In essence, these machines function by melting plastic filament and depositing it layer by layer to construct the desired object [56]. As their cost decreases and usability improves, it has become relatively easy to find high-quality 3D printers for a cheap price. At this price point, a 3D printer can be considered one of the most versatile pieces of equipment for a laboratory, offering adaptability across various fields of study [57]. However, the concept of 4DP should be discussed first to find out its capabilities for these applications.

The main differentiation between 3DP and 4DP technologies lies in the incorporation of the fourth dimension, which is time [58]. Smart materials are utilized as precursors, resulting in the creation of intelligent and dynamic structures. Additional distinctions in 4DP include characteristics such as bistability and shape memory effect (SME) observed in smart materials [59]. These factors contribute to the unique capabilities and functionalities of 4D-printed structures. Among the various characteristics, the SME is the most extensively utilized feature in 4DP. Its versatility in a wide range of applications is evident from the considerable academic focus dedicated to shape-memory materials over the past five years [60]. This highlights the significance and potential of shape-memory materials in advancing the field of 4DP.

By utilizing 4DP, the design and manufacturing of intricate actuating parts can be streamlined. Currently, various 4DP technologies are being employed, including stereolithography (SLA), selective laser sintering (SLS), FFF, digital light processing (DLP), material jetting (e.g., PolyJet), selective laser melting (SLM), direct ink writing (DIW), and electron beam melting (EBM) [61]. Design and production using either of the mentioned methods offer several advantages. Nevertheless, this study will focus on reviewing FFF due to its advantages for specific end-use products. The aim is to examine how FFF 4DP technology can be effectively utilized in the context of household gadget production and explore its potential benefits in this particular domain. Moreover, there is accessibility to various smart materials for 4DP, including SMPs and their composites, shape memory alloys (SMAs), liquid crystal elastomers (LCEs), dielectric elastomers, and hydrogels [62-67]. These materials are recognized for their ability to recover their original shape even after experiencing quasi-plastic deformation under specific stimuli. SMPs can undergo a programming step that enables them to undergo significantly more complex and adaptable shape transformations [68].

In 4DP, the transformation of shape is achieved by programmed spatially controlled anisotropies, which are created using 3DP techniques. These techniques typically involve the use of multilayer shapes with different components of materials, varying crosslink densities, percentages of weight, and alignments of diverse additives and fillers [69]. These factors contribute to the desired shape morphing pattern in 4DP. For instance, SMPs can be programmed to flatten into a compact surface, facilitating easier post-treatment, transportation, and storage [70]. Smart materials are multifunctional materials that possess the unique capability to remember their original shapes and can revert back to those shapes even after undergoing temporary deformation. This paper presents a perspective review of the emerging field of 4DP using FFF, which is a popular and easily accessible form of 3DP. The main focus is to provide an overview of the applications of FFF 4DP in the context of household products. The research work aims to educate and inform individuals already familiar with FFF 3DP about the additional capabilities and potential offered by 4DP. It highlights the innovative use of FFF-printed active materials, showcasing the transformative possibilities and functional advancements that can be achieved through 4DP.

2. Fused Filament Fabrication

2.1. Concept of SMP

SMPs possess a distinctive property known as the SME, which allows them to undergo predictable shape changes upon command [71]. This characteristic relies on the interplay between two systems present within the polymer: net points and switching segments. The SMP can be programmed into specific shapes and subsequently recover its original shape when stimulated, typically through the application of heat. The net points serve as the memory component of the polymer network, continuously working to restore the SMP to its initial shape. These net points often manifest as higher levels of polymer entanglements or crystallites, contributing to the SME of the SMPs [72].

The switching segments in SMPs play a crucial role in maintaining the polymer in its programmed shape [73]. These segments typically possess a lower degree of entanglement compared to the net points. When the triggering stimulus is applied to the polymer, the switching segments are the first to become mobile. This mobility allows the SMP to undergo the desired shape change and exhibit its SME [74]. The ability of the switching segments to transition from a fixed state to a mobile state is essential for the successful implementation of the shape memory behaviour in SMPs. The SME of SMPs enables them to be programmed into temporary shapes and subsequently recover their original shape [75]. In this context, there are two important indices employed to characterize the behaviour of SMPs. These indices are the shape recovery index and the shape fixity index [76]. The shape recovery index quantifies how effectively an SMP can return to its initial shape after the stimulus is removed. On the other hand, the shape fixity index measures the ability of a polymer to retain its programmed shape. These indices are crucial for comparing, characterizing, and selecting suitable SMPs for specific applications, providing valuable information for understanding and leveraging the shape memory properties of these materials.

The determination of the shape fixity index in an SMP involves the process of programming a rectangular sample to an elongated shape and subsequently measuring the residual stress after removing the stimulus [77]. On the other hand, the shape recovery index is calculated by dividing the residual stress by the programmed/anticipated stress, expressed as a proportion. Also, the calculation of the shape recovery index in an SMP involves the process of recovering a programmed rectangular sample and measuring the remaining stress. The shape fixity index, on the other hand, is determined by calculating the proportion of the recovered strain, which is the difference between the programmed strain and the strain after recovery. This unique characteristic makes them highly suitable for applications requiring dynamic and responsive structural changes. In the realm of 4DP, the characteristics of mentioned materials used in 3DP can undergo significant variations in response to external stimuli or environmental conditions. These stimuli encompass a range of factors, including heat [78], electricity [79], magnetic fields [80], light [81], water [82], pH [83], and pneumatic [84]. With the help of these stimuli, it is possible to activate the actuator for shape morphing or achieving the desired shape.

The utilization of the FFF technique extends to 4DP of diverse polymers and composite materials. Among the frequently employed materials, PLA and polyurethane (PU) stand out. PLA is a thermoplastic with semi-crystalline properties, making it a SMP [85,86]. PLA and PU possess the ability to undergo shape changes based on programmed strain-temperature protocols, as shown in **Figure 3a** [87]. For the hot programming process, FFF is employed to shape the printed part. Then, the sample is subjected to a temperature higher than its glass transition temperature (T_g), causing it to acquire a rubber-like consistency. The load is then placed on the sample, which is allowed to cool down and assume a temporary shape. Subsequently, the sample is reheated up to return to its original form. Subsequently, a cold programming process is utilized to transform the printed part into a second temporary shape. During the cold programming process, the printed structure is initially cooled down to a strain/stress-free glassy state and then deformed through external loading. Once the loading is removed, a residual plastic strain is generated, leading to the formation of the second temporary shape [88]. Finally, the sample undergoes heating to restore it to its original form. The printed structure encompasses both built-in inelastic strains and plastic strains induced by the hot and cold programming processes, respectively. Previous research studies have extensively documented the application of SMP in the FFF technique [89,90]. This utilization of SMP in 4DP introduces exciting possibilities in numerous HMI applications.

2.2. FFF process

FFF stands out as a highly popular 3DP technology and is widely employed in industrial settings for the manufacturing of parts, prototypes, tools, and dies [91]. The rapid progress of FFF 4DP has resulted in its quick acceptance as a method for manufacturing diverse parts, demonstrating its potential for a wide range of applications [92-95]. Desktop FFF 3D printers have gained widespread use in educational institutions, such as schools, as well as in libraries, design offices, and even home workshops [96].

FFF is a 3DP technique that utilizes the extrusion technique. The FFF printer and its extruder components are briefly illustrated in **Figure 3b**. With this technique, a filament is conveyed to the nozzle using a pinch roller, which is controlled by either an electric or hydraulic motor [97]. Afterwards, the filament is heated until it transforms into a liquid state and is propelled out through the nozzle with the assistance of a mechanical force. Subsequently, the material is placed onto a platform, forming a two-dimensional (2D) layer. This sequential process is repeated, leading to the formation of a 3D structure. The polymer substance that is extruded and deposited experiences solidification through diverse mechanisms, such as crystallization, reorientation or rearrangement of chains, restoration of non-covalent bonds, or chemical cross-linking [98].

The movement and extrusion of the filament along the desired shape are controlled based on instructions from a G-code file. The 3D printer interprets the commands within the G-code to produce each layer until the completion of the part. To generate the G-code, a CAD/computer-aided manufacturing (CAM) program is used. Initially, a 3D model or CAD file is created, which is then converted into a universal file format known as a stereolithography (STL) file. This STL file is subsequently processed by a CAM program, which includes a slicer that divides the STL file into individual layers and generates a tool path for the 3D printer to follow.

Product quality improvement is a constant pursuit in all manufacturing processes. In the case of FFF, numerous parameters play a crucial role in determining both the surface quality and mechanical properties of the produced items [99]. Consequently, the key to attaining high quality lies in optimizing the critical factors to minimize errors throughout the printing process. It is crucial to select the most suitable conditions to prevent defects and errors during the procedure [100]. The final products in FFF printing are significantly influenced by several main parameters, including filling pattern, nozzle temperature, bed temperature, nozzle diameter, build orientation, layer thickness, infill density, extrusion speed, printing speed, room temperature, and bed adhesion strategy [101-103]. These parameters play a crucial role in determining the quality and characteristics of the printed objects [104].

Moreover, in the field of HMI, kinematic mechanisms have played a crucial role in creating tangible, dynamic interfaces and objects. However, designing and fabricating these mechanisms poses challenges due to the complexities involved in spatial structures, step-by-step assembly processes, and the instability of joint connections caused by inevitable matching errors between separated parts [105]. By implementing and developing FFF 4DP along with the utilization of SMPs, it becomes feasible to overcome the challenges and issues associated with traditional FFF printing methods [106]. This combination allows for enhanced control and manipulation of the printed objects, resulting in improved printing procedures and outcomes [107]. SMPs exhibit the unique ability to recover their original shape upon exposure to specific stimuli, enabling the creation of complex and dynamic structures using FFF 4DP [108]. Consequently, this approach offers a promising solution to address the limitations and enhance the overall printing experience with the FFF technique.

Meanwhile, the potential impact of 3DP on toys, gadgets, and end-use products, highlighting significant cost savings and the ability to create novel products through open-source distributed manufacturing, was examined, and the importance of 3DP as household devices was evaluated [109-111]. Integrating FFF 4DP technology with humans opens up exciting possibilities. As an example, toys can be designed to have dynamic features or interactive elements that activate and transform over time. For example, a toy car may initially be printed in a compact form but can self-assemble into a larger, more intricate design. This not only enhances the play experience but also introduces an element of surprise and novelty for children. Furthermore, 4DP allows for the creation of daily products or construction with customizable and adaptive features. Parts of a machine can be designed to respond differently based on external factors, enabling a personalized and interactive play experience. Also, children can have the freedom to modify and shape their toys according to their preferences, fostering creativity and imagination.

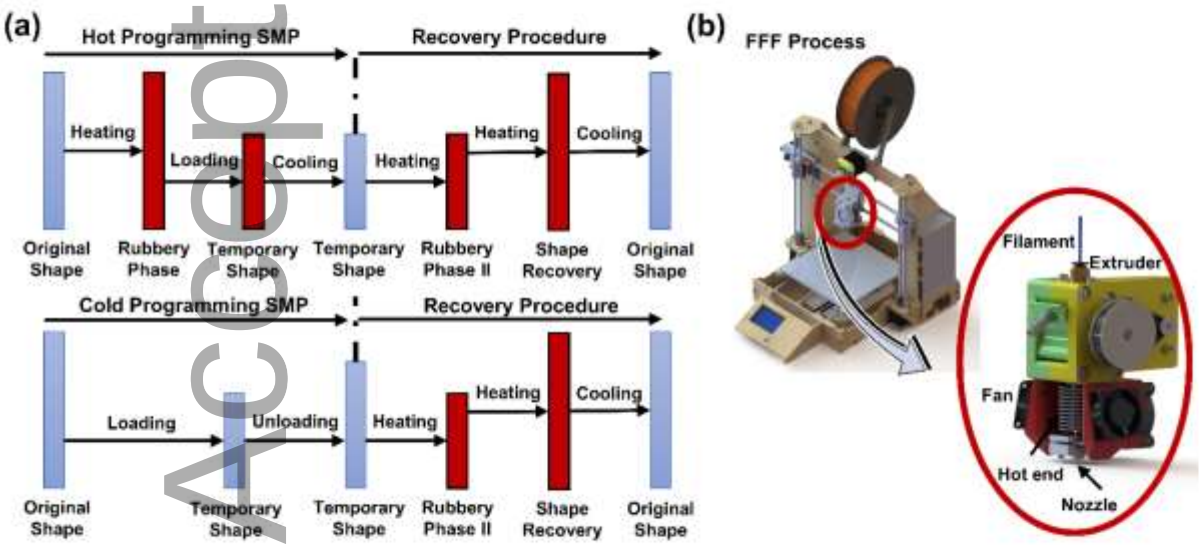

Figure 3. (a) The process of hot and cold programming of SMP material for the 4DP aspect and the subsequent activation of the actuator, and (b) the components of an FFF 3D printer including its nozzle.

3. FFF 4DP

3.1. Consumer Products

3DP and 4DP are emerging technologies that hold great promise for the future of consumer goods [112]. With 4DP, consumer goods can be designed to self-assemble, self-repair, or even change their functionality over time. Imagine a pair of shoes that can adjust their fit based on the wearer's foot movements, or a furniture piece that can morph its shape to accommodate different seating arrangements. The possibilities are endless, and 4DP has the potential to revolutionize the way we design, manufacture, and interact with consumer goods, offering us a glimpse into a future of intelligent and adaptive products.

As an example, from Prof. Ishii's research group at MIT, Wang et al. [113] introduced A-line, a 4DP system designed to create and produce 2D-to-3D structures using simple linear elements. A-line capitalized on the distinctive characteristics of thin lines. These properties included their suitability for compliant mechanisms and their ability to navigate narrow spaces, self-deploy, or self-lock on-site. A-line incorporated a novel method for controlling bending angles in up to eight directions for a single printed line segment, employing a single type of thermoplastic material. To facilitate the design and manufacturing of various A-line structures, a software platform was developed, offering support for design, simulation, and tool path generation. Line sculpting, compliant mechanisms, self-deploying structures, and self-locking structures were developed as applications of this study. Also, various end-use products were developed through this technique which could be used in daily life. In another study, Wang et al. [114] proposed an efficient and cost-effective 4DP approach that utilized multispeed FFF technique (see **Figure 4a**). This approach enabled the incorporation of graded built-in strain into flat precursory patterns, facilitating rapid and customizable shapeshifting upon exposure to heat. By systematically optimizing the printing parameters, they could directly construct complex 3D structures from flat precursory patterns with both flexibility and high fidelity. The researchers conducted experiments by printing PLA samples at various printing speeds. These samples were then subjected to heating to trigger shape transformations and achieve complex shapes. This method significantly reduces both the construction time and process complexity associated with 4DP.

Morphing materials offer exciting opportunities for novel interactions and fabrication methods by utilizing the dynamic behaviors of the materials. Zou et al. [115] presented a novel approach to direct 4DP using a single-material system that enables the transformation of continuous bilayer plates into doubly curved and multimodal 3D shapes, which could also be locked into position after deployment (see **Figure 4b**). They developed an inverse-design algorithm that integrates extrusion-based 3DP of a single-material system to directly shape a printed sheet (2D) into complex 3D geometries while ensuring shape locking. The inverse-design tool incorporated localized shape-memory anisotropy during the process, enabling the determination of processing conditions for achieving the desired 3D morphed geometry. This approach held promise for a wide range of applications, including biomedical devices, deployable structures, smart textiles, and pop-up origami/kirigami structures, utilizing conventional extrusion-based 3DP. Also, Gu et al. [116] focused on the morphing of continuous double-curvature surfaces and surface textures in Geodesy. They proposed a unique toolpath that involves printing thermoplastics along 2D closed geodesic paths, resulting in a surface with raised continuous double-curvature tiles when exposed to heat. They also explored more complex geometries composed of a network of rising tiles, which created surface textures. The paper describes both the design components and the computational pipeline involved in this approach and includes various examples of geometric shapes that have been successfully printed.

Moreover, Yang et al. [117] developed SimuLearn, a data-driven approach that combined finite element analysis and machine learning. By leveraging this technique, they could create morphing material simulators that achieve real-time performance (0.61 seconds) with a high level of accuracy (97%). They applied this method to mesh-like 4D-printed structures to demonstrate their capabilities (see **Figure 5a**). They developed prototype design tools that showcased the design workflows and spaces made possible by employing a fast and accurate simulation method. By placing this work in the context of existing literature, SimuLearn may be a timely and valuable addition to the human interaction CAD toolbox. Its implementation has the potential to significantly advance the utilization of morphing materials in various applications. Nevertheless, it is crucial to simplify the implementation of this system so that users can easily utilize it with a basic understanding.

Furthermore, it is possible to create and combine electronic circuit boards with consumer products that are manufactured using 4DP techniques. The integration of circuit boards into 3D shapes is a common requirement in manufacturing nonplanar electronics. Traditional methods involve embedding rigid circuit boards in cavities within the shapes, while alternative approaches such as 3DP or layer lamination require costly processes and materials. Moreover, these methods often face challenges when dealing with complex geometries, such as twisted surfaces or local minima. Wang et al. [118] developed MorphingCircuit, a workflow that combines design, simulation, and fabrication to integrate electronic functions with forms using 4DP. This approach offered benefits such as reduced costs, shorter production times, and minimized electronic waste. The process began by printing a flat substrate and assembling functional electronics on it. When triggered by external heating, the flat structure self-morphed into a predetermined 3D shape, as shown in **Figure 5b**. It took 10 min for the Christmas tree to be fully activated. The time taken to simulate the Christmas tree design is about 71.8 times less than the combined duration of its printing time and triggering time. The comprehensive pipeline for fabricating 3D electronics encompasses design, simulation, fabrication, and transformation, aiming to inspire designers, researchers, and makers to create conformal electronics on complex substrate geometries that were previously challenging or even impossible to design or manufacture.

Also, Qin et al. [119] introduced ExoForm, a compact and customizable wearable material system that was semi-rigid. It featured self-fusing edges and could autonomously assemble itself on-demand, while also incorporating integrated sensing, control, and mobility. The ExoForm system was designed to be user-friendly and easy to wear using PLA and a circuit board. To demonstrate the effectiveness of ExoForm, they fabricated wearable braces using this method. They also conducted preliminary evaluations to assess the performance of ExoForm in practical applications. Through their work, they aimed to address the challenges associated with achieving customizable and mobile-friendly wearable support structures.

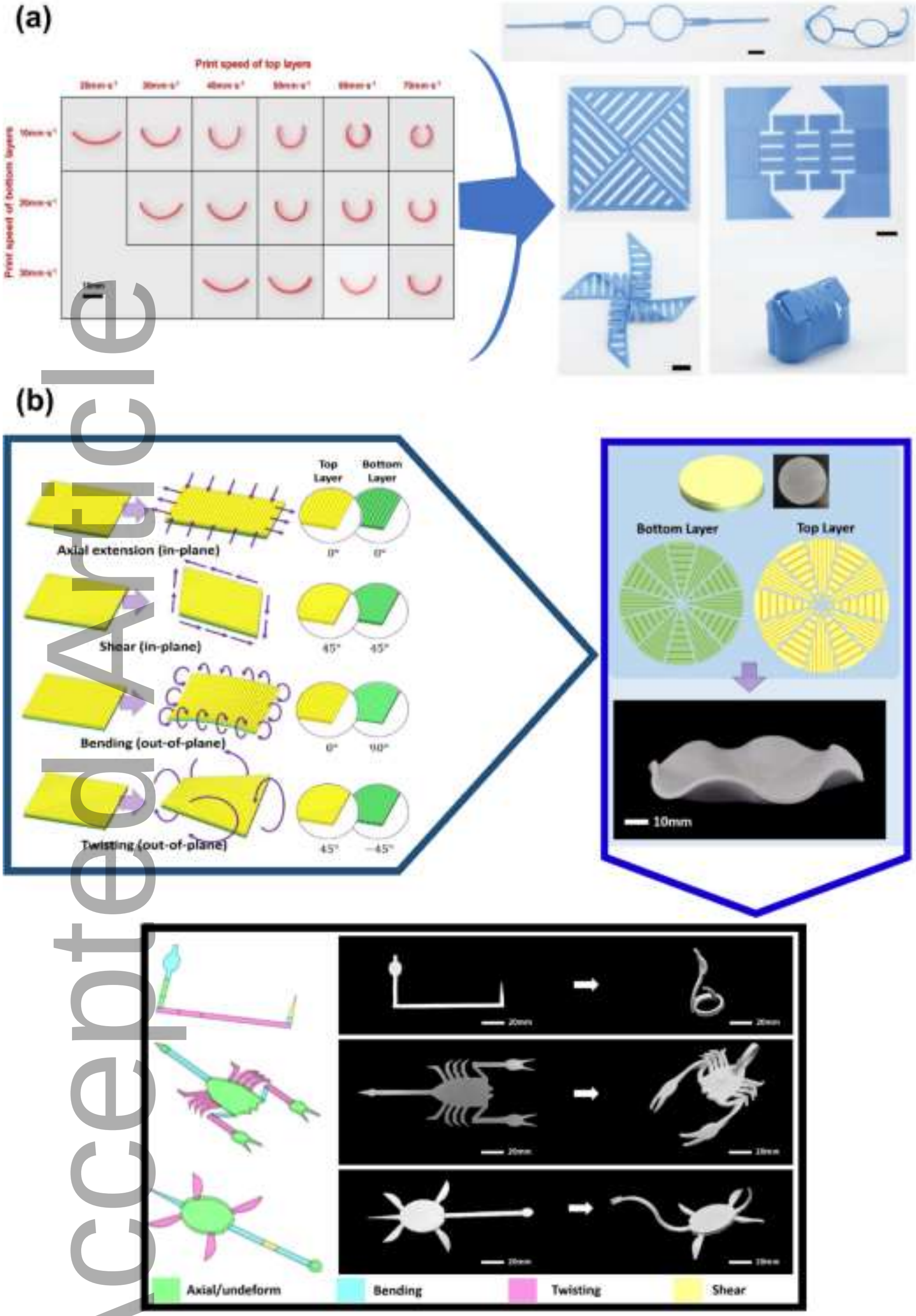

Figure 4. *(a) The PLA samples' profiles with initial dimensions of 30 mm × 5 mm × 1 mm. Various combinations of printing speed were employed during fabrication to develop spectacle frame, pinwheel, and house. (Scale bar: 10 mm) [114]. (b) There are four transformation modes associated with the direct 4DP of 2D bilayer plates. Additionally, an example of direct 4DP is provided, showcasing a wrinkled bilayer circular plate. Furthermore, additional examples of direct 4DP include a snake, a scorpion, and a plesiosaur, which exhibit multi-modal deformations encompassing in-plane axial and shear movements, as well as out-of-plane bending and twisting [115].*

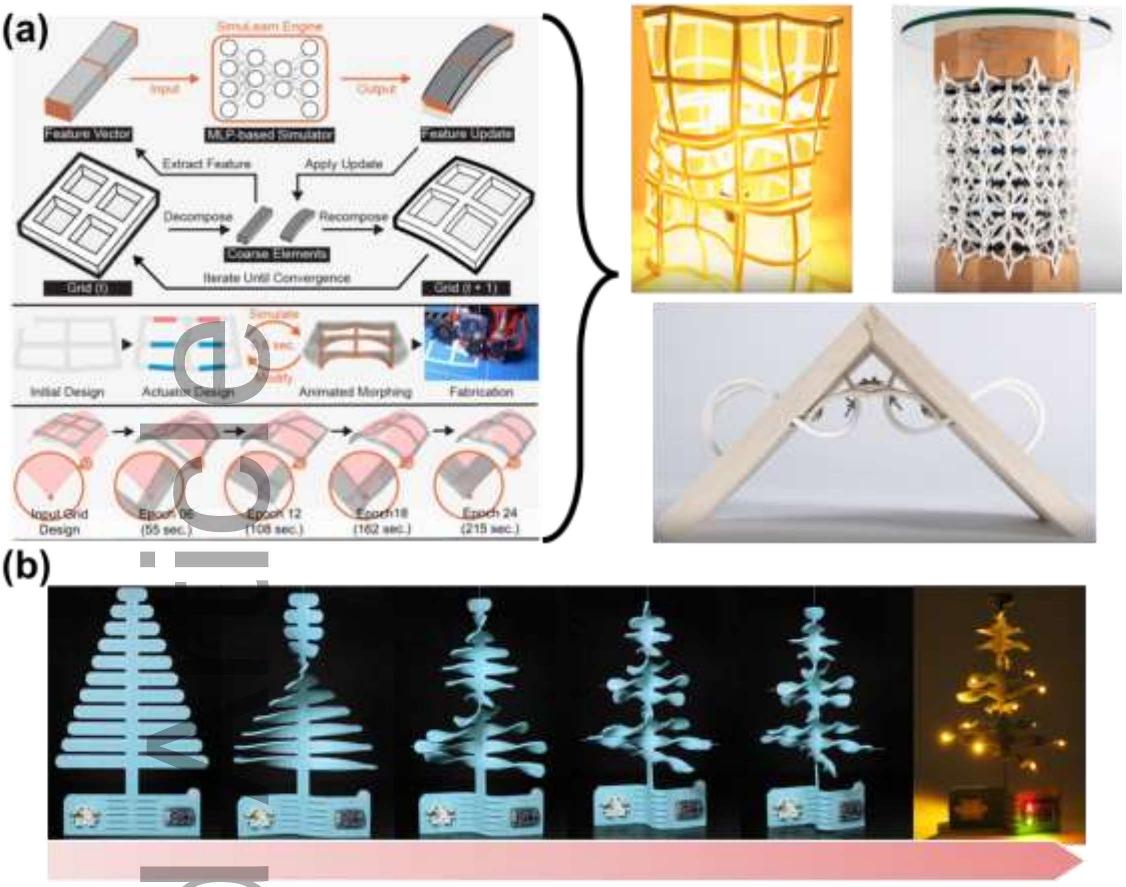

Figure 5. *(a) Image provides an overview of SimuLearn, highlighting its computational theme. It showcases how this tool facilitates rapid and accurate forward design iterations as well as inverse design optimizations. These workflows are particularly valuable for design spaces that require both simulation speed and precision, such as modularization (lampshade), material-driven parametric design (table stand), and interlocking mechanisms (decorative joinery) [117]. (b) The fabrication of the self-folding Christmas tree's twisted branches proves difficult when relying on conventional 3DP techniques. To overcome this challenge, the circuits and LEDs are first mounted onto a flat substrate before initiating the morphing process. This approach enables streamlined assembly and facilitates efficient transformation [120].*

3.2. Composite-based Products

The printed artefacts in FFF often exhibit structural weaknesses, and the design quality may be limited by less accurate material models and numerical simulations [121]. One approach to enhancing the structural strength of printed structures is through the utilization of composite and fiber-reinforced printing or the development of FFF printers. These composite materials incorporate SMPs with various additives such as glass fibers, nanohydroxyapatite, carbon fibers, carbon black, natural fibers, wood fibers, carbon nanotubes, ceramics, copper particles, and iron particles [47,98,122,123]. By incorporating reinforcing fibres into the printing material, the resulting printed artefacts exhibit increased strength and durability [124]. These additives serve a dual purpose: they not only reinforce and strengthen the SMPs but also act as an active medium that facilitates the shape-morphing ability [125]. Most polymer-based composites are made up of between 60% and 70% polymers as the matrix and between 30% and 40% of reinforcement material [126]. As an example, Yu et al. [36] proposed a composite structure design that combines two materials—PLA and carbon fiber-reinforced PLA—to enhance the structural strength of 4D printed artefacts. A comprehensive workflow was presented, which involved a series of physical experiments and dynamic mechanical analysis to characterize the materials. The accuracy of deformation induced by the triggering process was thoroughly validated through computational and experimental means. Several creative design examples were provided, showcasing the effectiveness of the workflow. The measured deformation accuracy was found to be at least 95%, with a confidence interval of (0.972, 0.985). The authors believed that the presented workflow played a crucial role in combining geometry, material mechanism, and design, and holds significant potential for diverse applications (see **Figure 6a**) [127].

Furthermore, the utilization of composite materials in the field of 3DP, specifically the FFF process, has gained significant popularity [128,129]. One commonly employed composite material in this context is PLA and its composites, which have found extensive applications across diverse industries [130]. These composite materials offer enhanced mechanical properties, improved durability, and increased functionality, making them ideal for the production of a wide range of products in fields such as engineering and consumer goods. The ability to print with composite materials opens up new possibilities for manufacturing intricate and customized objects that cater to specific industry requirements [131]. Wang et al. [8] incorporated thermochromic pigments as filler material in PLA composites produced through FDM technology, as illustrated in Figure 9(d). These pigments possess the capability to alter their color in response to thermal stimuli. The findings indicated that 4D-printed products, reinforced with thermochromic PLA, not only underwent shape transformations but also exhibited color changes. This characteristic could find applications in aesthetics or as a temperature signaling mechanism (see **Figure 6b**).

A new approach was developed by Lalegani Dezaki et al. [132] for encoding a wide range of shapes and forms using carbon black-filled conductive PLA and iron-filled magnetic PLA composite structures made of magneto-electroactive SMP materials, combined with sustainable FFF 4DP technology. These composite structures exhibited characteristics such as being electrically driven, remotely controllable, and having quick responsiveness (less than 2 seconds). They can repeatedly transition between various programmed temporary and permanent configurations, allowing for multiple designs within a single structure without wasting materials. FFF was utilized to create adaptive structures, enabling 1D/2D-to-2D/3D transformation through the application of a magnetic field. The benefits of these switchable, multi-stable structures include reducing material waste and minimizing effort, energy consumption, and enhancing efficiency, particularly in industries such as packaging (see **Figure 7a**).

Additionally, the utilization of FFF printers for manufacturing composite goods is extremely advantageous. In another research work, Cheng et al. [133] developed an ultraviolet (UV)-assisted FFF 4DP approach for producing elbow protector models using shape memory copolyester networks. Linear unsaturated copolyesters were synthesized, with PLA chosen as the hard segment for mechanical performance and printability. Poly(ε-caprolactone), known for its strong crystallizability, served as the switching segment. A functional coupling agent with double bonds was used to join these segments and facilitate the in-situ formation of a photo-crosslinking network during UV-assisted FFF printing. This process enhanced the bonding strength between layers and ensured good shape memory properties in the resulting objects. Three models with distinct Chinese characteristics were successfully printed, demonstrating an excellent 97% shape recovery ratio and 98% shape fixity (see **Figure 7b**).

Furthermore, personalized and patient-adaptable elbow protectors were developed, showcasing the robust applications of this approach. The UV-assisted FFF 4DP strategy holds significant potential for creating tailored treatment devices. Moreover, Nishihara et al. [134] developed a new method called Magashi. This innovative approach allowed users to design products in various shapes with intricate patterns using FFF-based food printing and baking (see **Figure 7c**). With this technique, when the printed food contains mesh patterns, it could transform into curved structures during the baking process. To achieve this, they optimized the ingredients, printing patterns, and thickness of the food material to control its drying process, causing it to bend either upward or downward when baked. In addition, they proposed several applications for creating shape-changing food and cutlery in different shapes, patterns, and curvatures, thereby expanding the creative possibilities in the realm of shape-changing food design [135].

The incorporation of developing materials, fiber-reinforced structures in 4DP, composite materials, and the use of UV-assisted devices have significant potential for enhancing the strength and reliability of printed objects. However, it should be acknowledged that the advancement of printers specifically designed for these applications is still in its nascent phase, and additional research and development are needed. One crucial aspect that requires attention is the reduction of costs associated with both 3D printers and the materials utilized, particularly for household devices [136-138]. At present, the utilization of UV-assisted and fiber-reinforced printing methods or the development of new materials or systems may result in higher expenses due to the added costs of fibres, materials, and specialized equipment required for handling and printing these materials. To promote the widespread adoption and accessibility of 4DP with these techniques, it is crucial to explore cost-effective solutions. Finding ways to reduce the overall expenses associated with UV-assisted and fiber-reinforced printing is essential to making this technology more accessible and widely adopted.

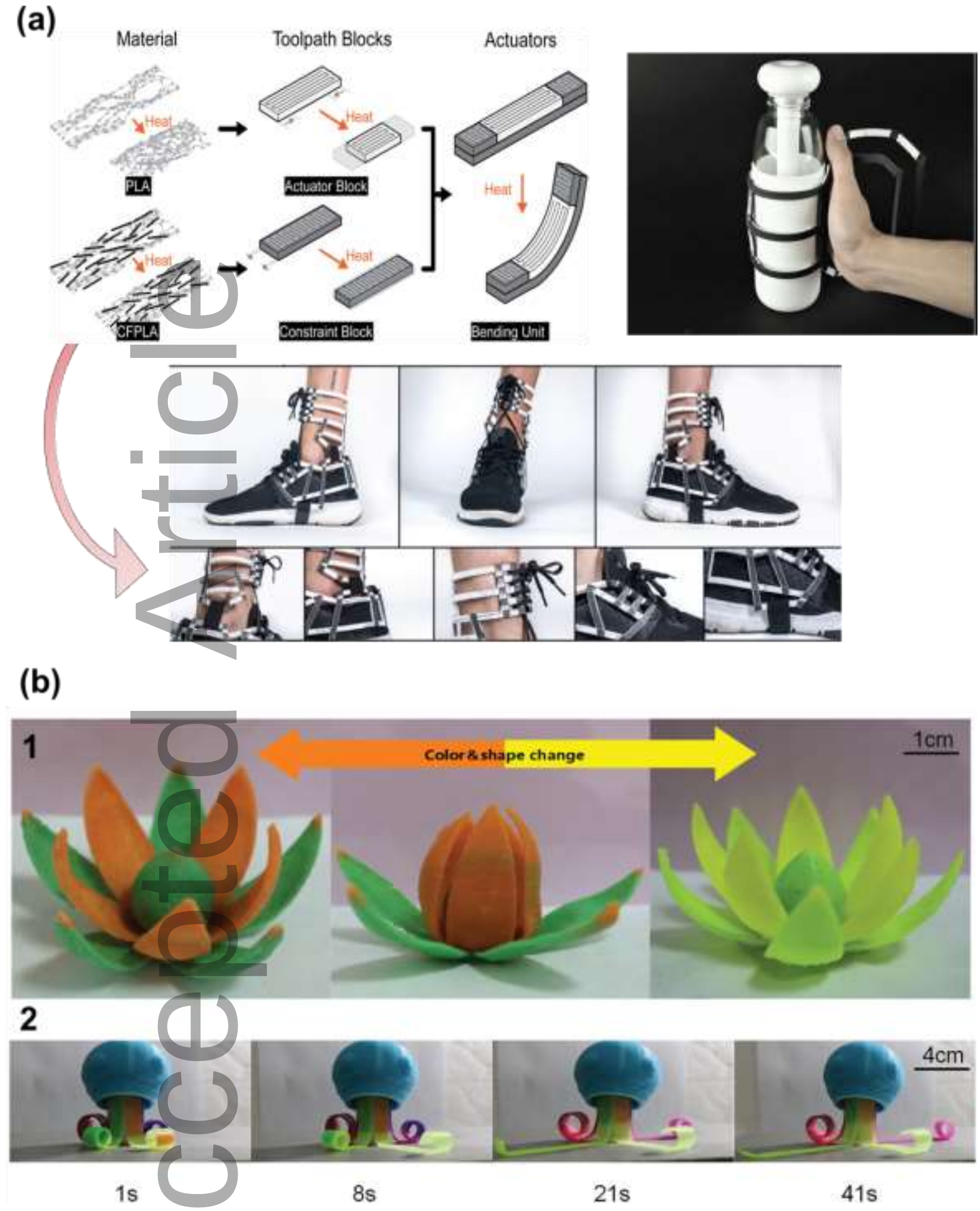

Figure 6. *(a) The concept of this study is the polymer chain arrangement. Additionally, there are anisotropic blocks that consist of two layers with different printing path directions: the actuator blocks (white) and the constraint blocks (grey). Furthermore, a bending unit is depicted, which includes the actuators (white) and constraints (grey). The design iteration of the bottle holder and the shoe supporter is developed as part of this study [36]. (b) 1. Using a multimaterial printer, a blooming and color-shifting flower is created. The green and orange flowers undergo a transition from a temporary bud shape to a vibrant yellow bloom. 2. Artificial octopus tentacles, initially curled, are systematically stretched out and adorned with various colors in sequence on a hot plate set at 80 °C. The distinct shape recovery speeds of each tentacle are achieved through careful design of print parameters, resulting in a dual-response matching effect [8].*

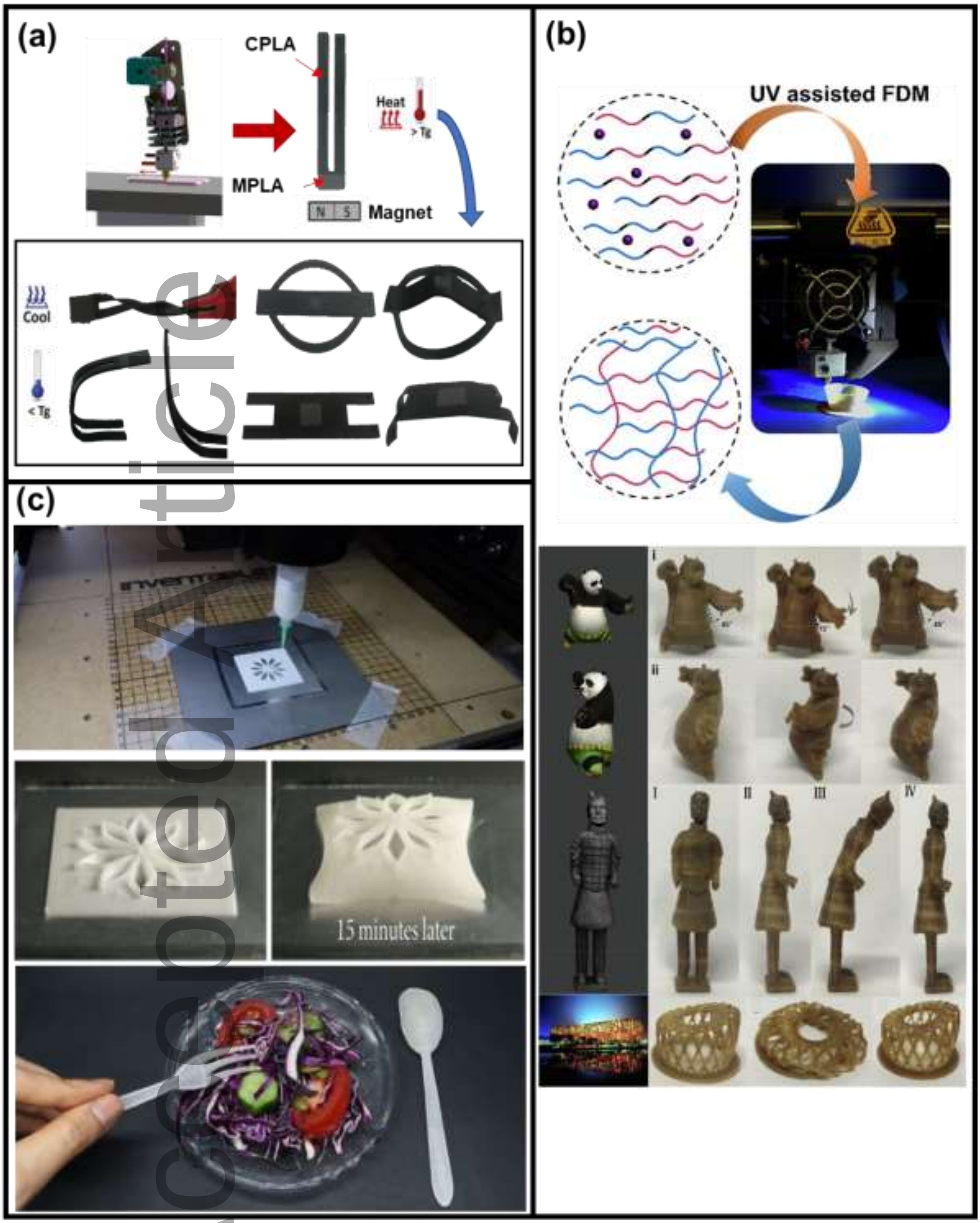

Figure 7. *(a) The concept of CPLA and MPLA 4DP in minimizing material waste within packaging [132]. (b) 4DP involves the fabrication of shape memory networks using a FFF-based 3D printer that is equipped with a UV lamp emitting a power density of 50 mW.cm^{-2}. The three different 4DP models using U-PLA4-PCL6 copolymer. The Kungfu Panda model showcases two actions in a shape memory cycle: vertical arm swinging (action I, front view) and horizontal arm swinging (action ii, side view). The Terracotta Warrior model is displayed in upright positions (I and II, front view and side view respectively), a bent position (III), and the recovered upright position (IV). The Bird's Nest stadium model is presented in its original state, a compressed state (middle), and the recovered state (right) [133]. (c) Process of printing material in 4DP rice flour paste. The printing bed containing the material is positioned inside the oven and heated to a temperature of 90 °C. The duration of the baking*

process varies based on the size and thickness of the print, typically ranging from 10 to 20 minutes. Once the material's bending movement is completed, the oven is turned off after a few minutes. To ensure proper cooling and prevent any residual humidity or heat from impacting the subsequent bake, the oven door is left open, and a fan is placed in front of it for approximately 10 minutes. The bottom image is the edible cutlery after printing and baking [135].

3.3. Pneumatic-based Products

Printed pneumatic actuation remains the predominant technology in the field of soft robotics due to its advantages such as lightweight design, quick response time, and ease of implementation [139]. The utilization of low-cost components like solenoids and diaphragm pumps makes pneumatic systems cost-effective. These robots incorporate fiber-reinforced actuators and soft pneumatic actuators, which consist of pneumatic networks [140]. These actuators exhibit high flexibility, safety, and the ability to undergo significant deformations. They also possess favourable power-to-weight ratios and can be produced at a low cost [141]. Pneumatic actuators can be activated using positive or negative pressures, with vacuum actuators being particularly suitable for situations with limited volumes [142,143]. Depending on their characteristics, printed pneumatic actuators are capable of various types of movements. The applications of actuators encompass areas such as minimally invasive surgery, rehabilitation, assistance for the elderly, HMI, and handling delicate materials [144,145]. However, there are challenges and limitations regarding the continuous supply of input power to maintain actuators in the desired position. Recent advancements in these actuators have focused on achieving consumer products such as gadgets, jewellery, and other products. Ang et al. [146] presented the design and preliminary investigation of a fully 3D-printed soft robotic hand exoskeleton, Print-it-Yourself (PIY) glove, for stroke patients. The PIY glove was fabricated with FFF using consumer-based 3DP technology to lower fabrication costs and allow patients to 3D print a rehabilitative and assistive device at home. The PIY glove used a novel, fold-based design of 3D-printed soft actuators to achieve bending motion in the fingers. Fabrication guidelines of the PIY Glove were laid out, and the characterization of the glove in terms of its range of motion and grip force was also presented. A control system that achieved control of the PIY glove was also described. This work paved the way for the implementation of printable pneumatics in real-world applications, particularly robot-assisted hand therapy.

Also, Gu et al. [147] developed a 3D-printed PneuMesh, an innovative truss-based shape-changing system that simplified the design and construction process while still enabling a wide range of tasks. PneuMesh did this by using an air channel connection strategy and configurable constraint design. This significantly cut down on the number of control units that were needed without compromising the complexity of shape-changing capabilities. Additionally, the authors developed a design tool featuring real-time simulation to aid users in designing the shape and motion of truss-based shape-changing robots and devices. A design session involving seven participants demonstrated the effectiveness of PneuMesh in empowering users to create truss structures with diverse shapes and functional motions. Also, to make blow moulding techniques more accessible in the field of HMI, Wang et al. [148] endeavored to simplify the challenging process of manual fabrication and enhance the design possibilities of blow molding by utilizing the thermoformability and heat deformability of 4D-printed thermoplastics. Their proposal introduced a novel and democratized blow molding technique called PneuFab, which was made possible by utilizing FFF 3D-printed custom structures and temporal triggering methods. Furthermore, they developed and evaluated a design tool that enabled users to manipulate parameters and preview the resulting forms until they achieved their desired shapes. Through the demonstration of design spaces encompassing artefacts with complex geometries and adjustable stiffness, the aim was to broaden access and explore the untapped potential of digital blow molding fabrication (see **Figure 8a**) [35].

Moreover, to enhance the shape-morphing capabilities of metamaterials, it is beneficial to develop methods that enable the integration of different cellular structures. In this regard, Dikici et al. [149] developed a rational material design process that combined auxetic and non-auxetic lattice structures using a shared grid of nodes. This integration allowed to achieve desired values of Poisson's ratios and Young's moduli, thereby providing control over deformation properties. These customized combinations can be conveniently 3D printed, enabling the fabrication of complex structures. One notable application was the integration of nodally integrated tubular lattice structures, which exhibited worm-like peristalsis or snake-like undulations, depending on the channel width. In the widest channels, at 45 mm wide, f-AnA had the best motility with 2.2 mm/s velocity. In narrower channels, at 35 mm wide, e-AnA was the fastest with almost 2 mm/s velocity (see **Figure 8b**). This resulted in faster speeds compared to the monophasic counterpart, with the worm-like structure excelling in narrow channels and the snake-like structure in wider channels. Remarkably, the worm-like hybrid metamaterial structure could traverse confined spaces that were otherwise impassable for the isotropic variant. These deformation mechanisms paved the way for designing customizable soft robot skins with improved performance in constrained environments.

Also, laminar jamming (LJ) technology is currently a highly discussed subject due to its ability to transform conventional rigid robots, known for their speed, precision, and high-force capabilities, into flexible, agile, and secure soft robots [150,151]. Lalegani Dezaki et al. [152] developed a simple innovative conceptual design for meta-laminar jamming (MLJ) actuators utilizing a meta-structure made from PU SMP, which was fabricated using FFF 4DP. These sustainable MLJ actuators exhibit both soft and hard robot behavior by employing hot and cold programming in conjunction with negative air pressure. Unlike conventional LJ actuators, MLJ actuators offer the advantage of not requiring continuous negative air pressure to activate them. The article also investigated the SMEs and shape recovery of both the meta-structures and MLJ actuators through hot air programming. MLJ actuators equipped with auxetic meta-structure cores exhibit superior performance in terms of contraction and bending, achieving 100% shape recovery following stimulation. These sustainable MLJ actuators possess the remarkable capabilities of shape recovery and shape locking without requiring any power input, even while holding a 200 g weight. The actuators effortlessly lift and hold objects of different weights and shapes, making them suitable for various applications such as end-effectors, lifters, lockers, and gripper devices, showcasing their versatility (see **Figure 8c**).

These examples showcase the application of pneumatic 4DP in consumer products, presenting a range of possibilities. The beauty of this technology lies in its simplicity: heating and blowing air allow for customizable designs tailored to specific requirements. However, while there are numerous advantages, a few challenges need to be taken into consideration. One such challenge is the assembly of these products. The intricate process of piecing together the various components and ensuring their proper alignment demands precision and expertise. Additionally, the heating stage poses another hurdle. Achieving the right temperature and maintaining it consistently throughout the manufacturing process requires careful control and monitoring. The shape formation step presents its own set of difficulties. Creating intricate shapes and structures with precision is a complex task that demand attention to detail and expertise. These challenges, while manageable for adults, may prove to be quite overwhelming for children attempting to work with such technology. However, by simplifying the assembly, heating, and shape formation processes, it becomes possible to enhance the safety and performance of the actuators used in these consumer products. Streamlining these aspects not only makes the technology more accessible to children but also improves overall usability and reliability. By making the technology more user-friendly, we can ensure that children can engage with it comfortably and safely. Simplifying the assembly process and incorporating safety measures can empower young users to participate in creative endeavours while minimizing the risks associated with complex machinery. Furthermore, enhancing the performance of actuators through simplification can lead to more efficient and effective end-use products, benefiting both consumers and manufacturers.

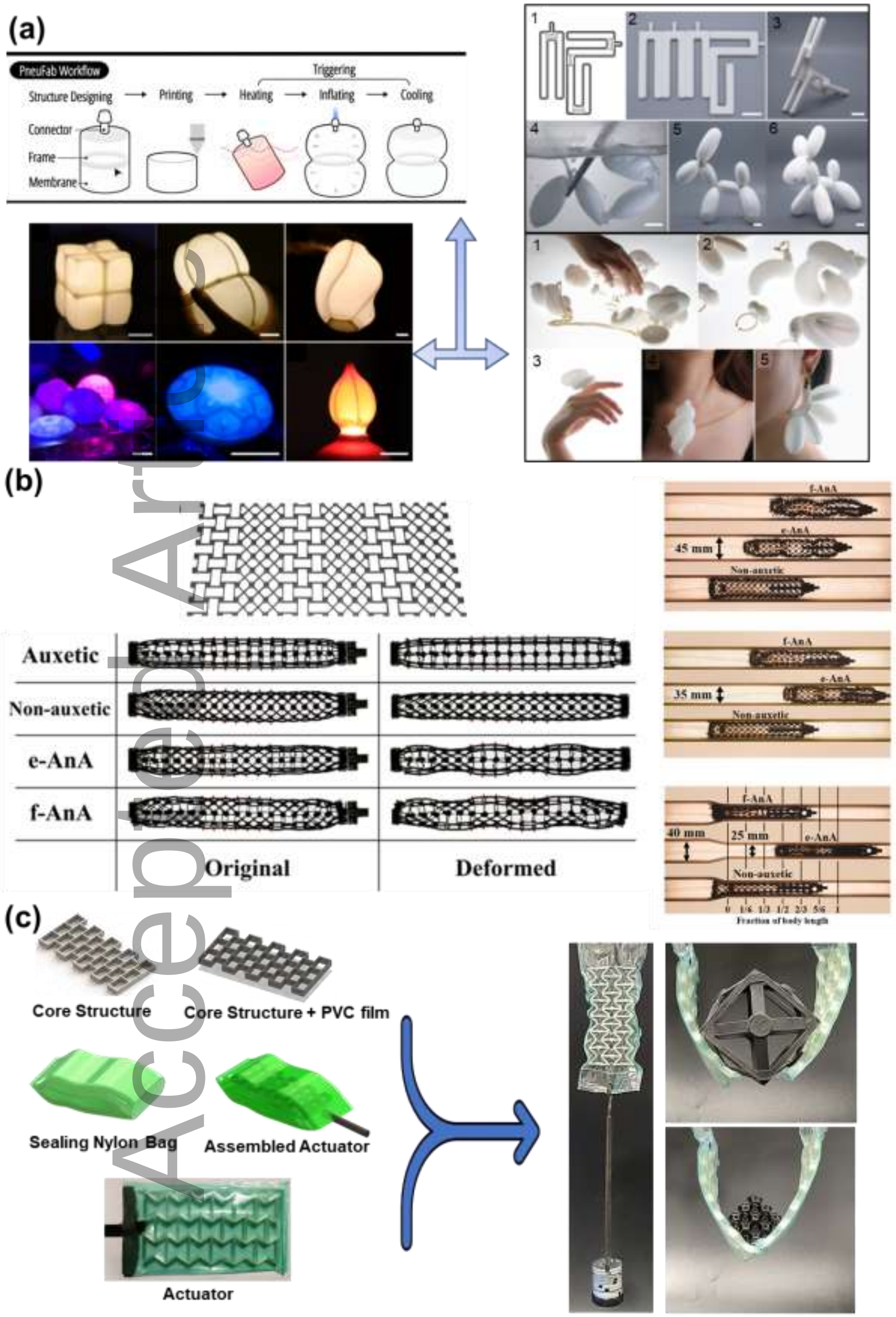

Figure 8. *(a) The PneuFab fabrication workflow, which includes transformative lamps and two modular structures of a balloon dog. The method can be used in the jewellery sector. The scale bar in the image represents a length of 20 mm. (The images are adopted with permission from [35]). (b)*

The image displays the design and various crawling soft robots. These robots utilize both auxetic and non-auxetic (AnA) lattices to enhance their ability to move through narrow spaces, such as the three channels depicted in the image. The movement of flexural AnA (F-AnA), expansional AnA (e-AnA), and non-auxetic modular robots is illustrated using pipes (The images are adopted with permission) [149]. (c) The process of constructing MLJ actuators and the technique of raising weights and grasping items using 0.4 bar of negative air pressure, achieve shape fixation without the need for an air supply [152].

3.4. Textile Products

4DP technology has experienced significant growth, with the global 4DP market projected to have a compound annual growth rate between 2019 and 2025 as mentioned. The main driver for this growth is programmable material, which holds the largest market share among the materials with the potential for 4DP. While the defence and space sectors have shown great interest in this technology, once it becomes available for mass production, it can cater to the demands of various other industries, including textiles and fashion [153,154].

The objective is to incorporate practical, flexible, and dynamic properties into fabrics by utilizing the concept of FFF 4DP. Fashion items, specifically footwear, jewellery, and textiles, are introduced with the application of 4DP, allowing users to easily adjust the flexible nature or required configuration of the products. This technique is combines tailored fabric tension, a 3D geometric model, and often a smart print filament with shape memory properties. By combining these materials, the entire surface of the fabric acquires the shape memory and material knowledge of the printed material, enabling precise patterns of movement in response to temperature changes. The model geometry is printed, resulting in a permanent shape. These constructs, leveraging computational models, could be folded back onto themselves during printing to minimize their thickness [155,156].

Fashion, as an artistic expression, encompasses various elements such as clothing, footwear, accessories, and hairstyles that represent a specific time and place. In the fashion industry, technological innovation plays a significant role, and 4DP has inspired designers and engineers to create materials that can be transformed into fashionable products. One notable technological innovation in the fashion industry is the development of color-changing fabric using a technology called ChroMorphus [157,158]. This technology incorporates microwires woven into the clothing, which can change the fabric's color when an electric current is passed through them. The wires heat up, activating special pigments embedded in the fabric, resulting in a change in color. Additionally, this technology allows for the alteration of patterns that can appear on the fabric.

The use of 4DP and color-changing fabric technology offers several advantages in fashion [159]. Traditionally, people tend to wear clothes of different colors depending on the season and occasion, leading to a larger number of garments. However, incorporating 4DP and color-changing fabric technology makes it possible to design fashionable clothes that can change color and patterns, offering versatility and reducing the need for multiple clothing items [13]. This shift toward color-changing clothes promotes sustainability by encouraging a more conscious and sustainable approach to wardrobe choices. Rather than having numerous garments, individuals can replace their wardrobes with color-changing clothes, contributing to a more sustainable lifestyle [160].

The functional principle of 4D textiles is based on the interplay between the properties of an elastically tensioned textile surface and beam-shaped reinforcements. This characteristic allows the material to be described using the principles of structural mechanics for membrane structures. In the case of 4D textiles, the textile surface acts as a membrane and is elastically pre-stressed, storing potential energy like an anisotropic spring. Specific areas of the textile are then printed on [161]. When the pre-tension is released, the textile generates a restoring force that opposes the elastic stiffness of the reinforcement in the printed areas. This results in the transformation of the planar printed structure into a 3D shape, establishing an energetic equilibrium state.

Koch et al. [162] reviewed 4D textiles by 3DP and developed a concept to create buttons for use in an interface using FFF. The buttons shown in **Figure 9a** can be activated with the force typically exerted by a human. The textile surface used was suitable for interaction with the human touch. They also presented the concept of combining polymer and textiles. As they explained, the textile transformed double-curved surfaces, which corresponded to the configuration with the lowest energy level. The resulting shape depended on whether the circumference of the structure could contract when the pre-stress was released or if it was constrained by the reinforcements. The shape of the reinforcements, either curved or straight, was determined by the stiffness of the chosen material. Furthermore, due to the tensions involved, 4D textiles could assume multiple equilibrium states, allowing for shape changes. By applying an initial force, the structures could transition between two or more metastable states.

Also, Leist et al. [163] focused on exploring the 4DP properties of a common PLA filament typically used in FFF printers. The study demonstrated that custom designs can be 3D printed, serving as the permanent shape for the 4D-printed component. Additionally, the research introduced the concept of 4DP smart textiles using 3D-printed PLA on nylon textiles (see **Figure 9b**). These smart textiles could be shaped into customized forms when subjected to heat treatment and could revert to their original flat shapes when heated above their T_g. This capability opens up possibilities for creating clothing with unique shapes and aesthetics, as well as enabling the encapsulation and release of materials triggered by environmental factors. In another study, Forman et al. [164] introduced DefeXtiles, a cost-effective and efficient technique for producing tulle-like fabrics using standard FFF printers without modifications (see **Figure 9c**). Print failures often occur due to under-extrusion of filament, resulting in periodic gap defects in printed objects. In this paper, they demonstrated how these defects can be deliberately controlled to rapidly create thinner and more flexible textiles compared to previous methods. Their approach allowed for precise control over structures ranging from micrometre to decametre scales and was compatible with commonly used 3DP materials. They presented the mechanism behind DefeXtiles and established a design framework using a set of primitives and detailed workflows. They also conducted mechanical property characterization of DefeXtiles by printing them with various materials and parameters. Furthermore, they showcased the interactive features and new applications of the approach through several examples, including fashion design prototyping, interactive objects, aesthetic patterning, and single-print actuators.

The textile sector has used 4DP FFF technology as a revolutionary strategy. With the aid of this ground-breaking technique, dynamic structures that can alter their shape, adapt to their environment, or react to outside stimuli may be created. Designers and academics are exploring unexplored waters in textile engineering by using 3DP's capabilities. This development makes practical, adaptable materials possible in previously unimaginable ways. We can anticipate significant developments that will revolutionise industries like fashion and healthcare as the 4DP in the textile industry continues to improve. A future in which our clothing and materials constantly change to improve comfort, performance, and aesthetics is now possible because of technological advancements that increase the possibilities for creating intelligent and interactive textile structures. The integration of SMP and thermoplastic materials through the utilization of FFF 4DP opens exciting possibilities in clothing design and manufacturing. By incorporating SMP plastic into the fabrication process, it becomes feasible to alter the shape of garments. For instance, a shirt's form can be transformed using SMP plastic, which possesses the unique characteristic of returning to its original shape when exposed to certain stimuli, such as heat. This innovation allows for dynamic and customizable clothing that can adapt to the wearer's preferences or specific environmental conditions, creating a new dimension of versatility and style in the world of fashion.

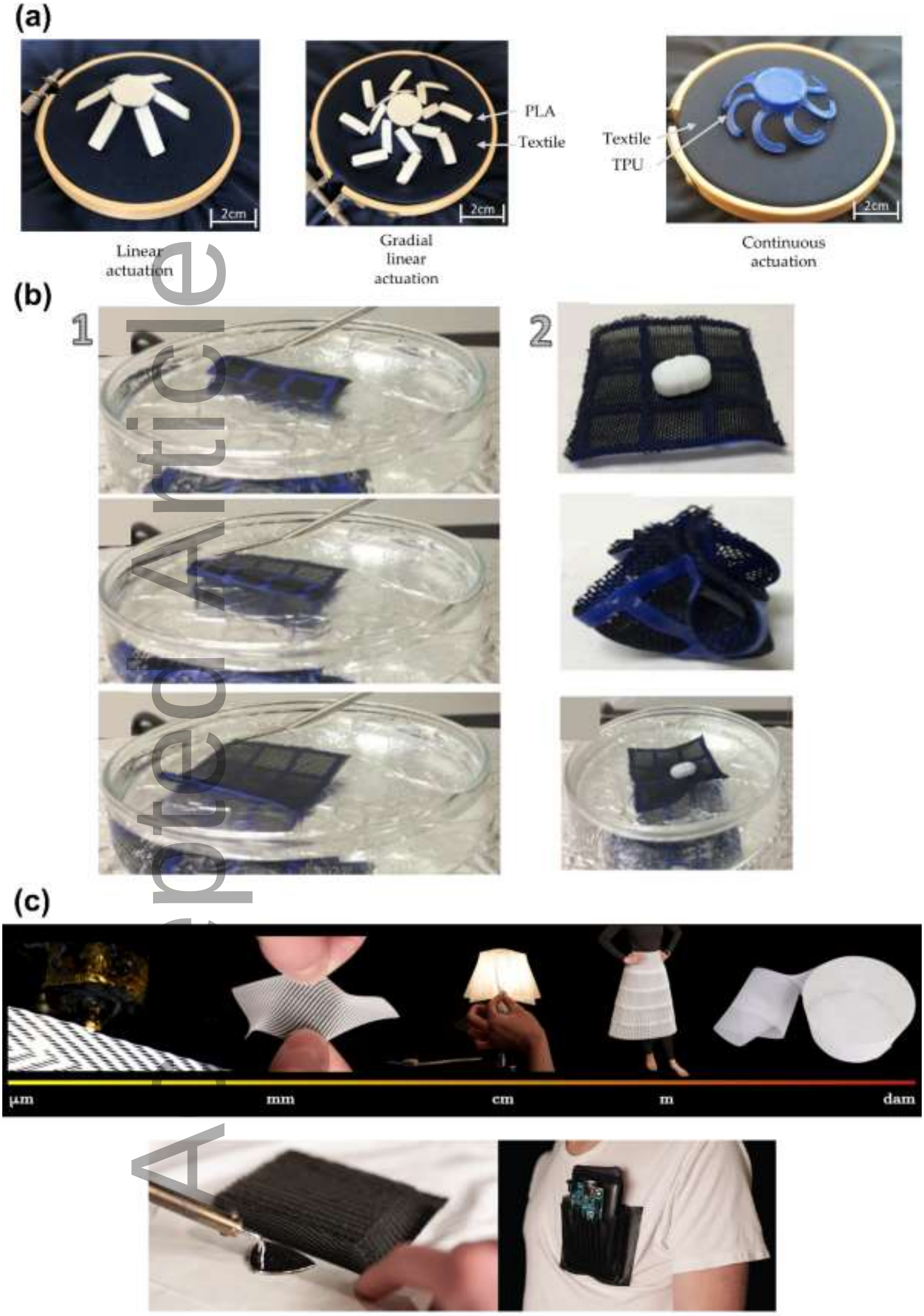

Figure 9. *(a) The actuators are constructed by securing buttons within embroidery hoops after printing. These actuators possess three types of actuations: linear actuation, gradual linear actuation, and continuous actuation [162]. (b) The first example demonstrates the process of using a combination of PLA and nylon fabric. The fabric is heated to 70 °C, rolled into a cylinder, and then*

cooled. When reheated in a pool of 70 °C water, the PLA nylon cylinder unfolds into its permanent flat shape. This process showcases the capability of smart textiles for encapsulation applications. For instance, a magnetic stir bar is placed in the centre of the PLA nylon fabric, which encapsulates the stir bar when heated to 70 °C. After removal from the heated water and cooling to room temperature, the fabric maintains its shape. When the PLA nylon fabric is returned to the heated bath, it unravels and releases the stir bar [163]. (c) The series of images from left to right depicts different stages and applications of DefeXtile. The first image showcases a microscopic view of a printed DefeXtile. The second image demonstrates a stretched DefeXtile. The third image features an interactive lampshade with capacitive sensing. The fourth image showcases a full-sized skirt made from DefeXtile. The final image depicts a 70-meter roll of fabric produced in a single print. The pleated DefeXtile pocket, bonded to a shirt using an iron, can support the weight of a phone, wallet, and Arduino board [165].

3.5. Wood-based Products

In the realm of consumer wood products, the integration of FFF 4DP technology with hygromorphic smart structures opens exciting possibilities. These structures, capable of passive movement, offer numerous advantages and find applications in diverse fields such as weather-responsive architectural building skins, adaptive wearables, and micro-robotics [166]. FFF 4DP, coupled with the utilization of biological water-responsive materials, enables the fabrication and programming of these dynamic structures. This manufacturing technique allows for precise control over the fabrication process at multiple scales and enables the physical programming of the printed objects [167]. The materials used in this context can change their size in response to variations in humidity [168]. By leveraging the absorption or release of water molecules, these materials can exploit evaporation and humidity gradients to perform a wide range of tasks. This characteristic becomes especially significant in addressing global energy challenges, promoting sustainable development, and mitigating environmental concerns such as greenhouse gas emissions [169]. Combining FFF 4DP and these materials in consumer wood products opens up exciting opportunities. For instance, imagine a wooden chair that adjusts its shape and ergonomics based on the ambient humidity, providing optimal comfort to the user. Similarly, a wooden table could adapt its surface texture to enhance grip or provide a smoother writing experience, all through its interaction with moisture in the environment. The integration of FFF 4DP and water-responsive materials in consumer wood products represents a leap forward in design and functionality. By harnessing the power of humidity, these products can offer enhanced user experiences, improved sustainability, and a broader range of applications in various industries [170].

The main focus of 4DP is to integrate a specific morphing function by controlling the material properties and architecture. Le Duigou et al. [171] looked into the possibility of customizing continuous flax-fiber (CFF) 4DP for hygromorph biocomposite (HBC), opening up possibilities for creating environmentally friendly metamaterials that could change shape in a sequential manner. HBCs were made of continuous flax fibers, known for their actuation capability, making them suitable for 4DP due to their hygromorphism function. The morphing performance of materials could be enhanced by choosing the right matrix material (see **Figure 10a**). The soft polybuthylene succinate (PBS) matrix demonstrated a significant 92% increase in responsiveness and an impressive 500% increase in reactivity when compared to the PLA/Flax HBC. By controlling the layer height within each layer during 4DP, complex actuation potential was achieved, allowing for local control of thickness and stiffness ratio. Additionally, the interfilament distance of the 0° oriented passive layer provides an opportunity to achieve non-uniform reactivity and responsiveness, enabling the creation of autonomous smart surfaces. Lastly, the arrangement of the flax yarn could be programmed spatially, along with introducing heterogeneities. For example, a simple compliant mechanism using localized microstructure changes is proposed as an illustration [172].

Tahouni et al. [173] proposed a co-design approach for 4DP hygromorphic structures using FFF. This approach involved the simultaneous development of two key aspects. Firstly, they focused on the production of biobased cellulose-filled filaments with varying stiffness and hygro-responsiveness. These filaments were created by compounding cellulose powder within two matrix polymers with high and low stiffness. Secondly, they incorporate designed mesoscale structuring into the printed elements. The research included the design, fabrication, and testing of a series of 4D-printed prototypes specifically designed to change shape in response to relative humidity (RH). These structures demonstrated the ability to fully transform, opening and closing, within the RH range of 35-90% (see **Figure 10b**). This range corresponded to the natural shifts in RH experienced during daily and seasonal weather cycles. Moreover, the motion of these structures was fast, occurring within minutes. It was also fully reversible and repeatable across numerous cycles.

The process of curved folding, which transforms a flat sheet into curved 3D structures, has the potential to create efficient static or dynamic structures. Tahouni et al. [174] introduced self-shaping curved folding, a method that utilized material programming to enable curved crease origami structures to self-assemble from a flat state to a folded 3D state when exposed to external stimuli. The proposed digital fabrication process involved 3DP shape-changing materials and a computational design workflow that correlates the crease pattern geometry with the printing toolpaths and arrangement of responsive and passive materials. This approach aimed to achieve a desired shape change. They validated the method by creating multiple prototypes and documenting their shape changes when activated using wood-filled filament and ABS.

While plants have served as inspiration for adaptive systems that can move without external energy, these systems have often been simplified into bilayers. Cheng et al. [175] presented computational design methods for 4DP that incorporated compound mechanisms to mimic the anisotropic arrangement of motile plant structures. FFF-based 3DP was utilized to tailor material systems at the mesoscale. The methodology was exemplified by applying the principle of force generation observed in a twining plant species (i.e., Dioscorea bulbifera) to create a self-tightening splint. By mimicking the tensioning of the plant's stem helix, which generated squeezing forces for stability against gravity, the functional strategies of D. bulbifera were abstracted and translated into customized 4D-printed material systems. In the study, the 3DP patterns of wood-polymer composite and ABS materials were examined to explore the resulting shapes when activated. The researchers aimed to investigate the deformation and transformation properties of these materials upon activation. The squeezing forces produced by these bio-inspired motion mechanisms were evaluated. The concept of self-tightening was then prototyped in a wrist-forearm splint, a commonly used orthotic device for alignment (see **Figure 10c**).

Also, Tahouni et al. [176] utilized FFF 3DP to create multi-layered, multi-material bilayers consisting of hygroscopic active layers and hydrophobic restrictive and blocking layers. The timescale of motion was controlled through the design of the layers and printing parameters such as thickness, porosity, and water permeability, as well as the filling ratio of the hydrophobic layers.

Increasing the thickness of the active layer or reducing its porosity leads to slower motion, while decreasing the thickness and filling ratio results in faster motion. Several prototypes are showcased, including an aperture with sequential movement of overlapping elements to avoid collision, and a self-locking mechanism where specific areas of the structure undergo multi-step self-shaping and locking (see **Figure 10d**).

The unique properties of hygroscopic plant structures are that they can move in response to environmental changes without consuming metabolic energy. Inspired by the multi-phase motion observed in plant structures, the researchers present a method to physically program the timescale and sequence of shape-change in 4D-printed hygromorphic structures [171]. However, there are substantial challenges associated with material limitations, such as printability, responsiveness, and mechanical properties, which hinder the achievement of reliable and repeatable humidity-responsive actuation [170,177]. The promising results of this study present new opportunities for leveraging 4DP and natural resources to develop functional humidity-responsive smart structures [178]. By overcoming material limitations through the co-design approach and incorporating cellulose-filled filaments, these structures showcase their potential for practical applications as end-use products [179]. It is now feasible to make wooden smart pots and plates in the convenience of your own home using the cutting-edge 4DP method. Utilising the capabilities of FFF opens up a whole new world of design options for creating useful and intelligent items. By using this technique, wooden objects may be shaped and formed as well as given smart elements to make dynamic and responsive creations. Using 4DP and FFF technology, you may create future designs for your house, such as a self-watering pot that changes its moisture levels based on plant demands or a plate that detects and controls food temperatures. The fusion of traditional materials like wood with cutting-edge advancements paves the way for personalized and sustainable creations, offering a glimpse into the future of home manufacturing.

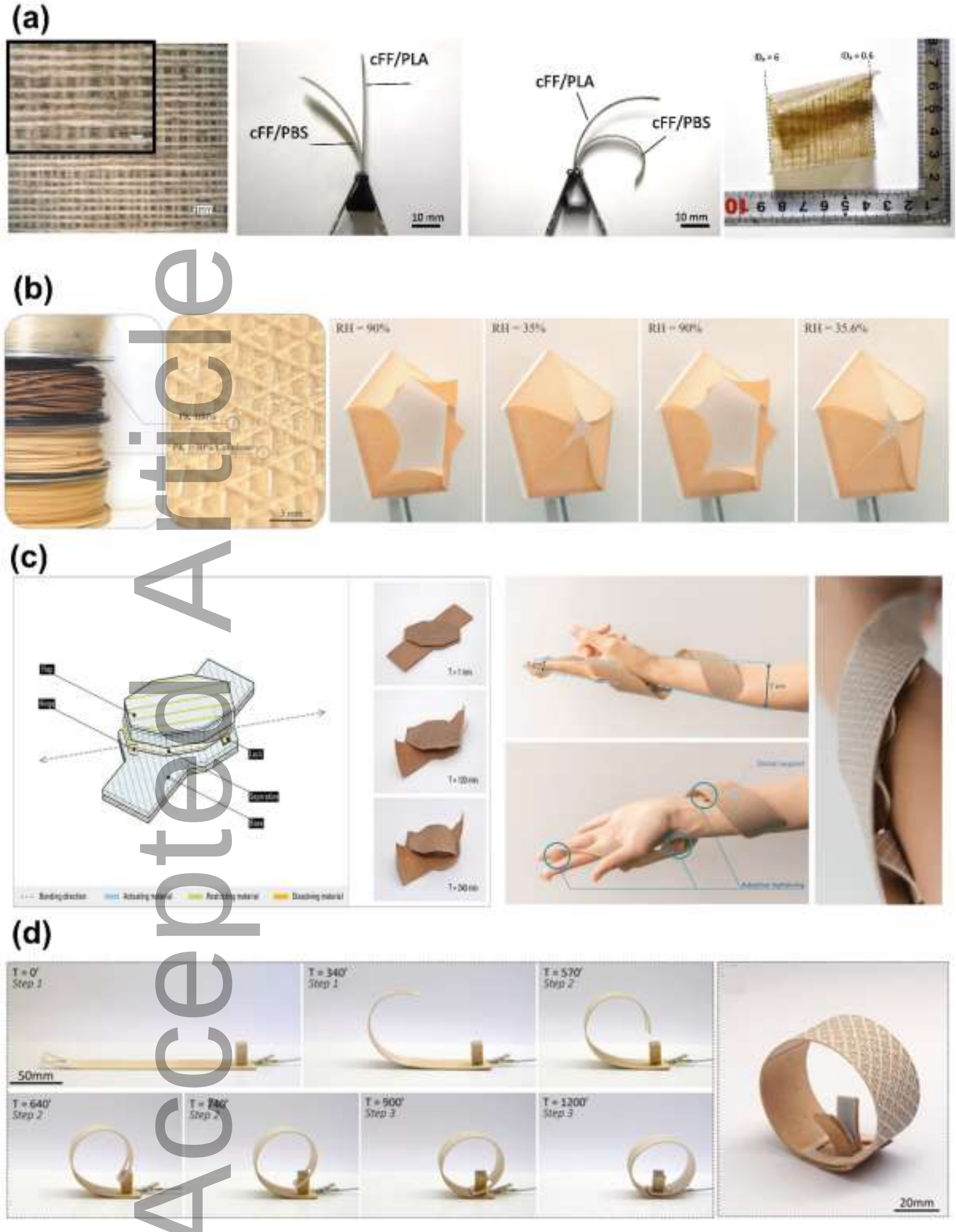

***Figure 10.** Various aspects of the hygromorphic 4DP biocomposites. In (a), a closer look reveals local misalignment and changes in interfilament distance. The image also compares the initial state of cFF/PLA and cFF/PBS after printing and immersion. It showcases the passive layer of cFF/PBS HBC and its response to water immersion [171]. (b) Showcases the development of a collection of custom hygroscopic printing filaments made up of biobased matrix polymers and cellulose powder. It provides a detailed view of 3D-printed mesostructures with designed anisotropy and porosity. The structure in the image is a humidity-responsive smart structure with a curved folding mechanism, featuring actuated surfaces and flexible hinges. The left side shows the structure in a folded*

configuration equalized in 90% RH, while the right side displays the structure in a flat configuration at 35.6% RH (at a temperature of 20°C) [173]. (c) displays the pocket mechanism comprising five components with different printing directions, each programmed for distinct morphing. The accompanying images present the initial prototype of a wrist-forearm splint, serving as an adaptive bio-inspired functional mechanism [175]. Lastly, (d) showcases a series of time-lapse images capturing the three-stage motion in the self-locking prototype [176].

4. 3D/4D Pen

In recent times, there has been significant interest and attention focused on 4DP within the realm of HMI [180]. However, the complexity of advanced configurations path planning, automatic printing, and intricate G-code controls in FFF 3D printers continues to present obstacles for newcomers. Conversely, 3D pens offer optimal versatility and accessibility, particularly for beginners and even children. A 3D pen is a tool designed in the shape of a pen that utilizes 3DP technology, which is a crucial advancement in the era of the 4th industrial revolution [181]. It enables the creation of 3D objects like the printing process. The combination of 3D pen technology and 3D printer technology is highly significant. The fundamental principles of a 3D pen involve the insertion of plastic filaments into its main body. These filaments melt inside the pen and flow out through the pen point, allowing users to create various three-dimensional shapes easily. The commonly used materials in 3D pens are acrylonitrile butadiene styrene (ABS) and PLA, which are durable plastic materials frequently employed in 3DP and widely available in daily life. When the button on the 3D pen is pressed, it produces heated plastic at the tip, which quickly hardens, enabling the creation of stable models [182]. This 3D pen is extensively used for educational purposes, particularly by students who can easily shape desired objects in mid-air. The 3D pen operates at a low temperature, making it safe and user-friendly for young students [183]. Additionally, it does not require special software or computers, making it accessible for anyone to use.

As an example, Wang et al. [184] introduced the 4D curve as an affordable and easily accessible approach to 4DP, specifically aimed at generating curves using 3DP pens. Unlike machine-based printing strategies that strictly adhered to a flat and layer-by-layer approach, the manual utilization of 3DP printing pens allowed for the creation of freely curved and non-planar printing paths, promoting spatial creativity and seamless integration with everyday objects. Furthermore, a guidance system was developed to provide users with curve path recommendations based on their specific deformation requirements. **Figure 11a** illustrates the utilization of a 3D pen to draw actuators using various paths, which are subsequently activated through the application of heat. The authors also showcased diverse application scenarios within the expansive design space, catering to fashion designers, craft enthusiasts, and individuals involved in personal fabrication. Also, Tao et al. [185] proposed transitioning from traditional 4DP, which heavily relies on 3D printers, to a more handcrafted approach that could allow users to better understand and continuously engage with the artefact and its transformability. To realize this vision, they introduced 4Doodle, a hybrid craft method that combined unique deformation control with five techniques for freehand 4DP using a 3D pen. To address the challenges associated with uncertain hands-on fabrication in shape-changing processes, they developed a mixed reality system that assists novices in mastering the manual skills required for 4DP. Additionally, they showed a series of 4D-printed artefacts created entirely through human intervention. The results of the study demonstrated that 4Doodle reduced the barrier to acquiring the skills needed for handcrafting 4D-printed artefacts, highlighting its potential for fostering creative production and spatial ability (see **Figure 11b**).

Moreover, sometimes drawing directly in 3D is difficult and creating precise models of even small molecules can be challenging. Bernard et al. [186] introduced a new approach to 3D modeling that overcomes these limitations. The approach involved using 3D templates that enable the drawing of molecular models directly in 3D. The modular nature of these templates allowed for the creation of a wide variety of structures. The resulting models accurately represented molecules, including correct bond angles and geometry. This innovative approach transforms 3D pens into powerful tools for modeling chemical structures in an educational setting [187]. As a 3D pen has a heated nozzle to extrude thermoplastic filaments, ultrafine particles may be emitted, leading to potential health implications, particularly for children and human health in general[188]. Particles are very small, and their inhalation can lead to respiratory issues and other health concerns. Given the potential risks, it is important to take precautions when using 3D pens, especially in educational or child-oriented settings. As an example, Kim et al. [189] characterized the emissions of ultrafine particles from two types of 3D pens and assessed the impact of the partitions on ultrafine particles exposure. For the studied 3D pen types, the highest average emission rates were observed with ABS filament, followed by PLA and polycaprolactone (PCL) filaments.

The utilization of 3D pens in design education holds significant importance in terms of its experiential nature. Even young students at the elementary level can effortlessly engage with 3D pens. Moreover, the versatility of the 3D pen allows for easy transformation into innovative products, building upon existing ones. Specifically, 3D pens have the potential to enhance art education and find application in the making field. This makes them suitable for design education, extending beyond architectural design to encompass various domains like costume design and product design. As 4DP technology continues to advance, individuals will have easier access to creating their products. In the future, the combination of 3D printers and 3D pens will likely enable individuals to produce personalized items according to their preferences. Given these circumstances, education utilizing 3D pens will assume a crucial role in 4DP. To enhance the safety of 3D pens for children, it is important to address concerns related to emissions and particles. This can be achieved by improving the design and materials used in the pens to minimize any potentially harmful emissions. Additionally, implementing proper filtration systems or incorporating safer filaments can help reduce the release of particles during the 3DP and 4DP processes.

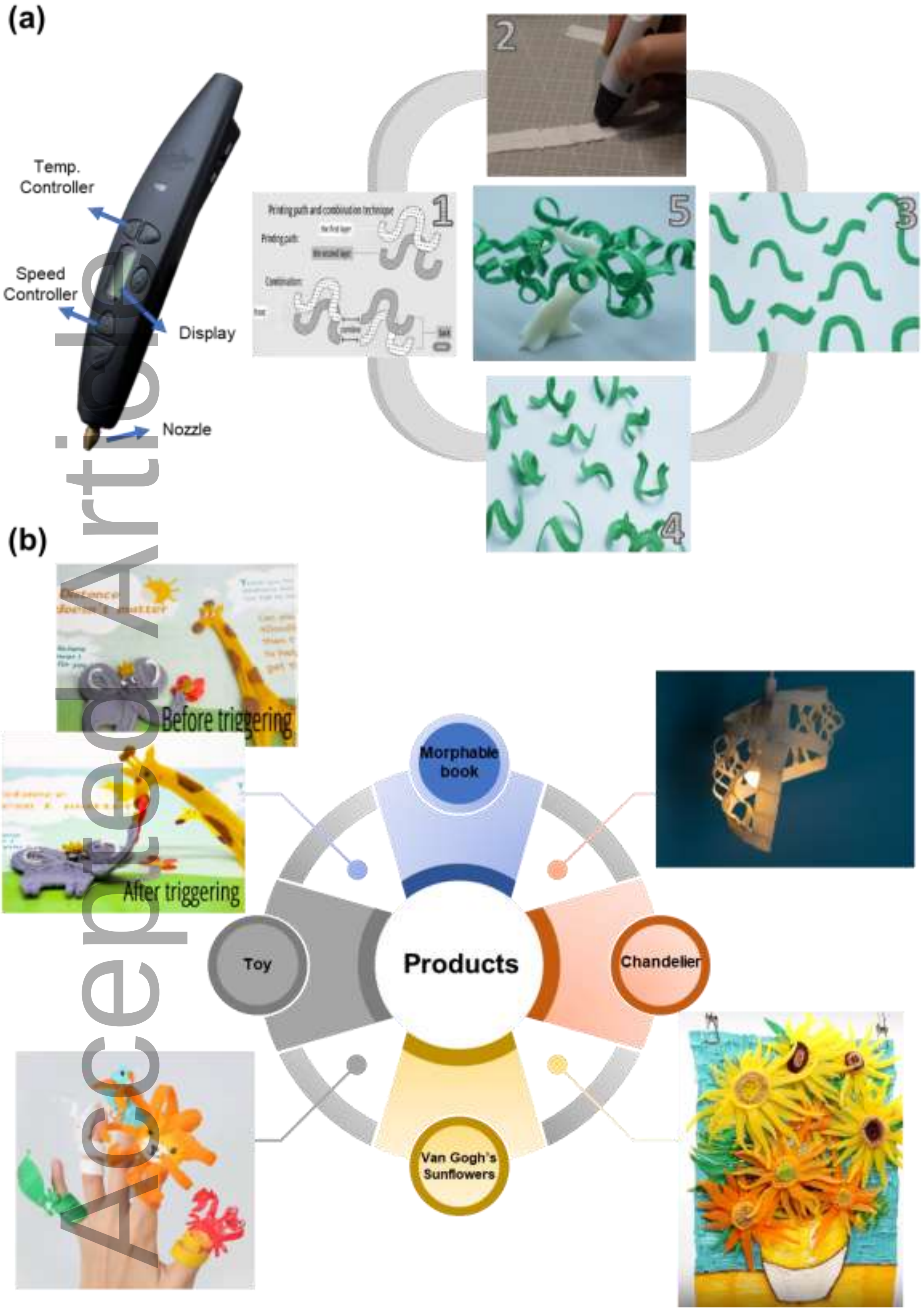

Figure 11. *(a) Schematic of 3D pen from 3Doodler and printed samples created using a 3D pen, which is activated through the application of heat and used as a toy resembling tree leaves [184]. (b) The application of using a 3D pen in the field of 4DP to produce crafts and toys [185].*

5. Summary and Challenges

Due to its reputation for supplying consistent quality and outstanding performance, FFF 3DP has significantly increased in popularity across a variety of sectors [190]. This technique has proven to be adaptable and can produce a wide range of end products, from playthings to industrial components, all while being, as noted, reasonably priced. FFF's well-established and advantageous manufacturing method is responsible for its broad adoption. This process is straightforward and accessible to a wide spectrum of people, from experts to hobbyists [191], allowing them to practically realise their ideas [192]. FFF delivers dependable quality and performance in addition to several other advantages.

The potential of FFF 4DP in producing end-use products has been the subject of evaluation. Unlike traditional 3DP, 4DP introduces a fascinating dimension by incorporating time-dependent changes into the design and specifications of a part, resulting in innovative and distinctive creations ranging from consumer goods to wood-based products. While the concept of 4DP is relatively new, the underlying fabrication process remains largely like that of 3DP. The fundamental steps of layer-by-layer deposition of molten thermoplastic material through a heated nozzle remain unchanged. However, what sets 4DP apart is the ability to introduce temporal variation in the printed objects. To achieve this temporal variation, careful consideration is given to the selection of printing materials and their properties [193].

The development of interactive and adaptable objects is one of the major potentials that FFF 4DP offers in HMI [113]. Objects created with FFF 4DP may be programmed to react to user interaction, alterations in the surroundings, or even physiological signs. This creates fresh opportunities for creating user interfaces that are simple to use and engaging. According to the user's preferences or the circumstances of usage, for instance, FFF 4D-printed control interfaces might dynamically alter their shape or texture, resulting in a more interesting and tailored interaction experience [105,184]. Furthermore, FFF 4DP can enable the incorporation of interactive elements like sensors, actuators, and other components right into the printed items, enabling direct and seamless human interactions with the digital world.

Evaluations of FFF 4DP's potential for creating end-use goods have been studied [119]. By adding time-dependent changes to the design and specifications of a part, 4DP, in contrast to typical 3DP, adds an intriguing dimension that leads to creative and unique inventions that range from consumer goods to wood-based items. Although 4DP is a relatively new idea, the fundamental manufacturing method is still quite like 3DP. The capacity to add temporal change to the printed items, however, is what distinguishes 4DP. The choice of printing materials and their qualities are carefully considered to create this temporal fluctuation. Certain materials possess the ability to respond to external stimuli such as heat, humidity, and air supply, enabling them to undergo controlled changes over time. By incorporating these materials into the design, 4DP allows for the creation of parts that exhibit dynamic characteristics and smart products.

The design and functioning of the final product might be completely transformed with the application of temporal variation in 4DP. This innovation makes it possible for objects to move beyond their static state and instead have the capacity to adjust and react to their surroundings or certain triggers. A new age of interactive and dynamic end-use goods is made possible by 4DP's capacity to change into various configurations over time [35]. This innovation offers creative solutions for consumer products, architecture, fashion, healthcare, and other fields, with broad ramifications for many different industries. Imagine a device that can adapt itself to improve performance, change its structure to accommodate changing demands, or even change its look in reaction to environmental influences in terms of sustainability and economy. Despite being in its infancy, 4DP has the potential to be a game-changing technology that upends established production methods. The capabilities of FFF 4DP will probably be improved by ongoing research and development, enabling the fabrication of ever-more complex designs with dynamic properties. We may anticipate significant advancements in creating goods for end use that are not only practical but also interactive and responsive to consumers' changing needs.

The article points out that even when utilizing less expensive FFF printers, traditional 3DP materials like PLA and its composites may be used as intelligent materials in 4DP undertakings. However, the requirement to broaden the selection of materials readily available for this purpose is a significant barrier to 4DP's development. For 4DP to reach its full potential, the range of printing options must be increased. In addition to finding materials that respond well to outside effects, other applications can demand materials that react especially to certain stimuli, like humidity. Due to 4DP's infancy, users may run into a number of difficulties, the main one being the complexity of constructing the structures that permit the required transformation into a certain shape [49]. Users might need to build supplemental components to assist material programming to accomplish sophisticated transformations. To achieve movements like folding, curling, twisting, linear expansion, and shrinkage, it becomes necessary to use several materials and unique printing processes and interfaces. The overall challenges users encounter in fully using the possibilities of 4DP technology are caused by a combination of these issues [194,195]. SMP and shape-changing materials, even though 4D-printed structures have demonstrated their capacity to change shape utilising a variety of materials and pre-designed internal tensions, are now thought to be the most preferred solutions because of their improved functionality.

When FFF 4DP is applied to metals and ceramics, this technology opens up new possibilities but introduces unique challenges. One notable limitation in the 4DP realm is the intricate control required for the transformation process. Achieving precise temporal control over the shape-morphing behavior of metals and ceramics demands an in-depth understanding of their thermomechanical properties, which can be inherently complex. For instance, metals may exhibit different phase transitions and thermal expansion coefficients, making it challenging to orchestrate a seamless transformation as end-use products. Ceramics, with their often brittle nature, present additional hurdles as their transformation requires careful consideration of stress distribution to prevent structural failure. The time-dependent aspect of 4DP introduces a layer of complexity in terms of material behavior and printing parameters. Innovations in temperature control, material science, and design methodologies are imperative to overcome these challenges and unlock the full potential of FFF 4D printing for metals and ceramics. Future material development efforts should focus on a few important areas to improve the industry. Reduced activation temperatures, multi-stimulus activation, remote and selective activation, shorter activation times, stronger activation forces, and multi-position actuation are a few of these. The applicability and efficiency of 4DP may be greatly increased by addressing these areas of development and creating new opportunities for these applications.

Complex calculations and modeling are essential in the design stage of 4DP to simulate the changes that take place based on the selected design, material attributes, and limitations [3]. Without access to appropriate simulation tools, even simple 4DP activities can become quite difficult. For understanding and forecasting the behavior of the printed item during the transformation process, sufficient simulation tools must be available. These technologies provide designers with the ability to efficiently optimise their designs and produce the desired results. Therefore, creating software that can forecast how a product will behave after activation would be advantageous [196,197]. Aside from improvements in 3DP technology, the creation of cutting-edge 4D materials is also essential. Strength, flexibility, and reusability are just a few examples of the fundamental mechanical qualities that may be improved upon in these materials. The development of multifunctional end-user devices is also made possible by additional performance indicators like electrical, thermal, or photo actuation capabilities. These enhancements enable these materials to be used for a variety of common products.

6. Conclusion

This article included an overview and analysis of the use of FFF 4DP in several fields, with an emphasis on smart consumer goods and products. The report also looked into FFF 4DP's possible effects on the HMI industry. The FFF technique was introduced in the opening section of the study, emphasising its importance in 3DP and its capacity to build complicated geometries layer by layer. The usage of FFF 4DP in the manufacture of consumer goods is then covered in depth. The article assessed various products constructed from SMP, PLA, pneumatic-based products, 4D textiles, and hygromorphic smart materials. Each product exhibited distinct functionalities and characteristics with respect to activation and response to stimuli. It covered the benefits and difficulties of using FFF 4DP methods to improve the functioning and appearance of consumer items. FFF 4DP offers exciting opportunities for the creation of interactive and adaptive objects that can enhance user experiences. However, several challenges need to be addressed for the widespread adoption and success of FFF 4DP.

One of the complexities encountered in FFF 4DP involves the simultaneous deposition of multiple materials, such as metal-infused plastics or ceramic-laden polymers. This challenge can be effectively addressed through advanced pre-processing techniques that enhance the capabilities of the extruder, enabling the amalgamation of these diverse materials and resulting in the creation of more robust 4D printed products. Concurrently, the optimization of process parameters plays a pivotal role in achieving not only high surface quality but also superior mechanical properties, particularly when dealing with innovative materials. Furthermore, it is noteworthy that the surface quality of printed plastics in FFF technology is not consistently optimal when compared to other 3D printing methodologies. Therefore, the integration of post-processing procedures becomes imperative to elevate the overall quality of the printed samples. These post-processing techniques are instrumental in refining the surface characteristics, addressing any imperfections, and ultimately enhancing the aesthetic and functional attributes of the 4D printed objects. In essence, a comprehensive approach that encompasses both advanced pre-processing and meticulous post-processing steps is essential for overcoming the multifaceted challenges associated with multimaterial printing in FFF 4DP technology.

Improving and eliminating these challenges and making the procedure simple, it is possible to build smart toys, gadgets, structures, and household products with hybrid materials. In the context of HMI, the paper suggested that FFF 4DP holds great potential for creating interactive and adaptive objects. It discussed how FFF 4D-printed products can enhance user experiences by responding to user input, environmental changes, or even physiological signals. The paper concluded by outlining the future research directions and challenges that need to be addressed to fully leverage the potential of FFF 4DP in the field of HMI. Future research should focus on developing advanced materials specifically tailored for FFF 4DP, exploring new design paradigms to fully exploit the potential of interactive and adaptive objects, and addressing the technical challenges associated with the integration of sensors, actuators, and other components within 3D-printed objects.

Author contributions

Mohammadreza Lalegani Dezaki: Conceptualization, Investigation, Methodology, Data curation, Formal analysis, Experiment, Writing - original draft.
Ali Zolfagharian: Methodology, Formal analysis, Writing - review & editing.
Frédéric Demoly: Methodology, Formal analysis, Writing - review & editing.
Mahdi Bodaghi: Methodology, Formal analysis, Project administration, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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