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Shape deformation/transformation in 4D printed food: A review

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Abstract
Four-dimensional (4D) printing is an emerging additive manufacturing technique which is an extension of 3D printing. In 4D printing, structures can change their shape and function over time in response to external stimuli such as water, temperature, pH and light. 4D printing is still in its nascent stage, and its application in the food industry is limited. The main factors composing 4D printing technology are software, printing ink, 3D printers, and stimulus. The most common stimulant used in 4D printing is temperature and microwaves have a significant impact on 4D objects' shape-changing behavior. In this review, we give an overview of the software, printer, printing ink and stimuli used for 4D printing and summarise the rheological effect on the printing ink and the current application of 4D food printing based on physical changes over time due to hydration and dehydration.

Keywords: 4D printing, 3D printer, stimulus, rheology of ink, shape change

1. Introduction

Four-dimensional (4D) printing is an emerging “Additive Manufacturing” (AM) technology or “Rapid Prototyping” method similar to Three-dimensional (3D) printing technology intended to reduce production waste, personalize goods, shorten supply chains and widen material sources [31, 41]. 3D printing is a technique for creating three-dimensional structures by modelling, slicing and layering as shown in Figure 1 [7]. 4D printing is an extension of 3D printing in which material is used to create dynamic structures through external stimulations such as temperature, pH, water, light, etc. [15]. Here, time is considered as a fourth dimension, which is combined with 3D printing to be known as 4D printing. So, 4D printing is nothing but 3-dimension space co-ordinates work with the 4th dimension of time, as illustrated in Figure 2 [21]. 4D concept was first introduced in 2013 by Professor Tibbits of the Massachusetts Institute of Technology (MIT) [39]. The merits of 4D printing over 3D printing include the capabilities of printed smart items, self-assembly and the ability to modify product shape as needed [19]. In the biomedical field, 4D-printed materials are being used in tissue engineering, drug delivery and sensors, among others [43]

In the food sector, 2D to 3D shape transformation is more typical, however 1D to 1D, 1D to 2D, 2D to 2D and 3D to 3D shape deformation are also considered [25]. In 4D printing technology, 3D printer, printing software, printing ink and stimuli are the basic requirements. Chocolate, dough, cheese, a mixture of fruits and vegetables, hydrocolloid starch and hydrogel are generally used to print the customised food but due to the lack of smart materials in foods, few studies have been conducted by the researcher. Researchers developed a flat-pack concept to minimise packaging size, shipping costs and storage space by adopting a "morphing" mechanism in which stimulus-responsive food transforms shape from 2D to 3D [42].

Accordingly, the present work aims to review and summarize significant current applications of 4D food printing based on physical changes over time. Moreover, this review provides an overview of the concept and research gap as well as future scope for 4D printing.

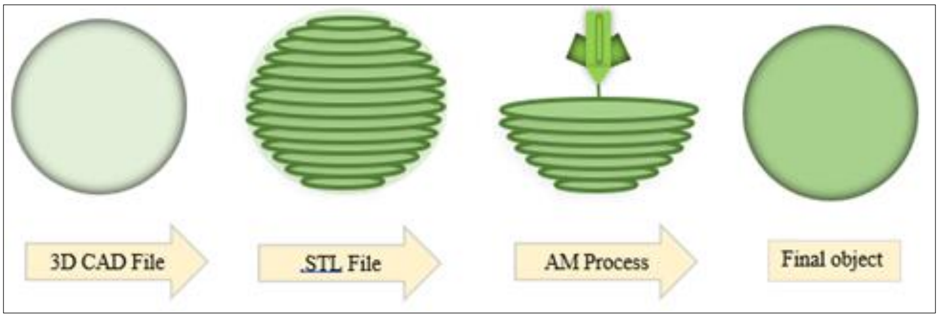

Fig 1: 3D printing process [7].

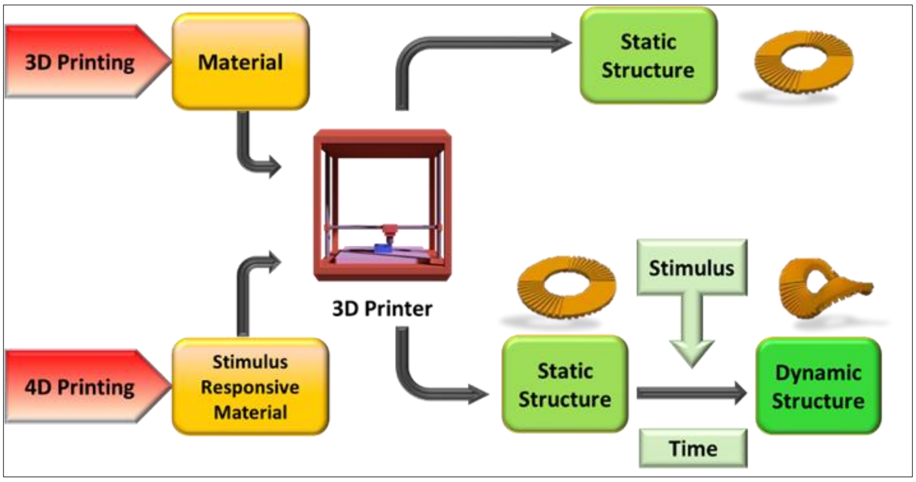

Fig 2: Difference between 3D and 4D printing

2. Model Design and Printing Process

2.1 Software and printer used in 4D printing

4D printing refers to the stimulus-induced shape changes in a 3D printed model. So, model design plays an important role in the 4D printing process. The basic idea behind 4D food printing is to build a 3D model using modelling software such as CATIA, Solidworks, Rhinoceros, Fusion 360, Creo and Blender [8]. A 3D model is sliced into a 2D model using slicer software, which generates a G-code that is then sent to the 3D printer. Slic3r (for faster slicing speed), Simplify 3D (for better slicing quality), Crafware, Cura, KISSSlicer, etc. are examples of common slicer software [5,8,27]. In 3D food printing, mainly Fused Deposition Modelling (FDM), Extrusion printing (syringe-based extrusion, screw-based extrusion, air pressure-driven extrusion), stereolithography, inkjet, binder jetting and selected laser melting technologies are used. Cartesian, Delta, Polar and Scara displacement platform configurations are utilised in FDM printers, with Cartesian being the most common [36].

2.2 4D printing materials

In 4D food printing, mainly hydrogels (gelatin, sodium alginate, pectin, xanthan gum, carrageenan, konjac gum, etc.) used to improve the flow behavior of natural food gels, and hydrocolloids that improve the rheological properties of food ink for suitable printing and commonly used as thickeners such as starch, xanthan, guar gum, locust bean gum, gum karaya, gum tragacanth, gum arabic, and cellulose derivatives [3]. The properties of polysaccharide make it a popular food additive because of its film-forming, thickening, gelling, and stabilizing abilities while polymer hydrogels have inherent swelling properties and water absorption abilities [4]. They can improve food printability by enhancing elasticity and

Table 1: Design software and printing parameter used in 4D printing process

Software	Printer	Printer parameter	References
Rhino 6.0 software	3D food printer (FOODBOT-MF)	Nozzle diameter of 1.2 mm, Printing speed of 20 mm/s Infill density was 60% 1. (Cuboid of 50×30×2.4 mm) 2. (Sheet double-layer structure 50×30 mm)	[13, 14]
` Rhinoceros	3D printer (Hangzhou Shiyin Co., Ltd., SHINNOVE-D1 China) Three-axis printer based on a Cartesian coordinate system	Plastic needle inner diameter 1.2 mm; Printing speed 15 mm/s; Printed object length 45 mm, width 24 mm with varied thickness; Filling rate 60%. Sheet double-layer structure	[2]
TINKERCAD (AUTODESK) and Slic3r	Dual nozzle 3D printer with Cartesian configuration. 35 ml plastic syringes-based extrusion system	Print speed 15 mm/s, Travel speed 10 mm/s, and Extrusion flow 100%. Three different infill densities (25%, 50%, and 75%) and infill patterns (Grid, Honeycomb (HC), and Stars)	[6]

Rhinoceros 5.0 and slicing Simplify3D software	Customized dual-nozzle 3D printer	Syringe tip diameter 1.2 mm, Printing speed of 25 mm/s, Infill density was 60%.	[24]
Rhinoceros 5.0	Syringe-based extrusion 3D printer (FOODBOT-MF)	Extrusion nozzle 0.8-mm, Printing speed 20 mm/s, Extrusion rate 35 mm^3/s and Layer height 0.8 mm	[9]
Inkscape software for G-code	Modified 3D printer with a digital air syringe dispenser	The nozzle (20-gauge, pink) diameter 0.6 mm, Printing pressure 8-10 psi.	[30]
Rhinoceros 6.0 and Repetier-Host slicing software	3D food printer (Foodbot-MF)	Nozzle diameter 0.8 mm, Printing speed 18 mm/s, Layer height 0.8 mm, Nozzle 1 wire diameter 20 mm and nozzle 2 wire diameter 22 mm.	[34]
Rhino 7.0 and slicing Simplify3D software	3D food printer (Foodbot-MF)	Nozzle diameter 0.8 mm, X/Y axis movement speed 17 mm/s, Z axis movement speed 16.7 mm/s, Layer height 0.8 mm	[10]
Rhinoceros 6.0 Simplify3D	Shiyin Technology Co. Ltd, Hangzhou, China	Nozzle with a diameter 0.8 mm, Printing speed 22 mm/s,	[16]

stability [32]. Protein (gelatin), carbohydrate (starch) and soluble fibre (agar) film absorb all water about five times their own weight that after ten minutes but insoluble fibre (ethyl cellulose film) cannot absorb any water and food gels hydrate by absorbing water due to their hydrophilic interaction with water, which also causes them to vary in volume as shown in Figure 3 [42]. The higher shrinkage rate, denser structure, and swelling characteristics of xerogels make them suitable for 4D printing food [26]. The insoluble fibre (ethyl cellulose) is used as a constraint material due to its non-toxic nature to humans and water-resistant property [17, 33, 35]. When gelatin film with or without glycerol and only ethyl cellulose (EC) strips are immersed in water, there is no shape change, but composite film exhibits shape transformation in the water [30]. The printability of food printing ink is a combination of rheological characteristics for smooth extrusion and mechanical strength to maintain mass and texture during the printing process [22]. Before application in 4D printing, the flow behaviour of printing ink is determined by its rheological properties. Rheology provides the framework for edible food printing design, development, and application [4]. For extrusion-based 3D printing, shear-thinning behaviour is preferred because it easily extrudes through a narrow opening [30]. The mechanical strength of a material is determined by its solid elastic behaviour which is known as the storage modulus (G′) and its viscoelastic or liquid behaviour is characterised by the loss modulus (G″) [28]. Recently, a few authors studied the effect of rheology on the ink matrix for shape change in 4D printing, as follows:

He *et al.* (2020) [13] studied the 3D printing characteristics of purple sweet potato powder with different formulations of edible salt (NaCl) and fructose syrup (F60-60% fructose), which were measured using a rotational rheometer and oscillation measurement (stress sweep). They found that the apparent viscosity of the material decreased with the addition of salt and with an increase in the shear rate, which shows the shear-thinning behaviour of the ink material. The viscosity of the material increased as the concentration of F60 increased. Salt reduced G' and G" of the purees, and F60 increased G' and G" of the purees.

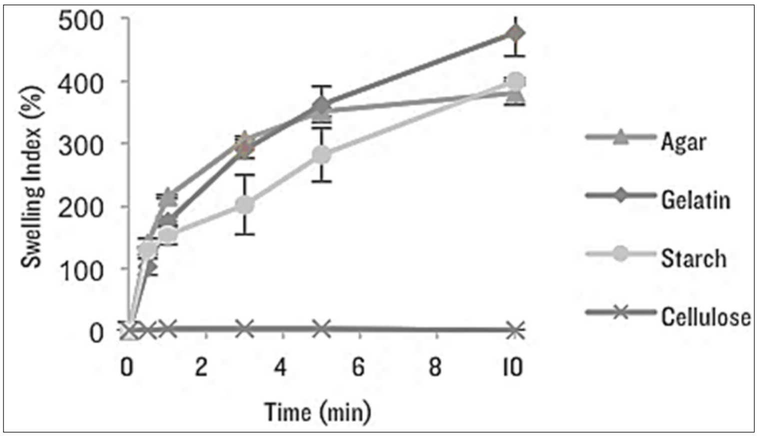

Fig 3: Swelling index of four different edible materials at 20 °C [42].

Printing ink was made separately from purple sweet potato powder (PSPP) and mashed potato (MP) with edible salt and butter (fat content of around 81%) to analyse the rheological property using a rotational rheometer [14]. The apparent viscosity of MP was higher than that of PSPP and increased with increasing MP and PSPP content but decreased with increased shear rate. MP showed better printing performance than PSPP because the G′ of MP was higher than PSPP.

The rheological properties of different formulations of pumpkin powder added with sodium alginate and water were characterised using frequency sweep and flow ramps tests [2]. They found that an apparent viscosity of puree decreased with increasing shear rate. The storage modulus was larger than the loss modulus, which is beneficial for maintaining printed structure due to weak gelation, but both decreased with increasing the solid-liquid ratio of puree.

The flow behaviour of the soy protein isolated (SPI) and soybean soluble polysaccharides (SSPS) dispersion was studied by a rheometer and oscillation test [23]. Because of the decrease in apparent viscosity with increasing shear rate, it behaves as pseudoplastic fluids. G′ decreased with increased SSPS concentration and G′ and G″ increased as a function of temperature.

The rheological characterization of gelatin was conducted by an amplitude sweep test and a frequency sweep test [30]. Printing ink showed frequency dependency in the frequency sweep test and G″ was higher than G′.

The rheological properties of ink with different purple potato powder and water ratios were tested by the temperature sweep test and rheometer [34]. At the same angular frequency, G′ and G″ of the purple potato puree decrease with increasing water content. G′ was greater than G″, but both changed as temperature increased.

Printability of mixed vegetable gels (MVG) made from cabbage puree, carrot powder and xanthan gum, were characterized by rheological properties. The apparent viscosity of MVG decrease with increase shear rate which shows pseudoplastic behaviour of printing material. G′ was larger than G″[16].

The flow behaviour of oat flour and soy protein isolate (SPI) was analysed by the rheometer and the storage modulus and loss modulus of the material were measured with a frequency range [10]. The viscosity of the printing ink decreased with an increase in shear rate, which shows the pseudoplastic non-newtonian fluid system.

The frequency sweep test on gelatin, glycerol and ethyl alcohol reveals that the printing ink has frequency dependency. The results imply that viscous properties are dominant, where the loss modulus values were higher than the storage modulus values (G″ > G′).

3. Stimuli-induced Shape Changes In 4D Printed Food

Food undergoes shape transformation as a result of hydration and dehydration processes [38]. In general, boiling water is utilised in hydration, whereas baking/microwave heating is employed in dehydration [37]. Temperature is the most commonly utilized stimulant in 4D printing and the shape-changing behaviour of the 4D object is significantly influenced by microwave. Microwave heating causes dehydration, which causes printed materials to shrink or bend [14]. Food gels hydrate by absorbing water due to their hydrophilic interaction with water, which also causes them to vary in volume. In hot water, edible films absorb water faster than in cold water [42]. Object shape-shifting is affected by the constraint material pattern and coverage applied to the top surface [11].

3.1 Shape changes due to hydration

In the case of deformation, the adhesion properties of two materials play a significant role in the stimulation of water absorption, since a poor adhesion can cause the separation of two materials in water, resulting in a failure of deformation [38]. Cold plasma treatment is employed because it consumes less energy, non-toxic and operates at room temperature. Surface etching caused by non-thermal cold plasma treatment improves adhesion in xerogel discs [12,17,35]. The shapeshifting is caused by shrinkage, expansion, anisotropic swelling and deswelling [18]. The shape is not changed by isotropic swelling, but it changes when there is an inhomogeneous density distribution, which leads to an anisotropic swelling of the product shown in Figure 4 [11]. Sessile drop drying of wheat [12,11], corn [18,35] and tapioca [17] are used to create a density gradient in xerogel discs and shape transformation is characterised by evaluating the parameters such as bending curvature, height, angle, and swelling power.

Gupta and Mahendran (2019) [11] developed monolayered shape-shifting food from refined wheat flour. A 10% (w/v) concentration of wheat flour suspension was gelatinized with distilled water then after the xerogel disc was created by pouring 1 ml of wheat flour suspension on a food-grade non-stick coated plate and drying it at ambient temperature for 20 hours. For shape transformation, ethyl cellulose was applied in varied patterns on the top surface of a xerogel disc as a constraint material, which acted like a semi-rigid structure that controlled the bending direction. The disc was soaked in hot water for 80 seconds at 90°C and it was observed that the top side of the disc swells more rapidly than the bottom side, resulting in anisotropic swelling, which results in an increase in bending angle, curvature, height and a decrease in end-to-end curve distance with time. In the absence of constraint material on the top surface, the xerogel disc bends to some extent due to anisotropic swelling, but it flattens out again. Depending on the constraint material pattern, the entire folding time was determined to be 50-60 seconds. Gupta *et al.*, (2020) [12] studied the shape transformation of wheat xerogel and investigated that the xerogel disc treated with cold plasma (7.32 W for 5 min) and

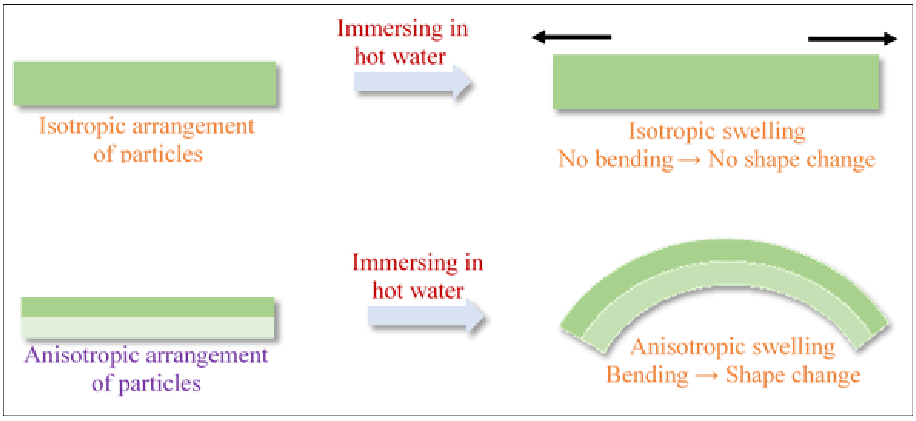

Fig 4: The technique employed for shape transformation [11]

constraint material (ethyl cellulose) showed more bending than untreated when immersed in 90 °C hot water. The saddle-like shape (3D) is transformed from a 2D flat disc due to bending. The top side (dense particles) has a higher water absorption capacity, but the swelling rate on the bottom side is lower, resulting in bending movement due to the stress gradient in the wheat xerogel sheet, and the wheat xerogel turns from clear to opaque white throughout the 4D change [33]. This demonstrates the re-gelatinization of starch polymers as they absorb hot water.

As cellulose acetate does not absorb oil, it can be used as an oil barrier to reduce the top surface oil absorption rate. Cellulose acetate was applied with a uniform pattern of 2 mm lines as constraint material on an optimised crack-free corn xerogel disc (5% and 85 °C) and deep-fried in coconut oil (220 °C). Within 2 seconds, a spiral shape was obtained. The top side of xerogel absorbed more oil than the bottom side, resulting in an increase bending angle, curvature, height and reduction in end-to-end distance observed by Stephen *et al.,* (2021) [35].

Corn flour dispersion (5 g/100 mL) was gelatinized to form hydrogel, which was further poured on a ceramic-coated aluminium plate using a micropipette for sessile drop drying. Hydro-responsive shape (spiral, tubular) deformation of corn xerogel with constraint (ethyl cellulose) material starts at a temperature of 90 °C within 30 s of time when immersed in hot water. Except for the end-to-end distance, the height, angle, and curvature of the corn xerogel disc increase over time observed by Jaspin *et al.,* (2022) [18].

Hydromorphic and oleomorphic shape change on tapioca xerogel investigated by Jaspin *et al.,* (2021) [17]. Tapioca xerogel is made from tapioca hydrogel (5%) using the sessile drop method. Before applying constraint material, the xerogel disc was treated for better binding on cold plasma. For hydromorphic shape change, ethyl cellulose was applied on top of a xerogel circular disc (2 cm diameter and 20 mm thickness) manually with a micropipette, and cellulose acetate was applied with a specific pattern for the oleomorphic shape change. Within 50 s, 2D to 3D shape change observed when a xerogel disc with constraint material is immersed in hot water (90 °C) and took 2 s when fried at 220 °C in oil. Irregular shapes are observed in unconstrained xerogel discs during hydromorphic and oleomorphic shape transformations.

Water contact angle is a parameter that is used to describe shape change and quantifies the wettability of a surface. The bending direction and degree of xerogels are determined by their wettability. A liquid's wettability depends on how much it spreads when it is deposited on a solid substrate [1]. The Soy protein isolated (SPI) dispersions prepared by SPI and deionized water. Soybean soluble polysaccharides (SSPS) was added at 0%, 1%, 2%, 3%, 4%, and 5% to the SPI/SSPS dispersions. During hydration, the greatest contact angle (24.17) was found in 3% SSPS xerogel, which was determined by a sessile water drop technique using an automated microscopic contact angle metre. The degree of bending is observed in the order of 3% > 2% > 1% > 0% [23].

4D shape changes of edible material is studied by Pulatsu *et al.,* (2022) [30]. To investigate shape deformation of edible material, pure gelatin film (PGF) and a composite glycerol-gelatin film (GGF) were cast with different volumes (10, 20, 30, and 40 ml) and constraint material ethyl cellulose printed on film with a specific pattern in Petri dishes with a diameter of 8 cm. When exposed to water, films containing glycerol GGF deformed much less than films containing pure (PGF). No matter how many EC lines are in the composite film, it deforms similarly. According to the results, the samples of PGF-10/EC, PGF-20/EC, PGF-30/EC, and PGF-40/EC required 6, 9, 15, and 19 minutes to reach their maximum curvatures, respectively, and the thinner sample (PGF-10) showed the highest curvature. The composites' responsive capability was found to be as follows: PGF-20/EC > GGF-20/EC, PGF-30/EC > GGF-30/EC, and PGF-40/EC > GGF-40/EC.

Water-triggered shape-transformable (2D to 3D) food for the flat packing Wang *et al.,* (2017) [42] developed a cold pasta salad out of edible gelatin gel (6% w/v) with squid ink, potato extract, or seaweed and ethyl cellulose printed on gelatin film that was immersed in water (30 °C). Within two minutes shape was changed. The self-wrapping film made from edible gelatin and printed cellulose solution with a line thickness of 1 mm, then a square-shaped (2×2 cm) sheet immersed in water at 35 °C, within 2 minutes film wraps fish caviar. Self-chopped noodles made using high and low-bloom gelatin in a seaweed extract and cellulose-printed film submerged in hot chicken soup. The transformation occurred within 5 minutes.

3.2 Shape changes due to dehydration

Food processing often involves dehydration to diffuse moisture from the sample, resulting in a moisture gradient. The moisture gradient creates stress and strain, causing the printed sample to deform. Liu *et al.,* (2021) [24] investigated the effect of added oil, fructose syrup (F60), and salt (NaCl) on the 4D shape change of food with different drying methods like microwave dehydration (MD), infrared dehydration (ID) and hot air dehydration (AD). For making printing ink, oil (0, 2, 4, 6, 8, 10 g), fructose syrup: water (60:40, 45:55, 30:70, 15:85, 0:100) and salt (0, 0.5, 0.75, 1 g) was added to the potato flakes/starch gel slurry, and an object (length: width: height = 50: 30: 2 mm) was printed with a customised dual-nozzle 3D printer. To investigate the bending deformation, the object was dehydrated through an air dryer (set air velocity and temperature at 1.5 m/s 50 °C, respectively), infrared radiation dryer (at 35 °C, 50 °C and 65 °C and the inlet air velocity was set at 1.5 m/s) and microwave dryer (set 1.0 W/g). The object was dehydrated using an air dryer (set air velocity and temperature at 1.5 m/s and 50 °C, respectively), an infrared radiation dryer (at 35 °C, 50 °C, and 65 °C, with the inlet air velocity set at 1.5 m/s), and a microwave dryer (set at 1.0 W/g) to investigate the bending deformation. As oil content increased from 0 to 2 g, the object's bending angle increased more in AD than MD, but at 4 g or greater, a sharp zero-degree angle was observed. The content of fructose syrup and salt decreased, the bending angle of AD and MD samples increased and the bending angle was observed in order to: AD > ID > MD.

The bending degree of samples increased with dehydration time, and it depends on the degree of infill, type of material, and drying conditions. This was because the evaporation of water caused the shrinkage of samples. The solid-liquid ratio of pumpkin puree (1:1.67) was chosen to observe the 4D deformation due to air drying [2]. Objects were printed with varying thicknesses (1.2 mm, 2.4 mm, 3.6 mm, 4.8 mm, and 6.0 mm with a constant printing path of 90°) and different printing paths (0°, 30°, 45°, 60°, 90°, 120°, 135°, and 150°) to evaluate the effect of thickness and printing path. The bending angle increased with decreasing thickness, and the printed object bent perpendicular when the printing path was kept at 0° or 90°. Opposite distortion deformation was observed in the cases of $0° < \theta < 90°$ and $90° < \theta < 180°$. When the angle was closer to 0° or 180°, the degree of bending was more, but when the angle was closer to 90°, the degree of bending was less.

Microwave (MW) drying induces 4D deformation and the effects of salt, fructose syrup, and morphology on printed objects, as studied by He *et al.*, (2020) [13]. The rate of dehydration increased with the increase in MW power and salt content in the printed sample, but the degree of deformation decreased. In the sample, water content decreased as fructose syrup content increased, resulting in a decrease in deformation. The authors observed that when infill angle increase, the bending deformation of the 3D printed 2D sheet decrease and always bent perpendicular to the infill line. He *et al.*, (2021) [14] also investigated the effect of edible salt and butter content on bending angle deformation through microwave dehydration (microwave power of 2.0 W/g) in 4D printed starch-based food products from purple sweet potato paste (PSPP) and mashed potato (MP). PSPP and MP bending angles increased as edible salt and butter content decreased. Under the same conditions, MP had higher bending angles than PSPP.

A shape-changing study was conducted by Shi *et al.*, (2022) [34] to analyse the influence of time and power of microwave on the bending angle and model height. The model was printed with different ratios of oleogel and purple potato puree. With constant power (60 W), model deformation was analyzed at a 15 s time interval from 0 to 135 s, and with 60 s of constant time, model deformation was analyzed at different levels of microwave power (0 W, 30 W, 60 W, 90 W, 120 W, 150 W, and 180 W). The bending angle increased with the increase in microwave power or time, but no changes occurred in the model when microwave time and power exceeded 105 s and 150 W, respectively.

Yellow peach powder and buckwheat powder were mixed (1:1) with water in a ratio of 1:2. Chinese yam powder and purple sweet potato powder were mixed with water to make ratios of 1:3 and 1:2.8, respectively. Using a T18 homogenizer, each mixture was homogenized for two minutes, and the homogenized mixture was heated in a household microwave oven (700 W) for 30 seconds to gelatinize the starch. The gelatinized mixture was printed in four-petal and single-petal shapes to evaluate the deformation through microwave drying [9]. A microwave power of 50, 100, 150, and 200 W induced the final bending of single petals at 240, 90, 60, and 30 seconds, respectively, while in the four-petal flower shape, deformation occurred less than 270, 240, 120, and 90 seconds. Within 90 s, yam and purple sweet potato printed petal showed deformation at 200 W microwave power.

A shape-changing study on the double-layer structure and different printed models like a vase, cross, hexagonal flower, four-petal flower and butterfly were conducted using a hot air oven drying method [16]. The structure was printed with a 3D printer using Chinese cabbage, carrot powder and xantham gum gel and at a constant temperature of 45°C, shape deformation was observed over time up to 210 min.

Guo *et al.*, (2023) [10] studied the effect of the proportion of soy protein isolate (SPI) in oat flour while using an external stimulus such as microwave heating. A printed butterfly model (46.37 mm x 23.94 mm x 24.00 mm) was heated in a microwave oven for 30 s at 230 W power. When the object was treated in a microwave oven, the best shape distortion was found when the oat flour and SPI ratio was 1:0.7.

Researchers developed a groove-induced morphing mechanism to change the shape of flour-based food materials. Hydration and dehydration are controlled by grooved geometrical features. Tao *et al.*, (2019) [37] developed flour-based pasta for the flat pack concept of packaging, which saves space ranging from 41% to 76%. Groove depth and direction affect the swelling and shrinkage properties of pasta. The pasta was made from semolina flour with a groove depth of 1.8 mm, and shape change was observed through hydration (boiling water) and dehydration (baking). The maximum bending curvature observed in a bi-layer composite structure of plain dough and oat fibre dough A grooving mechanism is used to create self-wrapping tacos and cannoli as a result of baking (dehydration). The hydration process bends more than the dehydration process with the same geometry.

Nishihara and Kakehi (2021) [29] developed 4D printed food from rice flour and shape-changing behaviour was evaluated with downward and upward bending. The shape-changing effect evaluate based on printing parameters, dispensing pressure (kPa) and baking time. The authors utilised an extrusion-based printer to produce several different food items, including self-wrapping film, monaka (Japanese sweet) wafer shell, edible cutlery and magashi.

Kan *et al.*, (2017) [20] investigated shape-changing behavior using pH stimuli. Chitosan films (20 x 7.5 mm) were prepared with chitosan powder (4% w/v) dissolved in acetic acid (3% v/v). The dry films were tested using different pH solutions, and it was observed that at pH 3 and 8, there was more swelling. Edible paper can be changed into an origami (Japanese art form) shape while adding acidic liquid [40]. Edible paper made with five flavours of fermented plums, carrots with tomato powder, carrots, fermented kohlrabi with mustard, and fermented kohlrabi. A shape-changing behaviour study was conducted on a carrot sheet which was made from carrot puree, NaHCO3, starch, glycerol, sodium alginate, agar, CMC-Na and dried in a dehydrator at 63 °C. Chitosan (6% w/v) was printed on the dry carrot sheet with the WiibooxSweetin 3D food printer, then lemon juice was pipetted onto the printed line to evaluate shape deformation from a 2D to a 3D shape.

4. Future Scope

The future of 4D printing in the food industry is promising, as it has the potential to bring about significant advances in food production, packaging, and consumption. Some possible future applications of 4D printing in the food industry include:

- Personalized nutrition: With 4D printing, it will be possible to create customized food products tailored to an individual's specific nutritional needs. This could help to improve overall health and wellness.
- Sustainable food production: 4D printing could be used to create plant-based meat alternatives that mimic the taste and texture of real meat, without the environmental impact. It could also be used to produce food in a more efficient and sustainable manner, reducing waste and minimizing the use of resources.
- Enhanced food safety: 4D printing could be used to create food packaging that is more effective at preventing contamination and spoilage, helping to ensure that food stays fresh and safe to eat for longer periods.
- Improved food aesthetics: 4D printing can create visually appealing and intricate designs for food, making it more attractive and appealing to consumers. This could lead to more diverse and interesting food offerings in restaurants and grocery stores.
- New culinary experiences: 4D printing could enable

chefs to create new culinary experiences by incorporating 4D-printed elements into their dishes. For example, a 4D-printed chocolate sculpture that slowly melts away as the diner eats it could create a unique and memorable dining experience.

Overall, the potential of 4D printing in the food industry is vast, and as the technology continues to develop, we are likely to see more innovative applications and exciting possibilities emerge.

5. Conclusion
In India, 4D printing is still in its nascent stage, and its application in the food industry is limited. However, some initiatives are being taken to explore the potential of this technology in food production and packaging. This technology also used for the manufacture of space food.
The Indian Institute of Food Processing Technology (IIFPT) is a leading research institution in the country that is actively engaged in exploring the use of 4D printing in food. The institution has developed a 4D-printed edible sensor that can detect the freshness of packaged foods. This technology has the potential to reduce food waste and improve food safety in India, where food spoilage is a significant issue.
In addition, some startups in India are working on 4D printing in the food industry. For example, a startup called Natural Machines is working on a 4D printing technology that can create food using natural ingredients such as fruits and vegetables.
However, the adoption of 4D printing in the food industry in India is still limited due to the high cost of technology and the lack of awareness and expertise in this field. There is a need for more investment in research and development, as well as training and education programs to promote the adoption of 4D printing in the food industry.
In conclusion, while the application of 4D printing in the food industry in India is still limited, there is potential for its growth and development in the future. With the right investments and initiatives, this technology could help to improve food safety, sustainability, and nutrition in the country.

6. References

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