

4D PRINTING IN FOOD TECHNOLOGY

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 articles 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, buckwheat dough, starch etc. A stimulus-responsive substance makes up the printing liquid ink utilised in 4D food printing, causing spontaneous modifications in 3D produced structures. Vanillin powder, anthocyanin, and curcumin are examples of stimulus-responsive compounds used in 4D food printing. Curcumin's colour will alter in reaction to pH.. It is feasible to conduct experiments using a variety of stimuli-responsive materials and stimulating stimuli, including light.

Keywords: Four-dimensional (4D) printing food printing, Shape memory polymers, Liquid crystal elastomers

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I. INTRODUCTION

Four-dimensional (4D) printing is an evolving area of printing and an additive method of manufacturing. The 4D printing method, which is an advancement of 3D printing, transforms the printed pattern as time goes on (Choi et al., 2015). This concept was first proposed in 2013 by a research group at the Massachusetts Institute of Technology (MIT) (Tibbitts, 2014). In terms of printing, 4D printing is similar to 3D printing, that employs 3D printers to generate structures and 3D designs (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). The majority of 4D printing materials are sole- or multilayer polymer (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.

II. 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 important parts of the 4D printing method include the application of additive manufacturing technology, sorts of stimuli employed, the type of stimulus-responsive substantial used, the relationship mechanism, and mechanical simulation (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.

III. 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.

- 1. Shape Memory Polymer (SMP):** When activated, these polymer compounds may undergo a brief modification to their form and structure before returning to their original shape. Although polylactic acid is among the utmost frequently usable SMP for 4D printing, other materials such as bisphenol, poly cyclo-octene, and others are also employed (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 frequently created with flaws. Deformation occurs as a result of being exposed at temperatures above the changeover temperature, cooling to temperatures below the threshold temperature, loading as well as unloading. Due to entropic flexibility, SMPs restore their pre-programmed form after being subjected to temperatures above the transition point (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.
- 2. Liquid Crystal Elastomers (LCE):** Mesogenic moieties tend to be added to the polymer network, either as neighbouring group or in a chain backbone, to provide the anisotropic features of LCEs (Sun et al., 2021). LCEs are antagonistic, stimuli-responsive, and reversible materials. External stimuli such as fields of magnets, sunlight, temperature, and electric fields can cause LCEs to alter shape. In the work of Ula et al. (2018), the most often utilised precursors for the production of LCEs include poly (hydrosiloxane) polymer compounds, acrylates, and methacrylates.

IV. 4D PRINTING IN THE FOOD INDUSTRY

MIT researchers pioneered the use of 4D printing in the food industry. 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. The printing ink may be used in a range of combinations of food constituents to cause stimulus-induced modifications within the 4D printed specimens of food, depending on the erection and unique food formulation (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 dye and material with food-grade ingredients, the nutritional content of printed food will grow.

- 1. 4D Food Printing Inks:** The printing ink used in 4D food printing is made of food components (Kewuyemi et al., 2021). Food ink must have both liquid-like and solid-like qualities formerly and subsequently 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). Similarly, anthocyanin works like a chemical that changes colour in accordance with a pH stimulation (He et al., 2021).

2. Food Printing Methods

- **Extrusion Printing:** The simplest form of food printing is Extrusion-based food printing. It is applicable to melted constituents who are measured by a semi-viscous system and temperature (Mantihal et al., 2020). A virtual 3D model is programmed for extrusion printing and then converted into layer designs and encryptions by means of 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 fluctuating the nozzle above a set level or by moving the machine beneath the nozzle to create a film. When the ejected films adhere to each other, a three-dimensional structure composed of layers is generated. (Sun et al., 2018). Researchers frequently used extrusion at ambient 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), carbohydrates (He, Zhang, & Devahastin, 2020) and puree (Shi et al., 2022) etc., utilized as printing materials in ambient temperature extrusion. Hot-melt extrusion develops innovative material by melting and heating a source material. The melted ink is formerly pressurised into a die in a precise 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 hardens shortly following extrusion and becomes bonded to the layer underneath. A higher temperature should be maintained throughout hot melt extrusion to manage consistency and flow rate at the printing nozzle, depending on the material used. Hot-melt extrusion produced goods that were uniform in thickness and density (Tan et al., 2018). In hydroforming extrusion, the hydrocolloid solution is distributed to the gel setting/hardening bath in the hydroforming extrusion process by a jet pipette, jet cutter, vibrant nozzle, and other parallel equipment (Fig. 3). According to Le-bail et al. (2020), The viscoelastic qualities of the materials are crucial and are dependent on their ability to gel in this process. The hydrocolloid solution in this procedure should initially display 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.

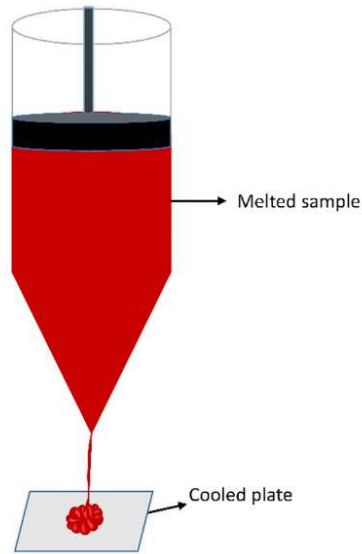


Figure 1: Diagram of the Hot-Melt Extrusion
(Source: (M. Navaf, K.V. Sunooj, B. Aaliya *et al.*, 2022))

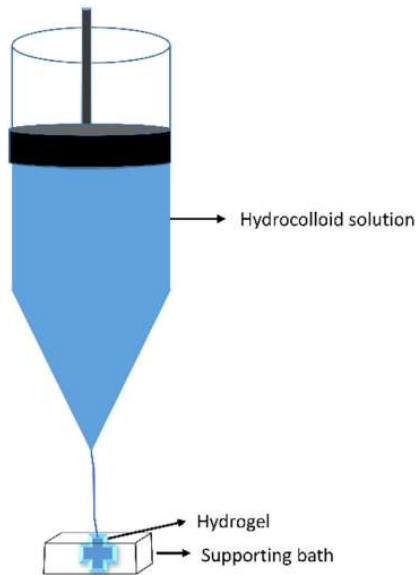


Figure 2: Diagram of the Hydroforming Extrusion
(Source: M. Navaf, K.V. Sunooj, B. Aaliya *et al.*, 2022)

- **Inkjet Printing:** This printing is frequently used in 4D printing as well as in confectionary (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 often used to sketch plane substances rather than intricate structures print. A big influence on inkjet

printing is of temperature. This will affect the substance's superficial viscosity and energy (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 making technique. The constituents are banquet 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 film (figure 3). In comparison to inkjet printing, pulse actuation only releases the binder or ink when it is essential. Usually, there is a use of counter-rotating roller to cover individual layer of the constituent with powder. To form the layer's 2D pattern, a liquid obligatory 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 not as much of 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.

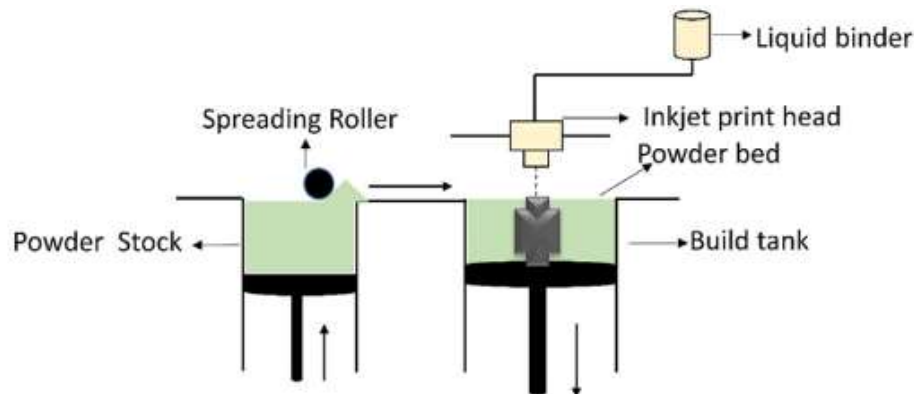


Figure 3: Schematic Representation of the Binder Jetting
(Source: M. Navaf, K.V. Sunooj, B. Aaliya *et al.*, 2022)

V. 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:

1. **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.

2. **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.

VI. CONCLUSION

4D printing is still in its initial stages in India, and there are just a limited 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 latent to decrease food surplus 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 implementation 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 usage of 4D printing technology 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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