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4D food printing technology: Structural changes to culinary art and beyond

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Abstract

The evolution of food manufacturing through 3D printing has expanded with the development of 4D printing technology and opened new possibilities in culinary applications. Compared to conventional 3D printing, 4D printing incorporates time as a new dimension, allowing for dynamic modifications to food structures. Self-assembly and reactions to external factors such as pH, moisture content, or temperature are examples of these alterations. The gastronomic design and nutritional possibilities have increased with the use of 4D printing in the food preparation process. Personalized nutrition is a significant use of 4D printing in the food industry. With the use of this technology, food products may be tailored to meet the dietary requirements of everyone, encouraging better eating practice and treating nutritional shortages. Furthermore, complex culinary designs that were previously difficult to accomplish are now possible by 4D printing. Intelligent materials that adapt their surroundings allow for self-adjusting forms or packaging, which lowers waste and promotes sustainable food practices. Transportation and food storage could be revolutionized by 4D printing. Food deterioration and waste can be reduced, and food quality preserved throughout storage and transportation with the help of self-adjusting packaging that adjusts to temperature fluctuations. Examining the most recent advancements in 4D food printing technology, this review highlights how this technology can revolutionize customized nutrition, sustainability, waste management, and culinary inventiveness.

Practical Applications

Understanding the concept and advances in food printing technology is important to develop nutritionally enriched food products with desired shape. The factors involved in 4D food printing technologies and the structural and biochemical changes in products during processing are critically analyzed.

KEYWORDS

modeling, 3D-printing, food, food manufacturing, sensory

1 | INTRODUCTION

The advancement of printing technology from 3D (three-dimensional), is where the antiquity of 4D printing begins. 3D printing is the layer-

Poornima Singh and Vinay Kumar Pandey shared equal first co-authorship.

by-layer of simple or complicated structures using software-enhanced computer-aided design (CAD). When Chuck Hull (of 3D Systems Corp.) submitted a patent for the stereolithographic technique, the world's interest in 3D printing surged. However, the phrase 3D printing was eventually linked to MIT's (Massachusetts Institute of Process) adhesive jetting technology that used a powder bed. Another name for industrial-scale 3D printing is additive manufacturing (AM), often known as rapid prototyping (RP) (Guo et al., 2020; He, Zhang, & Devahastin, 2020; He, Zhang, & Fang, 2020; He, Zhang, & Guo, 2020). Due to its ability to produce goods with high speed, low cost, and accuracy, 3D printing has sparked a lot of interest among academic institutions and major corporations (Phuhongsung, Zhang, & Bhandari, 2020). The expansion of 3D printing has encouraged this technique using 4D technology (Guo et al., 2020; He, Zhang, & Devahastin, 2020; He, Zhang, & Fang, 2020; He, Zhang, & Guo, 2020; Phuhongsung, Zhang, & Bhandari, 2020). 4D printing essentially encourages 3D printed goods to spontaneously change characteristics (such as color, form, and sensory attributes) in response to external inputs (Chen, Zhang, & Devahastin, 2021; Chen, Zhang, Guo, & Chen, 2021; Chen, Zhang, Liu, & Bhandari, 2021; Shanthamma et al., 2021). 3D printing has revolutionized industry, medicine, aircraft, and food production in recent years. 4D printing has advanced this breakthrough and brought new gastronomic possibilities. 4D printing lets food structures morph, self-assemble, or respond to environmental stimuli, giving food printing unparalleled versatility and utility. This study explores 4D printing, the next generation of food printing technology. In this paper, it is discussed how technology is changing food production, culinary art, and nutritional science. The potential of 4D printing to alter and improve desired sensory, flavor, nutritional, and other properties should result in creative food products catering to various customer groups' interests. Smart and advanced materials utilized in 4D printing can self-assemble, be versatile, and heal themselves (He, Zhang, & Devahastin, 2020; He, Zhang, & Fang, 2020; He, Zhang, & Guo, 2020). The most popular materials are single or multilateral polymers (Kuang et al., 2019). It consists of composite hydrogels, shape memory polymers, and elastomers of liquid crystals. 4D printing's stimulus-responsive shape modifications assist in reducing the need for storage and transportation space (Pei & Loh, 2018). A benefit of 4D printing is the ability to tailor material responsiveness setups and adaptability (Chu et al., 2020). The application of four-dimensional printing has the capacity to modify consumer attitudes and inclinations, especially with unique food items (Phuhongsung, Zhang, & Bhandari, 2020). Moreover, chefs may find it easier to determine the ideal cooking endpoint with the help of 4D printing's regulated and adjustable structural deformation, which would improve the dish's flavor and appearance (Chen, Zhang, & Devahastin, 2021; Chen, Zhang, Guo, & Chen, 2021; Chen, Zhang, Liu, & Bhandari, 2021). When 4D printing is employed, specific product attributes can be obtained as needed; however, over time, when made items are stored, these attributes may gradually erode. As such, a wide range of industries, including biomedicine, electronics, robotics, tissue engineering, and more, are now researching 4D printing (Ghazal et al., 2021). 4D printing in the food industry is emerging and the field is still in its infancy. An MIT study team created an edible 2D film made of starch, protein, and cellulose that change into a 3D structure when it meets water. Water adsorption initiates this transformation process, which is highly consistent with the idea of "flat packaging" to drastically reduce storage and shipping expenses. 4D printing uses a hybrid fabrication method, material-based design, and performance modeling to create these transformable edibles. Through a predefined simulation platform, users can modify food shape changes, and then use additive printing to manufacture these planned patterns. To display the shape, feel, and interaction with food items, three application techniques like 2D to 3D folding, temperature-induced self-fragmentation, and hydration-induced wrapping are offered (Wang et al., 2017). Unlike other 4D printing businesses, food makers utilize various arrangements of food ingredients as printing ink instead of intelligent materials (Jiang et al., 2019). The final product quality will depend on the type and structure of stimulating agent used. When stimuli like water, pH, temperature, and so forth are present., when printing ink is created using a specific formula, the attributes of the printed object will alter predictably (Zhao et al., 2020). A distinct character is created during the meal by the self-transformation of flavor, texture, color, and other printed item properties caused by 4D food printing as a function of time (Ghazal et al., 2019). The field of 4D food printing research is rapidly growing. The development of 3D printing, which is closely tied to 4D printing, can open new possibilities for the latter. The different 4D-printing study areas can be divided into two groups: equipment development and deformation mechanisms. The underpinnings of 4D printing are advanced printing technology and the synthesis of new materials with varied responses, both of which fall under the category of equipment development. In essence, 4D printers are a subcategory of 3D printers. Laser-assisted bioprinting, direct inkjet cure, and selective laser melting are some of the current 4D printing techniques that are relevant. The selection of the printer should be carefully considered in light of the many categories of smart materials that will be covered in more detail in the following section. 4D food printing has the potential to change how we create, consume, and interact with food. This article discusses 4D printing in the food sector, its applications, and its advantages over traditional food manufacturing methods. 4D printing promises a more personalized, creative, and efficient food sector by focusing on innovation, sustainability, and culinary quality. We hope this inquiry will stimulate more research and development in this intriguing and cutting-edge subject, uncovering 4D printing's culinary potential. As a result, this review focuses on various attributes of 4D-printed food (texture, color, taste, flavor, nutrition, and shape modification).

2 | TRANSFORMATION OF 3D TO 4D PRINTING

3D microstructures formed of intelligent materials that rely on these materials' capabilities can change in a specific way over time. A new phrase, "4D printing," has emerged as a result (Kang et al., 2018). Professor Tibbits (2014) made the initial 4D printing concept suggestion in 2013 (Khoo et al., 2015). In 3D bioprinting, 3D structures are created by layer-by-layer precisely arranging biochemicals, biological materials, and living cells along with spatially controlling the placement of functional components. Three-dimensional (3D) bioprinting uses a variety of techniques, such as mini-tissue building blocks, autonomous self-assembly, and biomimicry. These techniques are being developed by researchers to create 3D functional live human constructs with mechanical and biological qualities suited for organ function restoration and clinical tissue (Leist & Zhou, 2016; Li et al., 2016; Momeni et al., 2017). It is a purposeful evolution of a 3D-printed structure that achieves the deformation, self-assembly, and self-repair depicted in Figure 1. In the early phases of printing components for 3D-printed printed structures or components, the AM method utilizes intelligent materials. Charles W. Hull 1986 published the first description of 3D printing. His technique, which he called "stereolithography," involved sequentially tiny layers printing of a material that could be cured with UV radiation to create a solid 3D structure. Later, this method was used for the construction of three-dimensional scaffolds from sacrificial resin molds made of biological materials. New solvent-free aqueous-based technologies have enabled the direct printing of biological materials into 3D scaffolds that might be used for transplantation with or without seeded cells. Due to recent developments in 3D printing technology, cell biology, and materials science, the next stage in tissue engineering was 3D bioprinting (Murphy & Atala, 2014). The definition of 4D printing will be increasingly thorough as research and technology advance continuously. 4D printing is founded on the notion of incorporating the product's concept into flexible functional materials. Therefore, given time and activation conditions, microstructures can be deformed by the previously specified track. Nowadays, 4D printing can develop many objects in comparison with 3D printing, and these objects' color, volume, and geometry can change in reaction to environmental stressors and elements like heat and water (Khoo et al., 2015). 4D printing allows food things to morph, fold, or self-assemble in reaction to stimuli. Dynamic behavior improves food functionality and presentation. 4D printing allows food to self-assemble under certain conditions. Food packaging can adapt to protect and preserve the goods using this principle. 4D-printed foods can release nutrients or bioactive chemicals at precise digestion stages or in response to body needs. Personalized nutrition can improve health and wellness. 4D-printed food with self-adapting packaging may adjust to ambient conditions to preserve food quality and extend shelf life. 4D-printed food allows chefs to demonstrate their creativity and talents, improving the dining experience. 4D printing may reduce waste and resource use, helping the food business become more sustainable (Guo et al., 2020; Guo et al., 2020; He, Zhang, & Devahastin, 2020; He, Zhang, & Fang, 2020; He, Zhang, & Guo, 2020). In terms of material adaptability, 4D printing has an advantage over traditional production methods, which makes it simpler to precisely set component pliability. To create

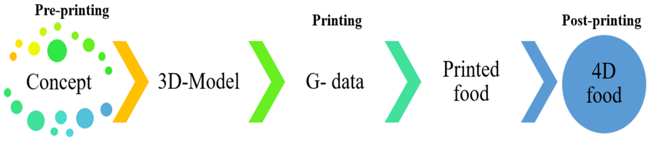

FIGURE 1 Flow diagram of the 4D-printing process.

a single, once-only printable object, different materials are often combined in the proper proportions to create a 4D printed framework (Raviv et al., 2014). The desired shape-shifting behavior will be caused by differences in material properties, equally as thermal expansion coefficient, and swelling ratio. For the creation of several co-structures with straightforward geometry, 3D printing is therefore required. In some fields, 4D printing has been successfully implemented. In other instances, simply introducing the advanced materials to the stimulus does not yield the correct shape of the 4D-printed product. In this review study, the interaction mechanism is defined as the requirement that the stimulus is applied in a specific order and throughout an adequate amount of time (Momeni et al., 2017). Constrained thermo-mechanics, for instance, is one of the primary interaction processes. The smart material in this method has a shape memory effect, and the stimulus is heated. It has a cycle with four steps. The framework first experiences a high-temperature deformation due to an external load. The temperature then starts to drop while the added load is kept constant. To get the correct shape, the structure is released at a low temperature. The fourth option is to preheat the structure to give it back its original form. For instance, one of the primary benefits of the emerging technology known as "bioprinting" is the transformation of living things into 3D structures such as organs, tissues, nourishment, and cells. The next generation of bioprinting technology is 4D bioprinting, which has numerous applications in food technology, medical science, materials engineering, chemistry, and computer science. The ability to modify the functionality of manufactured bio-structures is one of 4D bioprinting's primary benefits (Leist & Zhou, 2016; Momeni et al., 2017).

3 | COMPARATIVE ANALYSIS OF 3D, 4D, AND 5D PRINTING TECHNOLOGY

A range of improvements in AM are shown when 4D printing is contrasted with 3D and 5D printing. Despite being a pioneer in the creation of three-dimensional structures, 3D printing's versatility is limited by its static nature and frequently complex post-processing requirements (Vasiliadis et al., 2022). Alternatively, 4D printing adds the dimension of time, allowing for dynamic shape changes in reaction to outside stimuli and eliminating the need for intricate assembly. While more sophisticated 5D printing that uses artificial intelligence and computational algorithms has potential for complex designs, its actual use is fraught with difficulties (Demoly et al., 2021). A thorough comparison of different printing processes is given in the Table 1, which also highlights their unique features.

3.1 | Advantages of 4D printing

4D food printing is a nascent technology with the capacity to fundamentally transform the methods by which humans create and ingest food. Food structures are created and manufactured using 3D printing technology to undergo time-dependent changes triggered by internal or external stimuli (Ahmed et al., 2021). This process is an expansion of

TABLE 1 Comparative analysis of different types of printing along with specific characteristics.

Characteristic	3D printing	4D printing	5D printing	Reference
Dimensionality	Three-dimensional	Four-dimensional (introduces time)	Five-dimensional (incorporates complexity)	Konstantinov (2020)
Stimulus-responsive behavior	Limited; static structures	Dynamic response to external stimuli	Enhanced adaptability with optimized designs	Kumar et al. (2019)
Smart materials	Traditional materials like plastics, metals	Smart materials (shape-memory polymers, etc.)	Diverse materials with advanced functionalities	Lui et al. (2019)
Autonomous shape transformation	Rare; often requires postprocessing	Objects can autonomously change shape	Dependent on advanced algorithms and AI	Sajjad et al. (2023)
Manufacturing efficiency	May require complex assembly processes	Streamlined process with reduced waste	Potential challenges due to computational intensity	
Versatility	Widely used in rapid prototyping, limited versatility	Balances simplicity with sophistication	Potential for highly sophisticated applications	Kumar et al. (2019)
Material palette	Plastics, metals, ceramics	Expands to include smart materials, hydrogels	Broad range of materials for enhanced functionality	
Current industry applications	Manufacturing, prototyping	Healthcare, aerospace, robotics	Limited due to complexity, potential in specialized fields	Sadiq and Pradeep (2020)
Environmental impact	Varies based on material usage	Reduces waste through streamlined processes	Challenges in computational intensity may affect efficiency	Kumar et al. (2019)
Postprocessing requirements	Often needed for functional end-use products	Reduced need due to autonomous transformations	Varied based on complexity, may involve intricate postprocessing	Kumar et al. (2019); Sadiq and Pradeep (2020)

3D printing. Consequently, 4D-printed food possesses the capability to be personalized in both physical attributes, including form and consistency, as well as to be instructed to modify its characteristics over some time, encompassing aspects such as color, taste, or odor (Chandra et al., 2021). 4D food printing offers numerous benefits compared to conventional food preparation techniques. Several prominent benefits include: 4D food printing enables extensive customization, as it enables the printing of food in various shapes and sizes. This might be utilized to generate distinctive and customized culinary encounters. 4D food printing is a highly accurate procedure that enables the production of food with dependable and replicable outcomes. This is particularly crucial for dishes that necessitate a precise form or consistency (Chen, Zhang, & Devahastin, 2021; Chen, Zhang, Guo, & Chen, 2021; Chen, Zhang, Liu, & Bhandari, 2021). The utilization of 4D food printing technology can effectively mitigate food waste by enabling the production of food items as needed, eliminating the necessity for excessive food production. The utilization of 4D food printing enables the production of nutritionally enhanced foods by integrating nutrients into the printing procedure (Ghazal et al., 2021). The utilization of 4D food printing enables the creation of innovative culinary encounters, such as foods that undergo color or flavor transformations as time progresses. In general, 4D food printing can revolutionize the methods by which we cook and eat food. This technology is highly adaptable and can be utilized to produce a diverse range of foods with distinct and desirable characteristics (Ghazal et al., 2019). In the future, with the ongoing advancement of technology, we can anticipate witnessing further inventive and imaginative uses of 4D food printing.

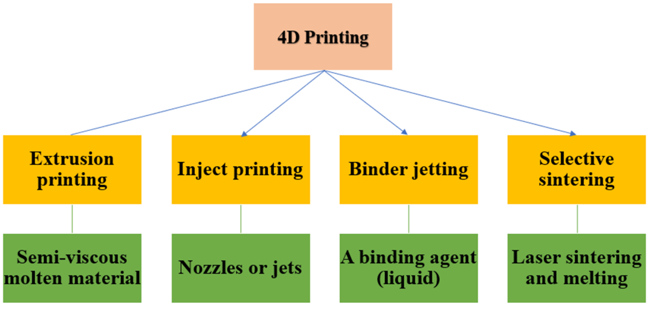

FIGURE 2 Schematic representation of methods used in 4D printing.

4 | FOOD PRINTING METHODS

Printing of food refers to the method of creating food products through the use of various AM processes (Figure 2). The printing ingredient is normally held in food-grade syringes before being applied layer by layer through a food-grade nozzle. The most powerful 4D food printers have recipes preinstalled, so users may remotely change their menu on PCs, smartphones, or Internet of Things gadgets. Food may be changed in terms of its texture, nutrition, color, flavor, and shape, which makes it very beneficial in fields like medical care and space research. components/ingredients (viscosity, particle size), operating parameters (nozzle dimension, printing speed, printing range), and postprocessing processes all have an impact on accurate and precise food printing (Zhao et al., 2020). The methods are discussed in Figure 2.

4.1 | Extrusion printing

Extrusion-based printing, one of the most straight forward techniques for printing food, has been widely used. Usually, it is used on molten substances that are temperature- or clammy-controlled. The initial step in extruded printing is to modulate a program that will create a virtual 3D model and slice it into distinct layer patterns and printing-specific codes (Mantihal et al., 2020). Attaching these codes to the printing machine and choosing the right recipe are the first steps in producing meals. Depending on the software used to create the item seen in Figure 3, materials are extruded by sliding the nozzle by moving or above a specific stage under the nozzle to form layers. Layers that have been extruded stick together, creating a 3D structure made of layers. The desirability of 3D food printing depends on the material's rheological properties (Sun et al., 2018). Additionally, crucial factors are stability during postdeposition and simplicity of dispensing. During post-printing procedures like baking, the material should maintain its stability. To smoothly release the material from the extruder via the nozzle, a certain mechanical force is required. The nozzle geometry and the substance's rheological properties determine the necessary force (Lille et al., 2018).

Extrusion at room temperature was extensively used by experts to craft 4D food products, as seen in Figure 3. Chen, Zhang, Guo, and Chen (2021); Chen, Zhang, Liu, and Bhandari (2021); Chen, Zhang, and Devahastin (2021) utilized an extruder with nozzle sizes of 1.2 mm and 1.5 mm to attempt to make a gel from powdered lotus root; this produced a rough surface. On the other hand, a 0.8 mm nozzle diameter produced a smooth and shiny surface. Like this, He, Zhang, and Devahastin (2020); He, Zhang, and Fang (2020); He, Zhang, and Guo (2020) also used a 1.2 mm nozzle diameter to 4D print potato purée. The printed purple sweet potato pastes with a layer height and nozzle diameter of 0.8 mm were produced using the 4D extrusion method and the study suggested that printing speed might affect extrusion-based food (Chen, Zhang, & Devahastin, 2021; Chen, Zhang, Guo, & Chen, 2021; Chen, Zhang, Liu, & Bhandari, 2021). The creation of 4D-printed foods uses printing rates of 25, 20, 18 mm/s, etc (Ghazal et al., 2019; Ghazal et al., 2021; He et al., 2021; He, Zhang, & Devahastin, 2020; He, Zhang, & Fang, 2020; He, Zhang, & Guo, 2020; Shi et al., 2022).

The three extrusion techniques utilized for 4-D printing food are hydroforming, hot melt, and room-temperature extrusion. In the room-temperature ejection of engraving materials like melted cheese and dough. Protein, carbs, puree, and other materials have all been used as printing materials in room-temperature extrusion. It is necessary to consider factors like nozzle size, printing speed, infill percentage, extrusion rate, layer height, and others (Gholamipour-Shirazi et al., 2019; He, Zhang, & Devahastin, 2020; He, Zhang, & Fang, 2020; He, Zhang, & Guo, 2020; Phuhongsung, Zhang, & Bhandari, 2020; Shi et al., 2022).Hot-melt extrusion is the technique of melting and heating the raw material to create a new substance. This process, which is primarily used to create polymeric materials, involves carefully pushing molten ink onto a die under regulated conditions. While using a mobile extrusion printer nozzle to extrude food-grade substances like chocolate, higher temperatures—like 90°C—can be reached. After extrusion, the material quickly solidifies and sticks to the layer that came before it. A reasonably higher temperature must be maintained during hot melt extrusion, which varies based on the various materials employed, to regulate the viscosity and permeability through the printing nozzle. Hot-melt extruded products have uniform density and thickness (Tan et al., 2018). With the hydroforming extrusion technique, syringe pipette, a vibrating nozzle, jet cutter, or other such instruments are used to dispense hydrocolloid liquid into a gel hardening bath. The process in this method is highly dependent on the material's viscoelastic qualities and gel-forming capacity (Le-bail et al., 2020). The transformation of the hydrocolloid solution into self-supporting gels reveals the viscoelastic features. A temporal controller is used in the printer to stop the material from gelling too soon (Godoi et al., 2016). Generally, there are three mechanisms encompassed in the creation of hydrogels: (1) chemical cross-linking, (2) the formation of complex coacervates (3) ionotropic cross-linking (Kirchmajer et al., 2015). Soft snacks made of fruit are frequently printed using this technology.

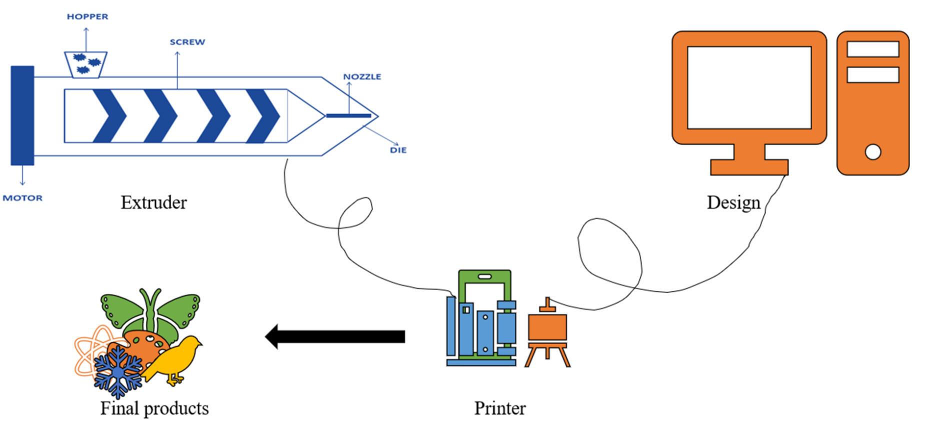

FIGURE 3 Schematic representation of steps involved in extrusion printing.

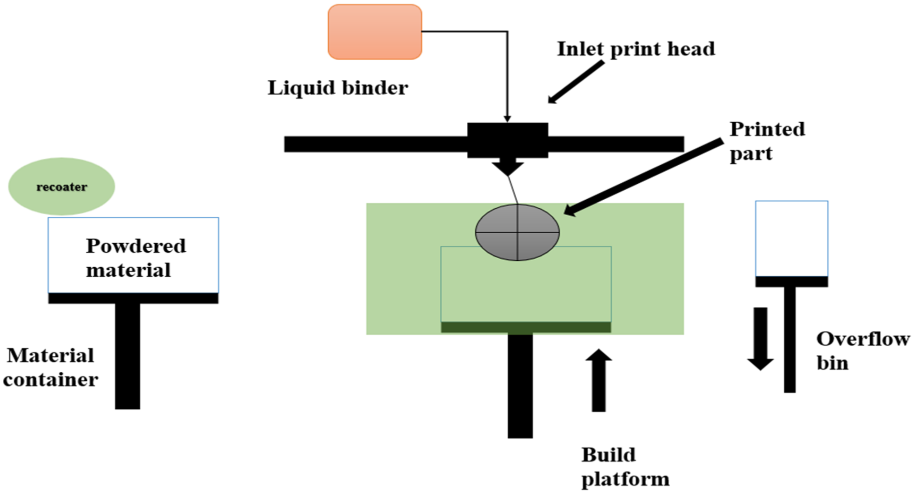

FIGURE 4 Diagrammatic representation of steps involved in binder jetting printing.

4.2 | Printing using inkjet

Inkjet printing is often used in confections, decorations, and often in 4D printing (Pallottino et al., 2016). Using this technique, food ink is sprayed onto moving objects via pneumatic membrane nozzles, or "jets," which are usually 20–50 μm in size. One or more nozzles can be used at once to create stacked structures by injecting printing ink into the printing stage. A digital image is created by the combination of the droplets via surface fills and cavity depositions. Since low-viscosity materials are usually used in inkjet printing, it is more appropriate for producing flat items than complex structures. Temperature has a significant impact on the process, changing the material's viscosity and surface energy (Le-bail et al., 2020). An innovative method for printing graphics on edible materials was based on a Young (2000) technology. By polishing the gum's surface or altering it with a moisture glaze, this invention improves the printing of low-viscosity materials on edible surfaces (Pallottino et al., 2016). Because inkjet printing prefers low-viscosity materials, it is not ideal for producing intricate food forms. Nonetheless, fills, microencapsulation, 3D nano printing, and, to a lesser degree, decorative ornamentation are among its uses (Godoi et al., 2018).

4.3 | Binder jetting

Binder jet printing is one type of AM technique. The powdered components are distributed evenly over a fabrication platform. To enable the binding of neighboring powder layers, frequently a liquid binding agent is spread over the powder layer by spray. Unlike inkjet printing, only pulse actuation is used to release the ink or binder as needed. A counter-rotating roller, as depicted in Figure 4, is usually used to apply powder coating to every layer of the component. To create the 2D design of the layer, the liquid binding agent is ejected into the powder bed by the head of an inkjet (Holland et al., 2019). This method has the benefits of being less expensive and taking less time to utilize. Therefore, less surface polishing is used. (Le-bail et al., 2020). Food is printed using binder jet technology by mixing a liquid binder with the powder ingredients. Powdered particles tend to clump together because of their increased hygroscopicity and stickiness. The adhesive force between the powder particles will be enhanced by the release of the liquid binder. The binder jetting process will be influenced by the properties of the material along with how it interacts with the substance that binds it. It is important to remember that at the material scoping stage of the binder jetting technique, small amounts of an appropriate substance can be added to hydrophobic or water-insoluble compounds to help them bind together (Holland et al., 2019).

4.4 | Selective sintering

Based on the sintering technique, selective sintering can be separated into selective melting and selective laser sintering. A common underlying feature across both sintering procedures is the application of a sintering agent to fuse powder, resulting in the production of solid structures. This technique's capacity to quickly generate food structures without the need for additional treatment is one of its main advantages over others (Le-bail et al., 2020). Sintered carbohydrates and carbohydrate powder can create complex solid structures when done correctly. This technique is maintained until the needed structure is accomplished (Sun et al., 2015). A scanner grabs the infrared laser beam, which is then reflected onto the printing medium (Godoi et al., 2016). The 3D digital specification in 3D software calculates the scanning of cross-section motion, and the laser beam successfully sinters powder materials and acts as a source of heat (Mantihal et al., 2020). It is a high-yield, solvent-free printing technique that does not require further post-processing or raw material monomer polymerization. Because this technique does not use any solvents, it is ideal for orienting materials that are solvent sensitive. The printed goods require no more processing, such as drying or curing, besides the collection of printouts from the loose powder, before they may be consumed (Charoo et al., 2020). The absorptivity indicates that the wavelength and frequency of the laser beam have a significant impact on the powder sintering.

Thus, choosing the right laser is an essential stage in this printing process (Gu et al., 2012).

5 | EFFECT OF 4D FOOD PRINTING ON FUNCTIONAL PROPERTIES OF FOOD PRODUCTS

The structure and texture of food items are greatly impacted by the drying process, which is an essential part of food processing. Food is stressed by dehydration, which causes moisture to diffuse throughout the sample and cause it to shrink and bend (Table 2). There is a lot of promise for 3D printing applications with this shape shift caused by dehydration. Numerous drying methods, such as osmosis, microwave, hot air, etc., use distinct mechanics (Jeevarathinam et al., 2021; Pandiselvam et al., 2022; Pravitha et al., 2022). The crook angle of a 3D-printed object is inversely correlated with moisture content, shrinkage ratio, and dielectric constant loss factor (Liu et al., 2021; Srivastava et al., 2023). The dehydration of pumpkin incorporated with paper in 4D at 25°C was also investigated (Chen, Zhang, & Devahastin, 2021; Chen, Zhang, Guo, & Chen, 2021; Chen, Zhang, Liu, & Bhandari, 2021). The drying time along with the additional layer's twisting angle was discovered to be positively connected by the investigators. It was discovered that the oligo gel and purple potato puree had changed after being heated in the microwave (Shi et al., 2022). They proposed the possibility that, at least in part, microwave time and power would correlate linearly. There is a significant relationship in the early phases of the microwave treatment between the bending angle and the rise in slurry moisture content (Shi et al., 2022; Singh, Pandey, et al., 2023; Singh, Singh, et al., 2023). With longer dehydration times at varying microwave power levels, the twisting angle of the starch-based 4D-printed sweet purple potato puree expanded (He, Zhang, & Devahastin, 2020; He, Zhang, & Fang, 2020; He, Zhang, & Guo, 2020). Moisture is dielectric that utilizes more microwave energy and speeds up the process of dehydration. Even so, deformation was not observed when the moisture content was <25% or the microwave power was greater than 150 W (Shi et al., 2022). At this moisture content, it might be because the sample size does not change and a rigid structure develops (He et al., 2021; Wang et al., 2018).

It was observed that several dehydration processes (air drying, microwave, and infrared radiation) affect the alteration of starch-based edible objects in the shape of 4D-printed. The air-dried sample exhibited the greatest bending along with the infrared and microwave-treated samples. In every scenario, the rate of bending increases more quickly toward the beginning of the exposure. Infrared-treated samples at lower temperatures exhibited a greater final bending angle than samples at higher temperatures. Rapid evaporation at higher temperatures creates a porous structure with a less volumetric shrink. The basic source of the 4D change in a variety of materials, including twisting, curling, wrapping, and bending, is the relative expansion of both passive and active materials. At constant moisture content, it is also possible that this occurs because a hard structure arises even while the sample volume stays constant (Wang et al., 2018).

5.1 | Effect on sensory

5.1.1 | Effect on color

Color changes caused by stimuli are being investigated the most in 4D-printed food. Various shades have evolved into optical characteristics that buyers use to assess the worth of a product before making a buying decision (Aydar et al., 2022; Kutlu et al., 2022). It can also influence how customers perceive the product's potential flavor and taste (Chandra et al., 2021). Due to climatic changes, some hues may change and variations in pH may modify the chemical structure. Anthocyanin and curcumin exhibited green and red colors in alkaline pH, yet in an acidic medium, they turned red and yellow, respectively. This can be used in 4D-printed food for modification of various shades over time by affecting a stimulus such as pH, temperature, and so on. Curcumin was used as the stimulus as researchers looked at the influence of microwave stimulation on lotus root powder gel

TABLE 2 The role and effect of inks used in 4D printing of food.

Agent	Ink used	Findings	References
Heat (microwave)	Complex made of gelatin and gum Arabic oil	Increment in the content of cinnamaldehyde	Guo et al. (2021)
pH	Lemon juice and potato starch with anthocyanins	Lower the pH-more the changes	Ghazal et al. (2019)
Dehydration (microwave)	Puree (purple sweet potato)	2D butterflies and flowers converted to 3D	He, Zhang, and Devahastin (2020); He, Zhang, and Fang (2020); He, Zhang, and Guo et al. (2020)
Heat (microwave and irradiation)	Starch	Changes in shape, the ratio of shrinkage, and dehydration rate	Liu et al. (2021)
pH	Betaline, beetroot soy protein isolates, and pumpkin	Higher the pH-changes in the color of food	Phuhongsung, Zhang, and Devahastin (2020); Singh, Singh, et al. (2023); Singh, Pandey, et al. (2023)

during 4D printing (Chen, Zhang, & Devahastin, 2021; Chen, Zhang, Guo, & Chen, 2021; Chen, Zhang, Liu, & Bhandari, 2021). Curcumin was used as the stimulus as researchers looked at the impact on printed lotus root powder gel of microwave stimulation 4D method. Similarly, microwave stimulation is being investigated with 4D-printed dough buckwheat (Guo et al., 2021). As a stimulus–response material, a mixture of compounds containing gelatin-gum and Arabic-oil complicated accrual microparticles was used. The microwave treatment increased the reddish color of the dough while decreasing its lightness. This is due to the capsule being destroyed by microwave exposure and the release of embedded oil. The color shift of the isolated 3D-printed soy protein, beetroot, and pumpkin combination rich in betalain was examined about surface pH. The scientists found that after 1 h of preservation at higher pH levels (above 6), the printed material exhibited minimal alterations in color intensity, although, the color values altered significantly at lower pH (Phuhongsung, Zhang, & Devahastin, 2020). Color values vary throughout time as a result ofthe degradation of color pigments due to oxidation. The degradation of color pigments in extremely acidic conditions is what causes the changes in color value at lower pH levels. In reaction to internal and external pH stimuli, a sizable change in color was seen in the multi-smart material structure used in 3D printing (Ghazal et al., 2021).

5.1.2 | Effect on flavor

Food printing technology is important in the formation of distinct flavors since it brings numerous components together to facilitate favorable reactions shown in Table 3. E-tongue analysis examines the variations in taste qualities of printed food items, which uses eight distinct sensations that match human tongue experiences of sourness, bitterness, sourness, aftertaste, umami, creaminess, and salty (Ghazal et al., 2021). AGS-MS analysis and electronic nose can be used to examine fluctuations in the constituents of the flavor of 3D-printed food structures. Treatment of samples at higher pH levels (pH 9 and 10) had a reduced response, whereas samples treated at lower pH levels exhibited a greater reaction. The vanillin (a phenol component), which has a pKa of 7.38 and reduces volatility in basic conditions, may be negatively charged, which accounts for the lower strength of odorant high pH values. pH-induced changes in the flavor attributes of 4D-printed food multi-smart components have also been found (Ghazal et al., 2021). When the pH value dropped, the umami and salty flavor diminished (2–10). Conversely, as the pH value decreases, the sourness increases. Similarly, a 3D-printed soy protein extract, beetroot, and pumpkin mixture had a high salty value of 10, and stronger astringency at a lower pH of 4 was noticed. An increase in the number of hydrogen ions decreases the pH of the sprayed solution at lower pH values (Phuhongsung, Zhang, & Devahastin, 2020). The interaction of sodium protein causes the release of sodium from printed objects, resulting in enhanced saltiness at high pH (Kuo & Lee, 2014). Vanillin is a food flavoring agent, and the intensity of its flavor is very sensitive to a variety of stimuli like pH, temperature, and moisture (Frenkel & Havkin-Frenkel, 2006). The study investigated the effect of microwave irradiation on 4D printed objects using vanilla flavoring in the printing ink. Vanillin was extensively used as a stimulus-responsive material in the 4D printing method by researchers (Ghazal et al., 2021; Phuhongsung, Zhang, & Bhandari, 2020).

5.1.3 | Effect on texture

Food texture, visual appearance, and taste are important in terms of consumer approval (Aslam et al., 2022; Shanker et al., 2023). The food inks are aligned layer by layer in 3D AM to create the food. The use of a twin extruder for thermal stabilization with near-infrared heating to produce a starch-based food texture that could be 3D printed (Fahmy et al., 2021). The researchers demonstrated that the two variables can affect the composition of the objects that are printed. (1) Calculated

TABLE 3 Effects of various treatments on food components.

Exposures	Food components/ interactants	Results	References
pH	Stimulated alteration of food	When pH changes (2–10), salty and umami flavor changes	Ghazal et al. (2021)
pH	Sodium protein interactions	Increased saltiness under high pH	Kuo and Lee (2014)
Microwave heating	Vanilla flavor	Vanilla is used as printing material in food. The food had a vanilla flavor	Phuhongsung, Zhang, and Bhandari (2020)
Anisotropy of structure	Double-layer structure of pumpkin	The hardness rose prepared by the pumpkin increased	Chen, Zhang, Guo, and Chen (2021); Chen, Zhang, Liu, and Bhandari (2021); Chen, Zhang, and Devahastin (2021)
Microwave heating	Lotus root powder gel	Increase in cohesiveness and greater force required to chew	Fan et al. (2020)
UV irradiation	Puree (sweet potato)	Improved vitamin D content	Chen, Zhang, Guo, and Chen (2021); Chen, Zhang, Liu, and Bhandari (2021); Chen, Zhang, and Devahastin (2021)
Microwave heating	Purple potato and beeswax	Reduction of the fat-printed product	Shi et al. (2022)

offsets between identical costume extruders in the Cartesian coordinate system. Offsets and slight changes in layer thickness along the z-axis have no impact on the textural qualities in the elastic zone. (2) The impact of printing options and slicing parameters on textual qualities. The infill density and edges significantly affect the hardness and chewiness of printed things, according to the researchers, who used a 4D structure of mashed potatoes with varying interior structures to test their hypothesis (Liu et al., 2018). Similar to this, a 4D deformation of the double-layered pumpkin incorporated with the paper structure was seen. The study mainly concentrated on the directional cues of the plane layer and the anisotropy of the structure to achieve the goal of 4D-directed deformation. The scientists found that with time there was an exponential increase in the hardness of the and had a negative relationship with time (Chen, Zhang, & Devahastin, 2021; Chen, Zhang, Guo, & Chen, 2021; Chen, Zhang, Liu, & Bhandari, 2021). Many items' mechanical properties are heavily influenced by their moisture content. Microwave stimulation greatly increased the hardness, chewiness, springiness, and cohesion of 4D-printed lotus root powder gel (Chen, Zhang, & Devahastin, 2021; Chen, Zhang, Guo, & Chen, 2021; Chen, Zhang, Liu, & Bhandari, 2021; Liu et al., 2018). After microwave exposure, the sample got tougher. Food that has been 4D-printed has a stronger and more compact structure as a result of moisture loss caused by microwave heat. An increase in cohesiveness results in a stronger internal force while a decrease in cohesion leads to a bigger need for force to chew the food (Fan et al., 2020).

5.2 | Effects on shapes

Due to their asymmetric swelling capacity, food hydrogels are used in food printing as materials that change shape (Stephen et al., 2021). The Hydration-stimulated modification in shape achieves programmable metamorphosis, a distinctive mouthfeel, and convenient shipment and storage. Cooking causes an asymmetrical swelling that transforms a cellulose, protein, and starch composite material's dimensions from 2D to 3D (Wang et al., 2017). The hydrogels have a bridge 3D network structure created by either chemical or physical contact (White et al., 2013). It is made of an expanding hydrophilic substance that enables shape-shifting in response to varied signals (Tao et al., 2019). The authors produced food film by printing cellulose onto gelatine films using a CNC platform with an adjustable mounted dispenser using a unique process of kneaded and sheet flour-based dough with an integrated design approach for food transformation during dehydration (such as baking) or hydration (such as boiling water). Similarly, it was seen that flour-based dough changed shape when cooked using an integrated design strategy. Researchers have explained a creative and straightforward technique that gives flour-based dough its shape-changing ability by using either the method of hydration/dehydration cooking processes. They provided comprehensive experimental findings, a personalized design tool, and a hybrid fabrication technique that allows for user input. Applications are created to show the possible design space for food based on flour that can change. The shape-changing ability of the Morphlour is intended to be achieved in both the baked and the boiled instances (Tao et al., 2019). 4D food printing could revolutionize texturized protein/meat manufacturing. Traditional meat production is resource-intensive and environmentally damaging. Plant-based proteins and other substances are used to generate meat-like items in 4D food printing, making it more sustainable. Layers of food are deposited onto a platform in a precise pattern for 4D food printing. Complex and elaborate structures that resemble meat can be made. Flavorings, minerals, and bioactive chemicals can be added to printed products to improve their nutritional value and taste (Yang et al., 2021). Food items can alter in shape and texture as a result of drying, which is a key food processing technique. Dehydration diffuses water from the sample, which stresses the food and produces product shrinkage and bending (Sannino et al., 2005). The folding angle of a 3D-printed item is positively connected with the moisture content and shrinking ratio and negatively correlated with the dielectric constant loss factor (Liu et al., 2021). Investigated was the dehydration of pumpkin/paper in 4D at 25°C (Chen, Zhang, & Devahastin, 2021; Chen, Zhang, Guo, & Chen, 2021; Chen, Zhang, Liu, & Bhandari, 2021). The link between a double layer's bending angle and drying time was found to be favorable by the researchers. Similarly, increasing the dehydration time at various microwave power levels enhanced the bowing angle of 4D-printed purple sweet potato puree made of starch (He, Zhang, & Devahastin, 2020; He, Zhang, & Fang, 2020; He, Zhang, & Guo, 2020). Oligo gel and purple potato puree with microwave treatment were said to have undergone form changes (Shi et al., 2022). They concluded that the relationships between microwave power, bending angle, and processing time, up to a point and linear. There is a direct relationship between the bending angle and the increase in slurry moisture content early in the microwave treatment phase (Shi et al., 2022). Because moisture is dielectric, it absorbs more microwave energy and speeds up the process of dehydration.

5.3 | Effect on nutritional composition

Food printing has the potential to modify the nutritive content of food as per customer demand. It is possible to achieve this by introducing healthy elements for example cellulose, plant compounds, and modified proteins while reducing harmful chemicals such as allergens and anti-nutritional compounds. The nutritional content of engraved food can be managed through the logical arrangement of nutrients in inks or alternate printing methods. Fruits and vegetables can add vitamins, polysaccharides, and other ingredients to food ink (Chen et al., 2022). Tissue engineering can be used in 4D printing to enhance the nutritional qualities of food printing. Food-grade ink and tissue will improve the nutritional value of printed food when used in 4D biotechnological printing. The nutritional value of printed food will be increased by the use of food-grade ink and tissue in 4D biotechnological printing. The subjection of the material to optimal situations stimulates tissue growth. Printing object represents animal or plant cells that, when stimulated, can form tissue-like design, and create nutrients (Teng et al., 2021). Printing foodstuff with microflora improves the nutritional quality of the engraved product. The addition of microalgae adds functional and nutritional components such as protein, sterol, vitamins, and fatty acids (Uribe-Wandurraga et al., 2020). The UV irradiation considerably increased the vitamin D_2 content of purple sweet potato pastes that were 4D-printed and included ergosterol, and an enhancement in vitamin D_2 content was seen in the irradiated area. Similarly, the use of microwave-stimulated, oleo gel powder ink of purple potato to create a reduced-fat printed product beeswax-based (Chen, Zhang, & Devahastin, 2021; Chen, Zhang, Guo, & Chen, 2021; Chen, Zhang, Liu, & Bhandari, 2021; Shi et al., 2022).

Selection of food materials, printing process, and post-processing can affect food nutrition during 4D food printing (He et al., 2020). This includes food material selection, printing, and post-processing. The food materials used in printing ink determine the nutritional value of printed food. Whole grains, fruits, and vegetables add fiber, vitamins, and minerals to printed cuisine compared to processed ingredients. The printing process can also affect food nutrition. Nutrient retention is affected by printing temperature, speed, and light exposure. Extreme heat during printing degrades heat-sensitive vitamins, while prolonged light exposure reduces vitamin C in some meals. Post-processing activities including drying, heating, and freezing can influence printed food nutrition. Drying concentrates nutrients but may destroy heat- and oxidation-sensitive vitamins (Chen, Zhang, & Devahastin, 2021; Chen, Zhang, Guo, & Chen, 2021; Chen, Zhang, Liu, & Bhandari, 2021; Shi et al., 2022). Cooking may destroy heat-sensitive vitamins yet improve nutrient digestion. 4D food printing allows customization and better dining experiences (He, Zhang, & Devahastin, 2020; He, Zhang, & Fang, 2020; He, Zhang, & Guo, 2020). Careful evaluation of potential nutritional content changes during printing is essential to guarantee that printed food remains nutritious and contributes to a balanced diet. Selecting nutrient-rich materials, optimizing printing conditions, using protective packaging, and minimizing postprocessing can retain 4D-printed food's nutritional integrity (Liu et al., 2021).

6 | INDUSTRIAL SCALABILITY OF 4D FOOD PRINTING

4D food printing is an advanced technique that builds on 3D printing. It allows for the creation of food structures that may alter their shape, structure, or qualities in reaction to external stimuli (Farid et al., 2021). This nascent technology has great potential to revolutionize the food sector, providing numerous possible uses and advantages in terms of the industrial scale. The industrial scalability of 4D food printing is facilitated by various aspects, which contribute to its potential for widespread use in the food sector (Khalid et al., 2022). The advancement of multihead printing systems and expanded print beds facilitates the manufacturing of 4D-printed food items on a bigger scale, hence enhancing efficiency and productivity. The ongoing advancement of novel 4D food printing materials, specifically hydrogels and shape-memory polymers, broadens the assortment of printable food products, accommodating various dietary requirements and preferences (Zhang et al., 2019). The implementation of automated 4D food printing, encompassing material preparation, printing, and post-processing stages, leads to reduced labor expenses, enhanced uniformity, and improved overall efficiency (Aldawood, 2023).

The variety and distinctive characteristics of 4D food printing offer numerous potential applications across diverse industries. 4D food printing allows for the production of personalized food items that are specifically designed to meet individual dietary restrictions, preferences, and medical necessities (Khalid et al., 2023). 4D food printing enables the creation of customized medical food products that cater to the unique dietary requirements and swallowing challenges of patients. This technology enhances the texture and nutrient composition of the food. 4D food printing addresses the needs of space missions by offering astronauts nourishing, durable, and convenient food choices that can endure extended periods of space travel (Hashemi et al., 2024). 4D food printing meets the specific requirements of military rations by producing food items that are lightweight, resilient, and easily transported, capable of enduring extreme climatic conditions. Restaurants benefit from 4D food printing since technology allows cooks to produce visually captivating, delicious, and intricate food creations with more accuracy and efficiency (Huang et al., 2021).

Comparing 4D printing to traditional printing methods reveals that it is a more affordable option for the food industries. The food industry benefits from 4D printing's cost-effectiveness because of its unique features, which reduce resource consumption and streamline production processes, promoting environmental and economic sustainability. Figure 5 shows how 4D printing is affordable in comparison with other classical technologies. The autonomous shape modification of 4D printing is a crucial feature that distinguishes it from other methods, as it does not require complex assembly or post-processing. To produce the intended result, traditional 3D printing frequently needs more manual effort and labor-intensive procedures, which raises production costs (Navaf et al., 2022). On the other hand, the self-assembly feature of 4D printing drastically lowers labor costs and shortens the production schedule. This efficacy raises the cost-effectiveness factor and establishes 4D printing as a competitive option for large-scale food production. One important aspect that makes 4D printing more affordable than other methods is the decrease in material waste. During the shaping and cutting phases, conventional printing techniques like 3D printing could produce a significant amount of waste (Vatanparast et al., 2023). 4D printing reduces material waste by using smart materials that have shape-memory capabilities and react to outside stimuli. This makes 4D printing a financially viable choice for the food business by optimizing the use of raw materials and lowering disposal expenses related to surplus trash (Bajpai et al., 2020). 4D printing's capacity for more customization presents an affordable way to produce one-of-a-kind culinary items. The degree of detailed customization that 4D printing makes possible may be beyond the

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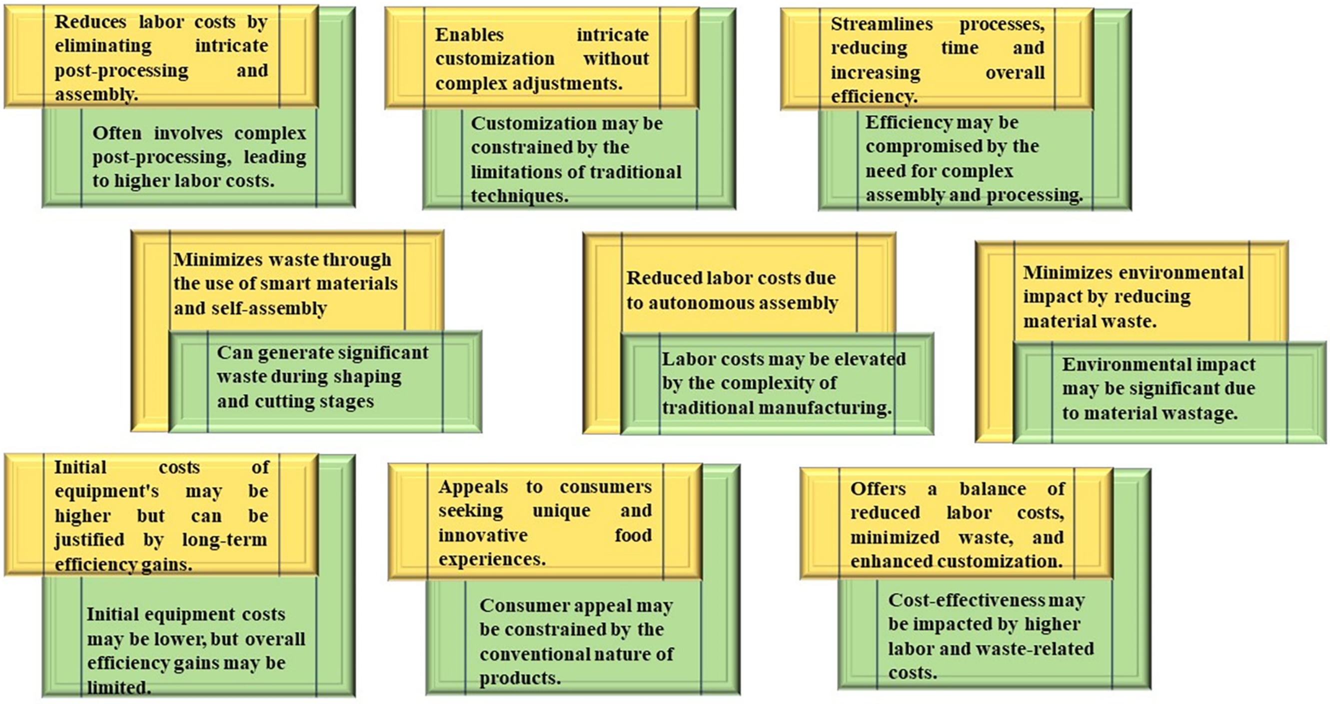

FIGURE 5 Detailed description for cost effectiveness of 4D printing in Food Industries in relationship with other printing techniques. All the yellow squares are representing 4D printing and Green Squares are for traditional printing.

capabilities of traditional printing techniques, such as 3D printing. The overall cost-effectiveness of 4D printing is increased by the capacity to customize food products to customer tastes without requiring intricate changes to the manufacturing process (Sajjad et al., 2023).

7 | POTENTIAL APPLICATIONS OF 4D FOOD PRINTING

Do-it-yourself food has boosted the enjoyment of existence. 4D food printing automation offers a viable solution that may meet specific meal preferences by modifying the colors, flavors, and shapes of foods. The creation of microcapsules with a gelatin–gum Arabic oil compound in an imprinted buckwheat flatbread having yellow fleshy peach. By progressively dissolving the microparticle structure with microwave heating, the encapsulated oil was released and distributed throughout the dough, changing its color and aroma. (Guo et al., 2020). Guo and his coworker also looked at the color which changed due to the pH in meals utilizing anthocyanins, which were red in acidic settings, purple in near-neutral conditions, and green in alkaline conditions. Due to this quality, colorful mashed potatoes can be printed in multiple materials using 3D technology (Guo et al., 2020). Furthermore, bilayered 3D-printed sweet potato purees were dehydrated using microwave irradiation, which led to shape deformation. More intriguingly, the alteration of the flavor of dishes using microwave heating. Carrageenan, vanilla flavor, and soy protein isolate were used in the printed foods. When the four newly synthesized flavor compounds were combined with the vanilla flavor, they were recognized (Phuhongsung, Zhang, & Bhandari, 2020). These illustrations allow us to conclude that stimulus-responsive food additives are key components of 4D food printing and will be the subject of further research. Digital programming is among the most famous uses of adaptable 4D-printed structures, which are made possible by integrating multiple material distortion algorithms with 4D printing technology. The structural outcome variety improves the spirited visual effects of aesthetic creations and allows artists to express themselves more expressively. As a result, it opens virtually endless design pattern options for designers and artists including varied digital geometrical shapes, works of associated art, and ceramics. An expanding reentrant honeycomb (150% area increase), a shrinkable reentrant honeycomb (200% area decrease), and an expandable anti-tetrarchical honeycomb (62% area increase) are three programmable honeycomb structures. They also demonstrated that the modification of the ETH university logo, which was made of an extendable reentrant honeycomb, may change shape. Actuation hinges were made using black carbon particles that also contained chitosan hydrogel ink. Due to the photothermal response characteristics of the hinge material, infrared light stimulation caused the polymer substrate comprised of polystyrene to deform. In particular, the hinges were made in the shapes of square, zigzag, and honeycomb, which allowed for various bending degrees of the polymer substrate. These structures and designs can be used in the food industry mainly in the confectionary and baking industries (Ahmed et al., 2021).

8 | CHALLENGES AND LIMITATIONS ASSOCIATED WITH 4D PRINTING TECHNOLOGY

Despite being a new technology, 4D printing has a lot of practical applications. But there are still a lot of obstacles to be overcome in this industry. The inability of current 4D printers to address fundamental 4D printing problems, such as avoiding support structures, especially for internal structures that are difficult to access, printing multiple material groups at once (such as metals and polymers), the scarcity of affordable printable materials, and lengthy print times, is one of the biggest challenges (Chen, Zhang, & Devahastin, 2021; Chen, Zhang, Guo, & Chen, 2021; Chen, Zhang, Liu, & Bhandari, 2021). 4D printing requires the introduction of a creative process, such as changing the topology or encouraging motion in the printed object (Aldawood, 2023). 3D printing is the act of producing an object. By fabricating the finished object with 4D printing technology, these features are made available. According to the findings of Miao et al.'s study, 4D printing is thought to be a promising option for creating biological scaffolds (Miao et al., 2016). The ability of a 4D-printed object to react to changes in the body's surroundings served as the foundation for this argument. Adam and colleagues argue that 4D printing will be the next generation of microrobot production due to its capabilities (Adam et al., 2021). Either new printing technologies must be created, or printing technologies must be radically enhanced. There is currently a lot of interest in 5-axis 4D printing to solve some of these 4D printing problems. The limitation imposed on the mechanical qualities of 4D-printed structures by the desired shape or property transformation is another significant difficulty. Adapting printing technology made for molten plastics and metals to the printing of delicate, living biological materials is a significant task. The main difficulty, therefore, is to replicate the intricate microarchitecture of extracellular matrix (ECM) elements and various cell types with enough clarity to recapitulate biological function (Shi et al., 2022). Other difficulties come from slow and incorrect actuation, an inability to control intermediate stages of deformation, and a lack of readily available materials. Future research could look into methods for managing moisture absorption for hydrogels or more effective ways to apply stimuli, including enhancing the application of heat in thermo-responsive SMPs. These developments might potentially enable greater actuation accuracy. Future product manufacture and design will undergo a revolution thanks to 4D printing once these issues are resolved. It will result in a new and effective business model by lowering the capital requirement, speeding up the marketing process, making products conveniently transportable, and shrinking their size. Due to its ability to withstand extreme environmental conditions, 4D-printed structures can be used in space missions. As they can self-assemble, satellite and aircraft parts produced via 4D printing may be simple to assemble in space. Additionally, employing 4D printed structures would not pose a challenge for the necessary deformations in space. The design of 3D constructions can be made simpler with the use of 4D printing. Additionally, macroscale structural modifications might result in unfavorable property changes (Phuhongsung, Zhang, & Bhandari, 2020). With the use of 4D printing technology, user-responsive items that can respond to user needs can be produced. They can perform according to user demands and adapt to their surroundings. increase its possible uses, but these have not been fully investigated. The possibilities of 4D printing could be improved by new materials such as printed wood grain, textile composites, and tailored carbon fibers (Ahmed et al., 2021). For now, the main use case for 4D printing is its shape-changing capabilities. But as research develops, many new applications for 3D printed structures can appear, making them multipurpose. Although this is a multidisciplinary field, increased cooperation between its component fields should provide these structures more control over how their shape changes over time. Future developments in 4D printing are predicted to have a big impact on how we live now.

4D printing has few drawbacks that should be carefully considered. The difficulty of creating appropriate smart materials with exact shape-memory capabilities is a major limitation. It is still very difficult to strike the right mix of durability, flexibility, and compatibility with 4D printing technologies. Furthermore, although though 4D printing has outstanding precision and resolution, it still has to be improved, especially for small-scale and complicated designs, in order to match the high standards of a variety of applications (Demoly et al., 2021). One practical limitation is the pace at which the transformation process proceeds, particularly in situations where quick response times are critical. The persistence of design complexity and simulation issues demands the development of computational models to streamline design and simulation procedures for wider accessibility. For industrial applications, scalability for mass production is a crucial factor that necessitates continuous research to guarantee reliable quality and effectiveness on a bigger scale (Ahmed et al., 2021). The goal of completely simplified production may be hampered by the fact that some 4D-printed goods may still need extra treatments, even though post-processing is minimized in comparison to older methods. Ensuring biocompatibility and safety is a significant challenge as 4D printing spreads into highly regulated areas like biomedicine. This calls for constant research and strict adherence to regulations. It is imperative to tackle these constraints if the technology is to advance further and be effectively incorporated into a range of sectors (Ramezani & Mohd Ripin, 2023).

9 | CONCLUSION AND FUTURE PROSPECTIVE

Since 4D food printing is still in its early stages of development, there are many prospects for in-depth investigation and study. While 4D printing as it is currently practiced uses traditional 3D printing technology, it is expected that 4D printing would resemble advances in printing apparatus or environments with improved capabilities. 4D printing is a development from well-known AM techniques like 3D printing, allowing printed items to alter spontaneously in reaction to outside stimuli. In the industrial and academic domains, there is a growing interest in 4D food printing. It is possible for the food that is printed in 4D to change in texture, flavor, color, and shape. Currently, 4D food printing research is restricted to materials including starch hydrogel, soy protein, and potato puree. A large portion of the research is concerned with the sources of stimuli, such as microwave heating or pH changes. Numerous research investigates how stimuli affect the color of food produced by 4D printing, enabling required alterations such as denaturation and distortion of food ink ingredients.

These days, microwave heating and pH changes are extremely interesting to researchers. But the field of 4D food printing may explore new stimulating agents such as light, ionic content variations, and more. There has not been much research done on stimulus-responsive materials for 4D food printing. Research on novel compounds such as diacetyl and vanillin could lead to a revolution in 4D food printing by using different stimuli-responsive materials to change several food qualities at once. Establishing a monitoring system to gauge the degree of changes could be useful to enable controlled alterations in 4D. Further investigation into texture and form alterations is also advised. The understanding of how 4D-printed products react to diverse stimuli may be improved by the addition of different stimuli-responsive components into the ink.

CONFLICT OF INTEREST STATEMENT

There is no conflict of interest between the authors.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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