4D Printing in Food Technology

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**Abstract**

# A form of additive manufacturing, four-dimensional printing is an advancement above 3D printing. 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

Four-dimensional (4D) printing is an emerging area of printing and an additive method of manufacturing. A development of 3D printing, the 4D printing process modifies the printed design over time (Choi et al., 2015). This idea was initially developed in 2013 by an investigation team at the Massachusetts Institute of Technology (MIT) (Tibbits, 2014). In terms of the printing procedure, 4D printing is comparable to 3D printing, which also uses 3D printers to produce structures and create 3D drawings (Choi et al., 2015). As 4D printed objects are capable of altering shape or function, they vary from 3D printed structures primarily in terms of innovative design and innovative materials (Pei & Loh, 2018). Most of materials used in 4D printing are single- or multilateral polymers (Kuang et al., 2019). The intended product qualities may be achieved through 4D printing at the ideal moment and may even change as manufactured things are kept. The food sector employs a variety of food resources as ink for printing instead of intelligent materials, in contrast to other 4D printing industries (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. The field of 4D food print is rapidly developing. The numerous stimulation agents, stimulus-responsive substances, and stimulus-induced modifications to the many characteristics of 4D print food (colour, taste, scent, texture, and shape alteration) are the main topics of this review.

**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 technology, the types of stimuli utilized, the kind of stimulus-responsive substance used, the relationship mechanism and mechanical simulation are the key elements of the 4D printing process (Ali et al., 2019). Since it is easy to use and adaptable to a range of inks, the micro-extrusion process is well-liked amongst numerous printing methods.

**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. If subjected to a stimulus, they have the ability to change the way their attributes are stored. There are several stimuli, such as temperatures pH, light, etc. Shape memory polymers and liquid crystal elastomers are two instances of single-material smart materials utilised in 4D printing. A composite metamaterial might be the cause.

**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). Due to the great tuning capabilities of the temperature at which transition occurs, the optical and mechanical properties, and the simplicity with which shape memory may be triggered, thermo-responsive SMPs are a popular research area. These are often produced with imperfections. Deformation results from exposure at a temperature over the transition temperature, cool to a temperature beneath the transition temperature, loading, and unloading. The SMPs recover their pre-programmed shape after being exposed to a temperature beyond the transition temperature due to entropic flexibility (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):**

# To offer the anisotropic properties of LCEs, mesogenic moieties are frequently added to the polymeric network, either as adjacent groups or in a chain backbone (Sun et al., 2021). LCEs are materials that are anisotropic, stimuli-responsive, and reversible. LCEs can change their form in response to external stimuli such magnetic fields, temperature, light, and electric fields. According to Ula et al. (2018), poly (hydrosiloxane) polymers, acrylates, and methacrylate are the most often used precursors for the manufacture of LCEs.

# 4D printing in the food industry

MIT researchers pioneered the application of 4D printing in the food business. They used water as an accelerator and produced a 2D film from protein, cellulose, and starch. 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. Temperature and pH are only two examples of the many stimuli that may cause food to change in form, colour, texture, and fragrance. According to the structure and specific food formula, the printing ink may be employed in a variety of combinations of food elements to generate the stimulus-induced changes in the 4D printed samples of food (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.

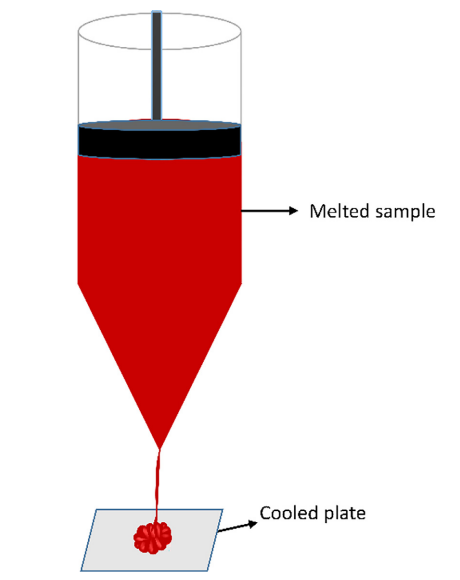
**4D food printing inks:**

The printing ink used in 4D food printing is made of food components (Kewuyemi et al., 2021). The food ink has to have each liquid-like and solid-like properties both earlier and afterward printing (Gholamipour-Shirazi et al., 2019). Element size was examined in relation to how effectively food inks printed. The bigger particles (307 m and 259 m), which have a skeletal-like cell structure, are more porous than the smaller particles (up to 172 m), according to the researchers. The dyes in printing ink generate 4D variations in food colour under various pH settings. These compounds respond to conditions or stimuli by changing their complexion, flavour, texture, and other qualities. Curcumin, which exhibits a yellow hue in acid or a neutral pH value and a red colour in alkali pH, is one of the stimulus-responsive materials used in 4D printing (C. Chen, Zhang, Guo, et al., 2021). Anthocyanin does similarly, acting as a chemical that changes colour in accordance with a pH stimulation (He et al., 2021).

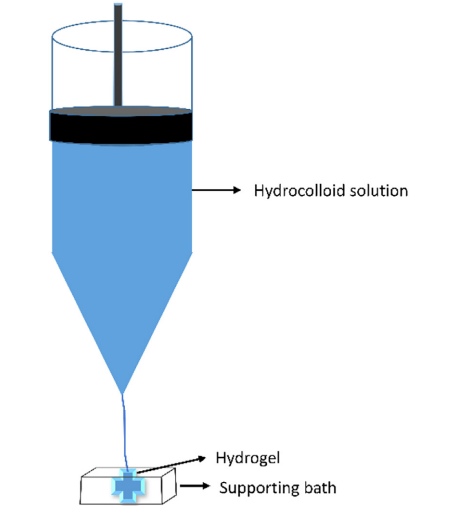
**Food printing methods:**

## **Extrusion printing:**

Extrusion-based food printing is simplest form of food printing. It is applicable to melted constituents which are measured by a temperature and semi-viscous system (Mantihal et al., 2020). A virtual 3D model is programmed for extrusion printing and then converted into layer patterns and codes by using slicing software. Before food can be printed together with the significant procedure these codes must be submitted to the printer. Dependent on the program design used to manufacture the item, materials are extruded by shifting the nozzle above a set level or by moving the machine under the nozzle to create a film. When the extruded layers attach to one another, a 3D structure formed of layers is produced (Sun et al., 2018). Researchers frequently used extrusion at room temperature to produce 4D food items. Chen, Zhang, Guo, et al. (2021) used an extruder with nozzle diameters of 1.2 mm and 1.5 mm to generate a rough surface in order to turn lotus root powder into a gel. Extrusion of printed materials at room temperature, such as melting cheese and dough. Extrusion at the ambient temperature is widely employed to produce confections that are difficult to make by hand yet have excellent repeatability. Additionally, extrusion at the ambient temperature may be used to print pasta. Materials including proteins (Phuhongsung, Zhang, & Bhandari, 2020), puree (Shi et al., 2022), carbohydrates (He, Zhang, & Devahastin, 2020) etc., have been utilized as printing materials in room temperature extrusion. Hot-melt extrusion develops new material by melting and heating the source material. The melted ink is then pressurised into a die in a controlled atmosphere. 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. It immediately hardens after extrusion and is sealed to the layer below. In order to control viscosity and flowability at the printing nozzle during hot melt extrusion, higher temperatures should be maintained based on the kind of material employed. Hot-melt extrusion produced goods that were uniform in thickness and density (Tan et al., 2018). In hydroforming extrusion, the hydrocolloid solution or dispersion is distributed to the gel setting/polymer/hardening bath in the hydroforming extrusion process using a nozzle pipette, jet cutter, vibrating nozzle, and other similar equipment (Fig. 3). According to Le-bail et al. (2020), In this process, the viscoelastic qualities of the materials are crucial and are dependent on their ability 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. According to Kirchmajer et al. (2015), the three main processes that contribute to the synthesis of hydrogels are chemical cross-linking, ionotropic cross-linking, and the development of complex coacervates. 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)**



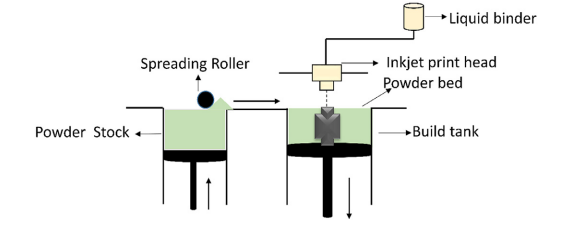
**Figure 2 - Schematic representation of the hydroforming extrusion (Source: M. Navaf, K.V. Sunooj, B. Aaliya *et al.,* 2022)**

## **Inkjet printing:**

This printing is frequently used in 4D printing as well as in confectionary and decorations (Pallottino et al., 2016). It is composed of several 20 to 50 micrometer-sized pneumatic membrane nozzles, or "jets," that are used to spray edible ink onto moving objects. One or more simultaneously operating nozzles can spray the printing ink onto the printing surface to produce layered structures. The droplets combine for formation of a digital picture through the aid of cavities depositions and surface fills. Inkjet printing often practices low viscosity constituents. So, it is used to sketch flat substances rather than print intricate structures. Temperature has a big influence on inkjet printing. It will affect the substance's superficial energy and viscosity (Le-bail et al., 2020). Inkjet printing often uses low viscosity materials. As a result, inkjet printing cannot be used to create complex food structures. According to Fernando C. Godoi et al. (2018), it may be utilised as 3D nano printing, fills, micro-encapsulation, and, to a lesser extent, visual adornment.

## **Binder jet printing:**

This is an additive manufacturing technique. The constituents are spread out in powder form on a fabrication platform. To bind adjacent powder layers together, a binding material—typically a liquid—is scattered over the powder layer (figure 3). In comparison to inkjet printing, pulse actuation only releases the binder or ink when it is essential. Usually, a counter-rotating roller is used to cover each layer of the component with powder. To create the layer's 2D pattern, a liquid binding agent is sprayed into the powder bed through the inkjet's head (S Holland et al., 2018). This approach has the compensations of costing less money and demanding less time to use. Nevertheless, there is not as much cleaning of the surface (Le-bail et al., 2020). Food is printed by binder jet technique by mixing a liquid binder with the powder ingredients. Pulverized constituents have a tendency to to clump together because of their increased hygroscopicity and stickiness.



**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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