4D Printing in Food Technology

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**Abstract**

# An improvement on 3D printing, 4D printing is an additive manufacturing process. A recently discovered field in 4D printing, food printing is still in its infancy. The academic and business communities are paying close attention to 4D food printing. There aren't many literature reviews accessible for 4D food printing compared to other 4D printing fields. The current article provides a general overview of 4D printing with a focus on printing food. The impact of numerous stimuli on the characteristics of 4D printed food samples, such as colour, flavour, texture, and shape, is discussed in this paper. Additionally, it discusses the creation of 4D designs, food printing ink, and numerous techniques for printing 4D foods. Microwave heating or the impact of pH on printed food items are focused more by majority of 4D food printing research. The characteristics of the meal, such as colour, taste, aroma, texture, and form, varied in response to stimuli. Food resources for 4D printing include potato purees, soy protein isolate, starch, buckwheat dough, etc. A stimulus-responsive substance makes up the printing ink utilised in 4D printing, causing spontaneous modifications in 3D produced structures. A few stimulus-responsive chemicals utilised in 4D food printing are vanillin powder, anthocyanin and curcumin. Curcumin will change colour in response to pH. It is feasible to conduct experiments using a variety of stimuli-responsive materials and stimulating stimuli, including light.

Keywords – 4D printing, Shape memory polymers, Liquid crystal elastomers

# Introduction

An additive manufacturing technology, four-dimensional (4D) printing is a relatively recent area of printing. The 4D printing technique is a new idea that alters the printed configuration over time and is an extension of 3D printing (Choi et al., 2015). A research team at the Massachusetts Institute of Technology (MIT) created this concept for the first time in 2013 (Tibbits, 2014). In terms of the printing process, 4D printing is similar to 3D printing, including the creation of 3D designs and the production of structures using 3D printers (Choi et al., 2015). Smart design and smart materials are the main differences between 4D and 3D printing because 4D printed structures are capable of changing shape or function (Pei & Loh, 2018). Most of materials used in 4D printing are single- or multilateral polymers (Kuang et al., 2019). With 4D printing, the desired product characteristics may be acquired at the right time and may even deteriorate as produced goods are stored. Contrary to other 4D printing industries, the food industry uses different combinations of food resources as printing ink rather than intelligent materials (Jiang et al., 2019). According to Ghazal et al. (2019), 4D food printing enables the printed object's colour, texture, flavour, and other attributes to change over time, giving it a distinctive personality and enhancing the dining experience visually. Research into 4D food printing is expanding quickly. Therefore, the focus of this review is on various stimulating agents, stimulus-responsive materials, and stimulus-induced changes in the various attributes of 4D printed food (colour, taste, aroma, texture, and shape modification).

**4D printing:**

4D printing, which offers a function of time, is an expanded form of 3D printing. A 3D printer, printing ink, printing software and stimulus are the basic elements of 4D printing technology. In general, customized foods may be printed using dough, chocolate cheese, hydrocolloid starch, a mix of fruits and vegetables and hydrogel; however, due to the absence of smart materials in food, very few studies have been conducted. It contributes to the growth of a dynamic structure that may modify its form, operation, and characteristics in response to changes in pH, temperature, electric and magnetic field, ionic concentration and other stimuli. The additive manufacturing technique, the sorts of stimuli employed, the type of stimulus-responsive material used, the interaction mechanism, and mechanical modelling are the main elements in the 4D printing process (Ali et al., 2019). The micro-extrusion method is popular among many printing technologies since it is simple to use and flexible when it comes to using a variety of inks.

**Materials for 4D printing:**

Smart materials are the materials used in 4D printing. Hydrogels (gelatin, sodium alginate, pectin, xanthan gum, carrageenan, konjac gum, etc.) in addition hydrocolloids (gum arabic ,starch, guar gum, gum karaya, xanthan, gum tragacanth, cellulose derivatives and locust bean gum) are the main ingredients used in 4D food printing to improve the flow behaviour of natural food gels. They have the capacity to alter their properties while being stored when exposed to a stimuli. The stimuli include things like heat, pH, light, etc. Liquid crystal elastomers as well as shape memory polymers are two examples of single-material smart materials that are used in 4D printing. It might be a composite metamaterial.

**A. Shape memory polymer (SMP):**

These polymeric materials may endure a transient change in form and structure and then resume their original configuration when stimulated. Polylactic acid is the most often used SMP for 4D printing, however other materials like bisphenol, poly cyclo-octene, etc. are also used (Ehrmann & Ehrmann, 2021). Thermo-responsive SMPs are a prominent study topic because to the excellent tunability of the transition temperature, the optical and mechanical characteristics, and the ease with which shape memory may be activated. These are frequently printed with deformities. Exposure at a temperature above the transition temperature followed by cooling to a temperature below the transition temperature, followed by unloading, causes deformation. After being subjected to a temperature above the transition temperature, the SMPs restore their pre-programmed form as a result of entropic elasticity (Ahmed et al., 2021). Compared to traditional printing materials, the SMP offers a number of advantages, such as low cost, light weight, improved shape deformability, processability, and greater recovery.

**B. Liquid crystal elastomers (LCE):**

Mesogenic moieties are typically added to the polymer network, either as side groups or in the chain backbone, to provide the anisotropic features of LCEs (Sun et al., 2021). LCEs are anisotropic, stimuli-responsive, reversible materials. LCEs can alter shape in response to environmental stimuli such as electric fields, light, magnetic fields and temperature. The most often utilized precursors for the production of LCEs are poly (hydrosiloxane) polymers, acrylates, and methacrylate (Ula et al., 2018).

# 4D printing in the food industry

The first use of 4D printing in the food industry was made by MIT researchers. They created a 2D film made of starch, cellulose, and protein and employed water as a stimulant. Then, a 2D movie became a 3D one when there was water present. Four-dimensionally printed food will be more personalised and have unique flavour created just for it. Food can alter in shape, colour, texture, and aroma in response to a variety of stimuli, including temperature and pH. The printing ink can be used in various combinations of food materials based on the structure and particular food formula to produce the stimulus-induced alterations in the 4D printed food samples (Teng et al., 2021). As food-grade materials are used in place of ink and tissue, printed food will have a higher nutritional value. As 4D biotechnological printing replaces ink and tissue with food-grade ingredients, the nutritional content of printed food will grow.

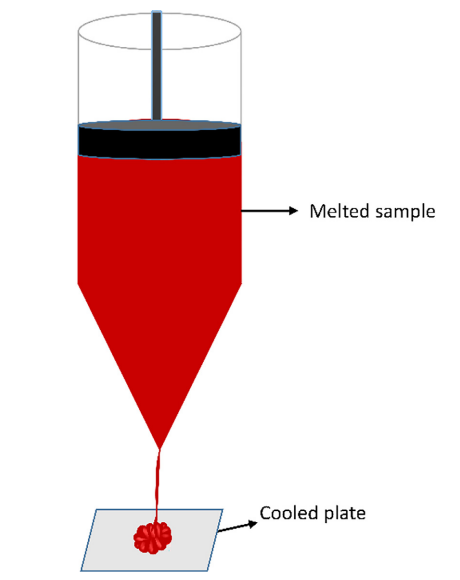
**4D food printing inks:**

The food ingredients utilised in 4D food printing are known as the printing ink (Kewuyemi et al., 2021). Before and after printing, the food ink must have both liquid-like and solid-like structures (Gholamipour-Shirazi et al., 2019). It was investigated how particle size affected how well food inks printed. According to the researchers, the larger particles (307 m and 259 m), which contain a skeletal-like cellular structure, are more permeable than the smaller particles (up to 172 m). Under varying pH conditions, 4D changes in food colour is caused by the pigments in printing ink. These substances alter their colour, flavour, texture, and other properties in response to certain circumstances or stimuli. One of the stimulus-responsive materials utilised in 4D printing is curcumin, which displays a yellow colour in acidic or neutral pH and a red colour in alkaline pH (C. Chen, Zhang, Guo, et al., 2021). Similar to this, anthocyanin functions as a stimulus-response substance and displays various colours in response to a pH stimulus (He et al., 2021).

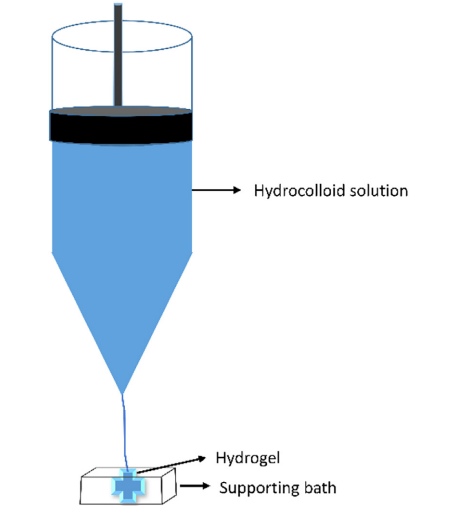
**Food printing methods:**

## **Extrusion printing:**

One of the simplest methods for printing food is extrusion-based printing, which has been utilised frequently. It is typically applied to molten materials that are controlled by a semi-viscous system or temperature (Mantihal et al., 2020). With the use of slicing software, a virtual 3D model is programmed for extrusion printing and then converted into particular layer patterns and codes. Before food can be printed, these codes must be uploaded to the printer together with the appropriate recipe. Materials are extruded by moving the nozzle above a fixed stage or by moving the stage under the nozzle to build a layer, depending on the programming used to create the object. When the extruded layers attach to one another, a 3D structure formed of layers is produced (Sun et al., 2018). Extrusion at room temperature was widely employed by researchers to create 4D food products. In order to create a gel from lotus root powder, Chen, Zhang, Guo, et al. (2021) employed an extruder with nozzle sizes of 1.2 mm and 1.5 mm, producing a rough surface. Extrusion of printed materials at room temperature, such as melting cheese and dough. Extrusion at room temperature is frequently used to create confections with great reproducibility that are challenging to create by hand. Pasta can also be printed using extrusion at room temperature. Materials including proteins (Phuhongsung, Zhang, & Bhandari, 2020), puree (Shi et al., 2022), carbohydrates (He, Zhang, & Devahastin, 2020) etc., have been used as printing materials in room temperature extrusion. By heating and melting the raw material, hot-melt extrusion creates new material. The molten ink is then controlled-environment forced into a die. Creating polymeric materials is its primary use. Higher temperatures (like 90 °C) can also be reached when using a moveable extrusion printer nozzle to extrude food-grade ingredients like chocolate. Following extrusion, it quickly solidifies and is sealed to the preceding layer. Depending on the kind of material used, a greater temperature should be maintained during hot melt extrusion to regulate viscosity and flowability through the printing nozzle. Hot-melt extrusion produced goods that were uniform in thickness and density (Tan et al., 2018). Extrusion in hydroforming. Using a syringe pipette, jet cutter, vibrating nozzle, and other similar tools, the hydrocolloid solution or dispersion is dispensed to the gel setting/polymer/hardening bath in the hydroforming extrusion process (Fig. 3). According to Le-bail et al. (2020), the viscoelastic properties of the materials play a major part in this process and depend on their capacity to gel. The hydrocolloid solution in this procedure should initially exhibit a viscoelastic quality before transforming into self-supporting gels. According to Godoi et al. (2016), a temporal control mechanism is used to stop material from pre-gelating in the printer. In general, there are three mechanisms involved in the creation of hydrogels: (1) chemical cross-linking, (2) ionotropic cross-linking, and (3) the formation of complex coacervates (Kirchmajer et al., 2015). Soft snacks made of fruit are frequently printed using this technology.



**Figure 1 - Schematic representation of the hot-melt extrusion (Source: (M. Navaf, K.V. Sunooj, B. Aaliya *et al.,* 2022)**



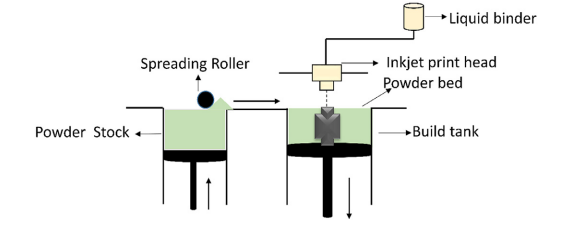
**Figure 2 - Schematic representation of the hydroforming extrusion (Source: M. Navaf, K.V. Sunooj, B. Aaliya *et al.,* 2022)**

## **Inkjet printing:**

Inkjet printing is typically employed in confectionery and decorations, and it is also frequently utilised in 4D printing (Pallottino et al., 2016). It is made up of several pneumatic membrane nozzles, or "jets," that are typically 20 to 50 micrometres in size and are used to spray food ink onto moving objects. The printing ink can be sprayed onto the printing platform using one or more concurrently operating nozzles to create layered structures. With the help of cavity depositions and surface fillings, the droplets come together to create a digital image. Low viscous materials are typically used in inkjet printing. So rather than printing complicated structures, it is utilised to draw flat products. Inkjet printing is significantly impacted by temperature. It will have an impact on the substance's viscosity and surface energy (Le-bail et al., 2020). Low viscous materials are typically utilised for inkjet printing. Consequently, the creation of intricate food structures cannot be done via inkjet printing. It can be used for 3D nano printing, fills, micro-encapsulation, and, to a lesser extent, graphic embellishment (Fernanda C. Godoi et al., 2018).

## **Binder jet printing:**

A method of additive manufacturing is binder jet printing. The materials are dispersed across a fabrication platform in powder form. To bind adjacent powder layers together, a binding agent—typically a liquid—is sprayed over the powder layer (figure 3). In contrast to inkjet printing, only when necessary is the binder or ink released by pulse actuation. Each layer of the component is typically coated with powder using a counter-rotating roller. The binding agent, which is a liquid, is sprayed through the head of an inkjet onto the powder bed to produce the layer's 2D design (S Holland et al., 2018). This method has the benefits of being inexpensive and taking less time to use. But there is less surface polishing (Le-bail et al., 2020). With the addition of a liquid binder to the powder components, food is printed using binder jet technology. Due to their higher hygroscopicity and stickiness, powdered materials have a propensity to clump together.



**Figure 3 – Schematic representation of the binder jetting (Source: M. Navaf, K.V. Sunooj, B. Aaliya *et al.,* 2022)**

# Future prospects and limitations with 4D food printing

A new method called 4D food printing gives 3D food printing an additional dimension by including the concept of time. This enables printed food to change or transform over time in reaction to environmental factors. Although this technology has enormous potential to revolutionise food production and personalization, it also has a number of drawbacks and potential implications for the future that must be taken into account:

**Future Aspects of 4D Food Printing:**

Personalized Nutrition: Tailoring meals to individual dietary needs and preferences.

Sustainability: Reducing waste, optimizing resource use, and exploring alternative ingredients.

Culinary Innovation: Merging taste with visual and interactive elements for unique dining experiences.

Medical and Functional Foods: Designing foods with specific health benefits, timed nutrient release, or medication delivery.

Education: Enhancing food awareness and culinary skills through interactive experiences.

Space Exploration: Providing diverse, nutritious food options for long space missions.

Collaborative Cooking: Enabling remote cooking collaboration through shared printer instructions.

As with any emerging technology, there are both challenges to overcome and exciting possibilities to explore in the dominion of 4D food printing. Continued research, collaboration, and innovation will shape its development and integration into our daily lives.

**Limitations:**

Material Suitability: Developing edible materials that can withstand printing, maintain safety, and transform as intended over time.

Printing Precision: Ensuring accurate printing of intricate designs while preserving taste and texture.

Hygiene and Safety: Adhering to food safety regulations and preventing contamination during printing and consumption.

Flavor and Texture Preservation: Overcoming changes in taste and texture due to printing processes and time delays.

Customized Nutrition: Creating nutritionally balanced and personalized meals using algorithms and nutritional databases.

Equipment Accessibility: Addressing the cost and availability of specialized printers for wider adoption.

# III. Conclusion

4D printing is still in its infancy in India, and there are just a few applications in the food sector. However, certain steps are being done to investigate this technology's potential in the preparation and packaging of food. Additionally, this technique is used to produce food for space travel. Leading research organisation in the nation currently investigating the use of 4D printing in food is the Indian Institute of Food Processing Technology (IIFPT). The organisation has created a freshness sensor for packaged foods that is 4D printed. In India, where food spoiling is a major problem, this technique has the potential to decrease food waste and enhance food safety. Additionally, a few startups in India are developing 4D printing technology for the food sector.For instance, Natural Machines, a firm, is creating 4D printing technology that will enable the production of food using organic ingredients like fruits and vegetables. But the adoption of 4D printing in the Indian food industry is still in its infancy due to the high cost of the technology as well as a lack of expertise and experience in this field. To encourage the use of 4D printing in the food business, more funding is required for research and development as well as training and teaching programmes. Conclusion: Despite the minimal use of 4D printing in India's food business today, there is room for future expansion and improvement. The proper investments and efforts could benefit from using this technology.

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