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Review Article

Advancements in Food Printing Technologies and Their Potential Culinary Applications: A Contemporary Exploration

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Food printing is a cutting-edge manufacturing technique that uses advanced printing methods such as binder jetting, extrusion-based printing, and inkjet printing to build an object layer by layer to achieve the required shape of food items such as chocolate and cheese. 3DFP (3-dimensional food printing) has the potential to combine delicate and easily degradable bioactive compounds and other functional elements into functional 3DFP food products, contributing greatly to the development of nutritious food. Many nations make different types of 3D food printers nowadays, creating specialty meals like space food, restaurants, elderly food, and floating food. Numerous benefits of 3DFP include the development of individualized food items with regard to taste and nutrition, the decentralisation of food production, the decrease of food waste, and commercial innovation. Based on the benefits of customizing current food to one's taste and use, three-dimensional food printing technology can be applied to a variety of food categories. One of the reasons for the increase in research into this technology is the ability to produce modified products that are tailored to suit the taste preferences and specific nutritional demands of consumers. In this review, the industrial situation of 3DFP technology was examined along with recommendations for expanding the market for 3D-printed food in the new typical age.

1. Introduction

The food sector is going through a standard transition. The development of new technologies that can satisfy consumers' new canons is being driven by the desire for new, specialized sensory capacities as well as consumers' expanding understanding of the food they consume. Among the novel technologies, 3D printing has existed for a long, but it was not brought to use in constructing food structures until 2007. Until then, 3D printing has been used to create sophisticated geometrical structures that exceed the capabilities of conventional methods of food production [1]. Methods like 3D printing, rapid prototyping (RP), and additive manufacturing (AM), or solid free-form fabrication (SFF), use digital models to create predesigned 3D items by layering adhesive components. Due to its potential benefits, including customizable geometry, a condensed manufacturing cycle, lower production costs, and almost unrestricted aesthetic complexity, it has advanced substantially in recent years. These benefits have been seen to support the third industrial revolution [2]. Numerous skills, opportunities, and possibilities have emerged for various scenarios, including nutritional considerations when it comes to the application of 3D printing (3DP) technology in the food sector. The study suggests that 3DP foods will allow you to create customized meals and digitized nutrition that take into account a person's age, nutritional status, physical/health condition (and fitness), and energy needs [3]. Milk protein distillates and edible insects were considered potential protein sources for 3DFP to enhance dietary value. By considering internal geometry or utilizing a multimaterial extruder with dual extrusion 3D printing, the textural characteristics of the 3D-printed product could be changed. But there is still a disparity between products made possible by 3D printing technology and conventional methods of producing food. Furthermore, the current state of 3DFP technology is challenging to recreate the feel of normal food, making it a significant barrier to food production. By using food krills containing plant cells, Vancauwenberghe et al. [4] have developed a revolutionary method to generate food that is similar to plant tissue (*Valerianella locusta*). *Valerianella locusta*, a leafy green vegetable in the Valerianaceae family, is also known as lamb's lettuce or corn salad. Its leaves are small, delicate, and oval in shape and have a subtle nutty flavor. It is prized for its high nutritional content, which includes vitamins, minerals, and antioxidants, and is frequently used in salads and culinary preparations. They demonstrated that plant-based ink is capable of 3D printing by incorporating lettuce cells with air bubbles into a matrix based on pectin. 3DFP integrates the 3D printing technique with the production of food and uses consumable ingredients, including liquids and powders from fruits and vegetables, starch, meat, and chocolate as printing inks. The ability to create intricate 3D structures is the primary aspect of 3D printing. However, in the food sector, the 3DFP technique may be most useful to distribute personalized nutrition and dietary choices [5]. The capability of the 3DFP technique can transform several areas of food production, making it simple to create personalized products at low cost and even allowing personalized nutrition control. The most popular substance suitable for 3DFP includes functional components, carbohydrates, proteins, fats, and fiber [6].

4D printing is the improvement in 3D printing on the "space-time axis," which was first projected by Professor Tibbits of the Massachusetts Institute of Technology (MIT) [7]. In a 2013 TED talk, 3D printing was distinguished from 4D printing as a novel approach of a sophisticated emergent design that gets altered over time as a result of the environment's interface. The original definition used the formula "4D printing = 3D printing + time," which refers to altering the shape, structure, or function of 3D printing over time [8]. Most of its applications in the food industry are around 3D printing. The texture, shape, color, and nutritional value of the printed samples of food products would change specifically after 3D printing under specified circumstances. Realistic parameter formation for 3D printing is an essential requirement for successful 4D printing. Similarly, to this, the essential component for effective 4D food printing is the materials' printing attributes [7]. By enhancing the existing 3D printing abilities, 4D printing is a new and sophisticated technology for producing advanced materials. These products have promising effects for the commercial production of environmentally friendly and sustainable agricultural plastics for use in greenhouse covers, shade nets, mulching films, and food packaging. The obstacles are peculiar to bioorigami, adaptive scaffolds, 4D joints, grippers, smart valves for acid/base, adaptive metal materials, hot/cold flow, laser-guided cell printing, and 4D nanoprinting. An additional barrier to the development of agricultural applications is the paucity of consistent proof of ideas and commercially available materials related to the technologies. The stimulus that induces phase changes in tissue manufacturing and engineering implementation is incomparable to the provocations found in farms, such as sunlight, moisture, or changes in pH associated with pesticides [9]. The progression of four-dimensional (4D) food printing has been supported in recent years by the increased consideration paid to the adjustable shape and color variations of 3D-printed food structures over time with the improving empathy of material properties and model design. Food printing technology is expected to balance out some constraints in food manufacturing that become difficult to fix with conventional processing techniques [7]. Rapid prototyping, accessibility, cost-effectiveness, exceptional design flexibility, lower material consumption, and geometric complexity are just a few of the many benefits that 4DP (4D printing) technology has over traditional subtractive manufacturing. External energy inputs, including ultraviolet (UV) light, pH, and heat, mainly cause a revolution in the shape of dynamic products [10]. It shows how 3D-printed objects made with innovative materials react to natural or appropriate artificial stimuli (like temperature, UV, water, pH, and light), which over time cause physical or chemical changes in the material state. Three main criteria need to be followed to produce 4D-printed materials. The first is the use of intelligent materials, which combine many materials with different assets. When exposed to specific environmental or human-caused incentives, these materials could favorably adjust their shape,

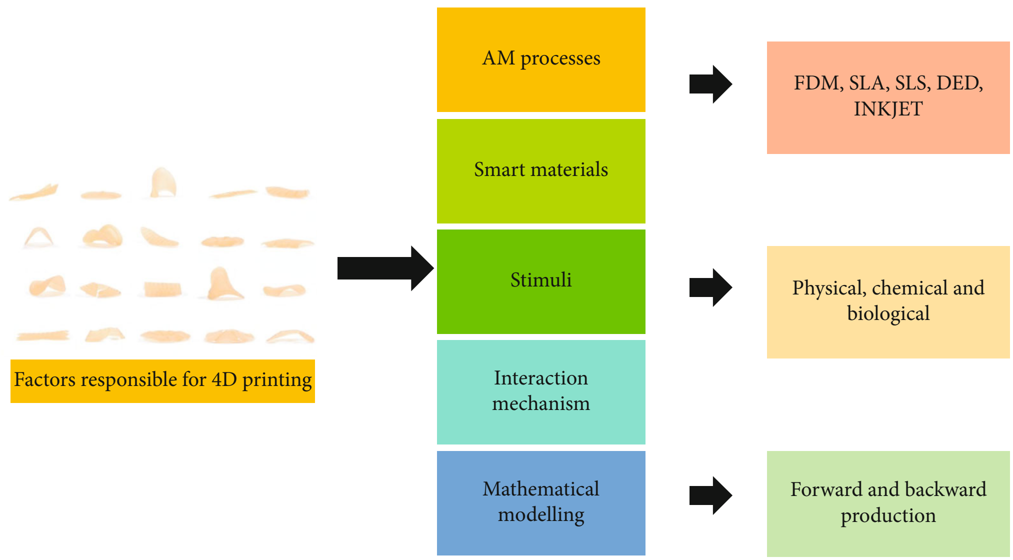

Figure 1: Diagrammatic representation of the factors responsible for the 4D printing. FDM: fused deposition modeling; SLA: stereolithography; AM: additive manufacturing; SLS: selective laser sintering.

color, or other features in many physical domains. The second factor is the stimulus that must be present for the 4D-printed object's shape, properties, or functionality to change. Its selection is governed by specific submission rules that also apply to the sorts of smart materials employed in 4D-printed products. The last aspect is the duration required for the mock-up procedure to be performed, which leads to the alteration of the state of the object [11]. Furthermore, 4D printing can adapt to changing consumer preferences and their need for fresh food commodities [12]. The diagrammatic representation of the factors responsible for the 4D printing is shown in Figure 1.

The concept of 5D printing was introduced by American universities in 2016. William Yerazunis, the senior primary research scientist of Mitsubishi Electric Research Labs (MERL), is in charge of carrying it out at the moment. A new-fangled branch of additive manufacturing is 5D printing. In this technique, both the print head and the printed item have five levels of autonomy. Instead of flat layers, it produces curved ones. As the printer head is printed in this method, the print component moves. As a result, printing follows the curve of the part being printed rather than proceeding in a straight layer, as is the case with 3D printers. The benefit of this technique is that it can build parts with curved layers and better assets [13]. In 5D printing, the table on which the item is printed also moves, causing the printer head to move in five distinct directions. These movements cause the printer head to print at various angles to produce any necessary planes and curves in the layers, which are not possible with 3D printing. Thus, materials are produced at various angles. 5D printing is a major technological development, since it allows for the creation of sturdy machines that are useful in the industry and that also adhere to safety standards. The advantages of 5D printing include the ability to create durable and sophisticated objects with less material. For instance, a concave cap could not be 3D printed due to its complex design and the necessity for several fillers and supports. However, 5D printing makes printing easier because it can print curved layers [14]. The 5D printing of food and food packaging materials may be possible with this technology. Using 5D printing technology, food goods with intricate shapes like ball-shaped candies, concave-shaped chips, or snacks can be printed. In addition, it can be used in food packaging to create intricately shaped boxes, and 5D technology can be used to produce tableware such as cups and bowls that need extra support material when printed in 3D [15].

5D-printed goods that experience regulated sensory alterations in response to outside stimuli are considered 6D-printed goods. To create more inventive food preparations and broaden the scope of services available to particular groups, 6D printing combines 5D printing with the ability to alter shape, color, and taste over time in response to stimulation from 4D printing [16]. Consequently, the food business is expected to benefit from a wide range of potential applications for 6D printing. In addition, 6D printing is also set to offer a promising application range for the food industry [15].

Potential advantages of various dimensional techniques are shown in Table 1.

Since 6D printing is still in its conceptual stages and is short of the results of 3D printing in terms of structure strength and complexity, the computational model and algorithm must be developed, used, and optimized to fit the design. The pairing of edible inks with 6D printers is crucial to achieving the printing mark and the printing output. Rheology could be useful in improving the edible ink formulas for 6D printing, simulating the printing process, and helping in the selection of the proper processing parameters. The structural stability of 6D-printed materials is rheologically

Table 1: Advantages of various dimensional techniques.

Printing type	Advantage	Application	Reference
3D	Formation of complex 3D structures and personalized foods	Specifically formulated foods for warriors, athletes, and expectant mothers	[5]
4D	Rapid prototyping, lower material consumption, accessibility, cost-effectiveness, geometric complexity, and excellent design flexibility	Self-folding food packaging, macro-/microscale soft robots for different engineering applications	[10]
5D	Production of robust complex objects with less material	Jewellery to the automotive prototyping industry can be benefited	[14]
6D	The creation of the intelligent final object, or the ability for the thing to change its shape in response to an external stimulus	For the manufacturing of advanced on-demand products	[17]

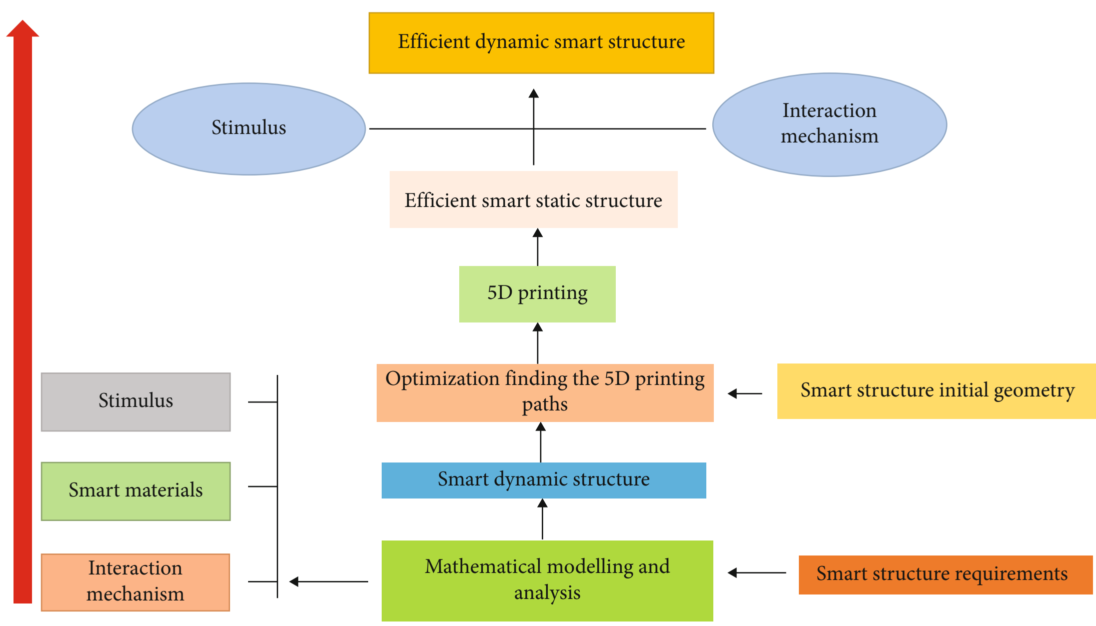

Figure 2: Concept of the 6D printing process.

examined in a similar way to that of 5D-printed samples, with a promising robust structure [18]. The basic concept is depicted in Figure 2.

2. Working Principle of 4D Printing

The prerequisites for the successful use of 4D printing are well conducted or carefully chosen 3D printing, stimulus-response material, stimulus source, stimulus-response material interaction mechanisms, and computer-aided strategy algorithms. The main prerequisite to cause changes in the functions, characteristics, and shape of 4D-printed materials is stimulation. The second aspect includes the production of composite materials that respond to stimuli. The next step is to provide the printed substance with a stimulus that will cause a certain response. The distinctive characteristic of this method is that it does not rely on any supporting substance, such as a thin plastic sheet, to facilitate distortion [19]. Active shape change of materials is primarily mediated by four mechanisms: shape memory effect, bistability, deformation mismatch, and self-assembly of parts. Hydrogel, shape memory polymer, and materials created by internal stress are some of the common types of materials used in 4DP. For 4DP materials to provide the necessary functionality and adaptability, a multicomponent or multimaterial idea is necessary [20]. With numerous methodologies and material advancements, 4DP technology has continued to advance. The successful implementation of appropriate additive manufacturing techniques and interpretation of the functioning of shape memory materials (SMMs) are managed by the fabrication of 4D-printed products. These SMMs enabled polymeric prototypes to respond to certain environmental stimuli and work together with them. For instance, when exposed to nature or other fonts, photoresponsive chromophores can capture light and deform as a user-determined model. Similarly, an object containing unstable solvents can expand when exposed to heat from thermal or electrical sources [21]. When exposed to high temperatures, the items prepared can change from their provisional structures to their preliminary shapes. Recent years have seen the emergence of 4D-printed structures that are not just powered by heat but also by electricity, light, magnetism, solvent, pH, and biological indicators. As a result, the capabilities of the combined 4D-printed components could be enhanced by the capability to distribute mechanical and electrical energy. As a result, the concept of material combination will cause the qualities and functionality of 4D-printed products to change as they are created [22]. Investigations of the relationship among material qualities, heating mechanisms, and shape change behavior revealed that a specific level of adherence to the printing medium was necessary to comprehend the programmed shape change of printed samples. The degree of bending is inversely correlated with the shrinkage ratio, the dielectric constant loss factor, and the amount of water that evaporates. The dielectric microwave dehydration (MD), the dehydration rate, and the internal heating model did not help the samples. During air dehydration (AD), the greater shrinkage ratio and the "bending accumulation effect," which was triggered from the surface to the inside, helped expand the degree of bending of the samples. Using materials with various deformation capabilities, previous researchers created a bilayer structure in the situation of altering the shape of edible components. Bilayers' nonuniform deformation properties were what caused them to take on a predetermined shape in response to stimuli such as heat or dehydration [23]. The substances used in 4D food printing are known as printing inks. The food ink used for printing should have both liquid and solid-like structures before and after printing. The dimension of the ink particle influences the physical or functional properties of the printed object, such as the oil uptake capacity, moisture content, and density. Furthermore, the mixture utilized in 4D printing for food ink incorporates a number of stimulus-response components. In reaction to severe conditions or stimuli, these compounds change their color, texture, flavor, and other characteristics. As a result, the responsiveness of the particular stimulus in food printing ink is a crucial factor in the 4D modifications in printed items. The pigments in printing ink generate 4D variations in food color under various pH settings. Curcumin, a stimulus-responsive substance used in 4D printing, has a red hue at an alkaline pH and a yellow tint at an acidic or neutral pH. By using the appropriate delivery methods, such as uniform gradient or patterned administration of its apparatuses, it is possible to realize the measured changes in the belongings of the 4D-printed entities under various stimuli [24]. Polyelectrolytes are an electric field-sensitive complex that can change its swelling properties, leading to shrinking and bending deformation on the basis of the initial form and the electric field applied. A polylactic acid (acid) that rapidly reduces the electric field due to electrophoresis and electroosmosis is one famous example. Light is another additional stimulus that has been thoroughly studied in 4D bioprinting and has the distinct advantage of being able to operate with greater spatial and temporal resolution [25].

3. Potential Applications of Food Printing

3.1. 3D Printing of Chocolate. With the ability to produce highly customizable foods for submissions in upscale markets and controlled sustenance intake, additive manufacturing and 3D printing techniques are dominating the newly rising industry of food printing. The confectionery sector has taken notice of this high level of customization to increase market share with ever-novel and attractive items. Additionally, applications are accessible for clients who are instructed to consume highly regulated diets, such as athletes, the elderly, and ill, or people who have difficulty chewing or swallowing food. The Netherlands Organization for Applied Scientific Research (TNO) has predicted this application as a midterm perspective for developing food printing sector [26]. In 2007, Dr. Liang Hao (Exeter University) had the idea to advance a chocolate production technology able to create beautiful and personalized chocolate items that can be sold to customers by merging 3D printing with chocolate processing. The first 3D chocolate printer, called "the Choc Creator 1," was created by the Choc Edge Ltd. company and released to the public in April 2012 [27]. Chocolates are commonly used for the demonstration of 3DFP because it can be patterned by hot melt extrusion and becomes solid at room temperature. Chocolate has the ability to be extruded out of the nozzle and regulate the shape following layer-by-layer deposition, which is related to the concept of printability. Waseda University also developed an electrostatic inkjet printer with a nozzle that contains a small ABS resin fiber at the end to reduce droplet size and print chocolate with remarkable precision up to 50 m [28]. Aside from sintering, which would definitely require much less fat than chocolate frequently contains [29], printing chocolate does not require flow boosters because it can handle viscous components [30], nor does it change its composition; additionally, it is contested regardless of whether inkjet printing is truly classified as a 3D printing technology, since it is frequently used to generate only simpler 2D designs [31]. While dark chocolate or commercial milk is frequently used in materials, the addition of additives is a growing area of study. Various formulations have been explored, such as cranberry powder and methylcellulose or milk chocolate with vitamin C [32]. Due to their particle structure, these additives can increase flow by reducing screw extrusion slippage and improving nutritional content. Chocolate 3D shapes were created using a deposition procedure by Hao et al. [32] using a 3D printer. Extrusion rate, nozzle height, and nozzle velocity from the printer bed were the key variables amid chocolate depositions, according to Hao et al.'s study. Several methods, including precise temperature control amid extrusion, optimization of the size of the chocolate unit, and additive integration, could be employed to increase the printability of the chocolate fragments. Smooth melting during printing is achieved by grinding chocolate to reduce its particle size [33]. By adjusting the infill structures (infill patterns as well as percentages) for textural or sensory evaluations, Mantihal et al. [33] created 3D-printed chocolates in their study. Dimensional characteristics of the chocolate produced, including width, length, and thickness, meaningfully coordinated the intended geometry, demonstrating the effectiveness and precision of 3DFP as a tool for design customization. The weight of chocolate produced by 3D printing was predicted with an increase in the infill %, which also influenced the texture and, possibly, the price and energy density per piece. The research demonstrated that 3D-printed chocolates (with 100% filling) were less stiff than cast chocolates because the layers did not work well together and were accentuated by subsequent layering amid extrusion deposition [34].

Although claims of the health advantages of chocolate have been made for many years, it is only fair that some of these claims have now received a more thorough examination. Due to the presence of tyramine and caffeine in chocolate, designing chocolate-based dosage forms should include potential food-drug interactions to avoid particular drug classes like monoamine oxidase. Hot melt extrusion accompanied by fused deposition modeling (FDM) has previously been utilized to create pediatric tablets that look like candy in a variety of shapes (heart, lion, ring, bottle, etc.). Additionally, it might open up the possibility of including delicate patient populations, such as the pediatric population, in the customized design process, improving the healthcare experience and the general acceptability of the end product. Four pediatric patients between the ages of 3 and 16 have recently been tested to see whether 3D-printed chewable isoleucine tablets created in a hospital setting by semisolid extrusion 3DP are acceptable. The children readily accepted the prints, which came in a variety of colors and flavors, and also expressed clear preferences for certain colors and flavors

3.2. 3D Printing of Meat-Based Products. As demand for meat has grown over the past 50 years, overall meat production has gradually increased; this growth will continue in the upcoming decades. However, due to the problems with conventional meat production, this is considered unsustainable. The Food and Agriculture Organization (FAO) estimates that global livestock emissions account for 14.5% of all greenhouse gas emissions and 8% of fresh water use worldwide. Due to intense factory farming and poor conditions for the welfare of the animals, conventional meat production raises health concerns, such as diseases related to nutrition and foodborne illnesses. In addition, they encourage the spread of diseases such as swine flu and bovine spongiform encephalopathy. In addition, the ethics of raising cattle and killing animals have been examined [35]. A common method of changing one's diet is to replace meat with plant foods like soy and peas. Another tactic is to produce lab meat, also known as cultured meat, using tissue cultures to produce animal muscle cells. For the creation of meat analogs, alternative materials from sources such as insects and mycoproteins have also been suggested. However, a multifaceted approach has been recommended that incorporates new plant material-derived substitutes, improved waste management, or policy restructuring to combat the unfavorable perception of cattle production. In this sense, 3D printing is an effective technique that could sustainably create goods that can be customized and have intricate shapes and textures [36]. Three-dimensional printing (3DP) is a developing technique for the food sector that exhibits a significant possibility to capture meat by-products for the creation of personalized meat commodities. Through the fusion of various food ingredients and printing processes, it gives the opportunity to produce innovative food products with digitized intricate shapes, untested textures, and better nutritional content. However, the printability of the meat paste must first be assessed to produce a 3D-printed beef product with the necessary design, sensory profile, and nutritional content. Any food item's capacity to be handled and bestowed by a 3D printer into a freeform structure is referred to as printability. Printing circumstances and the rheological qualities of the materials influence printability [37]. The printability of any food ink could be evaluated on the basis of its form stability, extrudability, filament characterization, and printing accuracy in 3D printing by extrusion, which is typically used for printing hydrogels. The link must change amid the extrusion-based printing method from its dormant state inside the print head to a high-shearing state amid extrusion and then back to its dormant state once it is deposited. These transitions are primarily driven by the following rheological characteristics: viscosity, yield stress, storage modulus, shear thinning behavior, and shear recovery. Thickeners increase the viscosity of the paste to provide comfort during initial or continuous extrusion, as well as consistency in the printed product. Gelling agents aid in the development of viscoelastic systems with variable strengths, which are advantageous for stability or shape fidelity. Heat resistance, solubility, and consistency of hydrocolloids used in 3D-printed meat products must be understood to be practical for postprocessing [38]. It could help personalize unique food products according to consumer preferences and needs, helping to streamline traditional food supply chains. The 3D-printed sample's dietary fiber content, 5.36 0.19 g/100 g, was found to contribute significantly to RDA [39]. In order to ensure 3D printability, the fibrillar protein network in chicken meat requires the appropriate preprocessing procedure. Ground chicken meat was made printable, and the printing conditions were enhanced with the addition of refined wheat flour. The results showed that the product could be printed more precisely and accurately at a speed of 1000 mm/min using a 0.82 mm nozzle with an extrusion rate of 8.8 mm^3/s and a 0.64 mm nozzle height at a constant motor speed of 360 rpm. Furthermore, it was discovered that extrusion-based 3D printing could be used to produce chicken meat with unique shapes [40]. The results of NMR and scanning electron microscopy (SEM) showed that the liquid in the chicken gel slowly transformed to free water and was also depleted because of the shear effect of 3D printing, culminating in a comparative protein concentration. As a result, after cooking, a much more dense and consistent hydrogel structure was formed. According to the rheology and gel strength results, the chicken paste that had been exposed to sodium chloride exhibited shear thinning behavior or had sufficient gel strength, indicating that it had found an acceptable compromise between gently pulling from the tip or sustaining the framework after deposition. Furthermore, the cooking feasibility of 3D-printed objects was discovered by merging them with mold-shaped (MS) products. Cooked 3D-printed samples demonstrated similar textural properties to MS samples under ideal conditions; however, they had a more severe cooking loss [41].

3.3. 3D Printing of Fruits. Fruits and vegetables were important components of the human diet because they can be used to supplement a balanced diet with vitamins, minerals, antioxidants, carbohydrates, and bioactive substances. The benefits of eating fruits and vegetables are well known around the world. The prevention and reduction of the risk of many chronic and degenerative diseases, particularly cardiovascular disease (CVD), metabolic or degenerative diseases, and specific types of malignancies, have been linked to diets rich in vegetables and fruits in several clinical and epidemiological studies. Furthermore, the cost of healthcare components has increased, making it more important than ever to prevent degenerative diseases. Therefore, implementing a healthy diet full of fruits and vegetables is a good way to protect the health of consumers. In this situation, 3DF printing may be a key component of the technology used to create advanced 3D structures made from customized food formulations that incorporate elements from fruits and vegetables that have particular nutritional features, such as bioactive chemicals [42]. One of the most widely grown fruits in the world, the banana is incredibly nutritious and medicinal and is rich in nutrients such as calcium and potassium. The polysaccharides found in bananas, including starch and water-soluble dietary fiber, a rich mouthfeel, have a high viscosity and a texture that makes them suitable as 3D printing materials. The assimilation of pea protein isolate (PPI) into the banana gel matrix may be a useful technique to overcome the long paste behavior to quickly manage material flow during 3D printing and to improve nutritional balance. The addition of PPI improved the entanglement of the protein with the banana matrix, increasing the loss modulus, storage modulus, or adhesion force, while decreasing the percentage of recovery and elongation at break. However, the inclusion of more than 20% of PPI led to protein accretion in the matrix, which prevented a complete recovery of the structure and caused the 3D-printed line to break, as well as erratic extrusion [43]. Regarding the sensory and nutritional aspects of foods tailored to specific consumer sections of the population, the aged, pregnant women, adolescents, athletes, etc., 3DFP is capable of meeting all these requirements. Printing makes it possible for food to have a pyramid shape and a more aesthetically pleasing appearance than a smoothie without printing. The sensory properties of the samples, as well as their antioxidant capacity and total phenolic content, were not affected by the printing. The ability to faithfully reproduce the specified virtual model is a crucial issue from the point of view of the printing process and is closely related to several printing variables. Although the total phenolic content decreased from 18.8 to 10.5 mg GAE/100 g after storage, the antioxidant capacity remained constant at 10.9 mg 28 Trolox/100 g [44]. The prevalent method of 3D printing is extrusion-based because it has several benefits, including being environmentally friendly and reducing energy and food waste. The provision of sustainable nutrition, as well as food security, is the overarching goal and primary emphasis of 3D printing. Water is the main ingredient in fruits and vegetables, and the concentration of water varies from plant to plant. Moisture content hampers the ability to perform 3D printing on fruits and vegetables, mostly due to its limitless impact on the viscosity of pastes. Furthermore, the strain is completely responsible for the successful adaptation of probiotic microbes to fruit products. Making 3D fruit-based probiotic food is possible using various probiotic strains, individually or in groups. Another significant obstacle to the commercialization of 3D printing is the limited printing speed, which restricts market production. Due to the difficult food operation on the printer, the shelf life of printed food is also a challenge. Therefore, food safety is a key task in this technique. The microbial load and food protection before, during, and after printing should also be studied [45]. An equal mixture of banana peel (BP) and sugarcane bagasse (SCB) was shown to be more suitable for use as food packaging, as per the description of the 3D-printed prototypes. To explain the capability of agricultural waste as a valuable resource for 3D-printed food packaging applications, the produced 3D build might be designated as a primary proposal. The capacity of these agrowastes to absorb water can be improved by further study. Increasing the effectiveness of surface coatings for foods with high moisture content would be very appropriate. Additionally, containers can be altered into different shapes by applying optimal printing conditions, promoting a reduced dependence on single-use plastic food packaging materials (plates) [46]. With its ability to produce individualized food, 3DFP technology can be used as a replacement technique to support an oral diet. The capability to produce foods with a variety of textures, a wide variety of food materials, and a deceptive appearance of food are three of the important elements of the potential of 3DP that have been identified as having the potential to improve oral intake in patients. In addition to clinical therapies, providing food with the right texture, nutrition, and aesthetics can increase oral intake and be conducive to reducing disease time, preventing disease progression, and lowering the mortality rate. The potential of 3DPF to provide personalized meals has been demonstrated, despite the company's lack of formal affiliation with hospital nutrition services. The healthcare industry and hospital nutrition services are advised to consider the use of 3DFP to improve oral intake of immunosuppressed patients, particularly in this COVID-19 condition, where some of the malnourished patients were increasing [47].

3.4. 3D Printing of Dough-Based Products. Traditional, age-old food preparation techniques such as fermentation and malting are employed to speed up food preparation for consumption. The former is a sophisticated bioprocess that benefits from the transformation of innate components of food materials through the inoculation of specific microbial strains or natural flora. The desired modification in nutrition, bioavailability, and organoleptic qualities is frequently accompanied by the resultant products. The latter, on the other hand, is motivated by the incomplete hydrating of food grains and unevenly moistening them under regulated circumstances to positively affect the conformation of the substrate by the glistening actions of hydrolytic enzymes. Consuming fermented or malted products has been shown to increase the health of the host immune program and reduce the risk of acquiring metabolic disorders related to chronic diseases. Cookie dough is a product that invariably requires postprocessing, but it soon buckles after baking, implying a major decrease in the completed goods' quality. The mixture for 3D-printed sugar cookies, on the other hand, is created with changed quantities of butter, eggs, and sugar, which may boost the product's shape's resilience after postprocessing. Furthermore, such a drastic compositional change makes recalling the textural features of the intended final product impossible. It is critical to retain material characteristics during postmachining to avoid deformation while maintaining the original features expected of completed goods [48]. Currently, several meals, including dough, cheese, mashed potatoes, or meat, are prepared using extrusion-type 3D printing and have a variety of intricate and distinctive structures. Yang et al. [41] examined the baked dough formation and its physical qualities when varying amounts of water, sugar, butter, flour, and eggs were added. They discovered that with substantially higher elasticity, gel strength, and extrudability, as well as relatively lower ductility, the good shape of the extruded sample could be attained. Severini et al. [44] prepared snacks out of dough made from wheat and supplemented with ground yellow mealworm larvae, a significant source of protein. They discovered that adding ground insects up to a specific amount made the dough softer and caused it to overflow, leading to an increase in the height, diameter, and weight of the food samples. The best printing quality was achieved in a 5 : 3 flour-to-water ratio without the addition of freeze-dried mango powder or olive oil, according to research on the impact of material composition on the quality of 3D-printed food using freeze-dried mango powder, wheat flour, olive oil, or water. The finest food samples showed some advantages, such as a well-organized packaging structure, a distinct internal texture profile, or a reduced amount of general deformation [49]. Broken wheat biscuits (flour) with grape pomace powder were created using the 3D printing technique. These grape by-products directly affect the rheology, nutritional value, texture, and sensory attributes of the resulting product. Through more simplified procedures, 3D printing technology in food enables the creation of delicatessen with individualized designs or textures. This method also reduces the environmental impact of material recycling and local manufacturing. The inclusion of grape pomace improved the nutritional content or antioxidant ability of the cookies. Interestingly, the product produced is also abundant in proteins, dietary fiber, and a variety of bioactive ingredients. With a strong customer desire, this method maximizes the potential for the addition of value from industrial waste streams. As a result, customizing the nutritional value of meals can be a great addition to the unmatched degrees of personalization that 3DP offers, while also opening opportunities for cleaner manufacturing methods as well as better resource recovery from food processing waste [50]. The printability and postprocessing capacity of cookie dough preparations with various types of fat (butter and shortening), flour (wheat, rice, and tapioca), the quantity of nonfat milk (32.5 or 65 g/100 g flour), and the level of sugar (37.5 or 55 g/100 g flour) were examined. The microstructure, rheological characteristics, and printability of printing inks were monitored, and the moisture loss and postbaking structural properties of printed and baked structures, respectively, were examined. To produce 3D composite structures that were anatomically stable and unaffected by deformation during baking, the recipe was modified by varying the amount of milk and sugar. The yield stress was correlated with the extrudability and mechanical strength of the cookie dough, according to the rheological characterization. The deformability of the samples increased as the milk content of the cookie dough formulation increased. When exposed to baking, the form was observed to degrade more when the sugar content was higher. Confocal images of cookie dough samples showed that the kind of flour had an impact on the internal network and determined how the fat was distributed, both of which were related to the physicochemical qualities of the flour [51].

3.5. 3D Printing of Cheese. Milk has long been regarded as a vital component of the human diet or nutrition. The reason is that milk or dairy products include both macronutrients and micronutrients, creating storage of energy in the form of proteins, carbs, minerals, lipids, or vitamins. Cheese is one of these dairy products. The production of cheese can be categorized on the basis of some factors, including the coagulating agent employed, the cheese's ripening environment, the cheese's fat and moisture content, and the numerous heat treatments applied. In addition to its sensory qualities, it offers many health advantages, including inhibitory effects of angiotensin-converting enzyme (ACE), which are mainly due to the presence of lactic acid bacteria (such as probiotic strains) [52]. Cheese is frequently consumed; thus, there is always a chance that adulterants will be added, making it vulnerable to adulteration. In particular, it is frequently seen in the trade of dairy products that cheese made from milk with a higher commercial value has been contaminated with less upscale types of milk. This deceitful practice has a significant negative impact on the health of societal subgroups that are allergic to particular dairy products. To appropriately label expensive, certified, and high-added value dairy products, the food industry is happy to confirm both the source of dairy products and their contents following EU Directive 273/2008. In addition to examining the components of the cheese protein using a polymerase chain reaction (PCR), adulteration could also be detected using electrophoretic, chromatographic, and spectroscopic analyses. However, these methods are expensive, require a lot of instrumentation, are time-consuming, and are exhausting. Electrochemical immunosensors, on the other hand, are more suitable for on-site investigation because of their low cost, mobility of the device, ease of use, high sensitivity, and selectivity. Integrated electrochemical sensors and devices can be made by three-dimensional (3D) printing. The innovative design for an electrochemical immune-sensing device includes a 3D-printed microcell with two thermoplastic electrodes and a working electrode made of Sb_2O_5/SnO_2-modified graphite. The taxation of cheese made from a blend of goat/cow milk and ewe/milk serves as evidence of the applicability of the immune device to the examination of complex media [53]. The growing demand to create different custom food concepts with artistic appeal and custom nutrients has been attributed to the growth of 3DP in the food or dairy industry. Numerous studies have been reported on the use of different edible materials such as bioinks for 3DFP that can provide the desired nutrients and sensory customization. Studies on skim and semiskim milk powder-based bioinks are discussed to gauge their ability to develop various dairy hypotheses and control the effect of component interaction on material qualities separately related to their printability [54]. A mixture of natural cheeses, vegetable fats, other dairy products, water, emulsifying salts, proteins, and additives is heated, blended, and emulsified to create processed cheese. Processed cheese functions as a stabilized, structured viscoelastic emulsion at room temperature. Since processed cheese is frequently used in molten forms, such as in pizzas and hamburgers, its melting characteristics are kept quite well. In comparison to untreated and melted cheese, the cheese created by 3D printing technology had much less hardness and more reliability. Confocal laser scanning microscopy (CLSM) was used to investigate the shearing or solidification processes that occur simultaneously, unsettling fat globules while fixing them in place upon solidification, in a partially coalesced, nonspherical state [55]. When applying 3D printing to any food product, we have to take care of multiple factors. When creating "printable" formulae for processed cheese, pH and structural protein composition are the key factors. According to users' perceptions of the texture or printing accuracy and the desired product suitability for the intended use, these characteristics can be optimized. In the case of processed cheese, mixes with a viscosity of 7.55 to 10.94 Pa·s are regarded suitable for printing, which means that the produced mixtures are acceptable according to printing accuracy due to their ideal texture or flow. Temperature is a key processing variable that can impact "printability" in terms of ideal texture and printing precision. Compared to lipid globules in samples printed at lower temperatures (40°C), it was determined that at higher temperatures having to be printed (65°C), the structure becomes harder and more resistant to compressive forces, where the congealing impact of lipid globules is accelerated and the droplet size increases [56]. By combining the fused deposition modelling technique with clearly specified 3D printing paradigms, a casein structure for 3D printing was constructed. The use of the low-fat Pickering emulsions in 3DFP may open the door for customized nutrition for a particular health problem. Pickering emulsions high in acetylated microcrystalline cellulose (MCC) were found to have the shear-thinning, viscoelastic, thixotropic, and thermos-reversible properties of the ideal ink in this aspect. Reduced-fat 3D-printed items have a greater hardness compared to freezing, which improves the freeze-thaw stability of 3D-printed buildings. In terms of mouthfeel, adding saliva into 3D-printed samples increased the friction coefficient compared to the saliva-free product. According to sensory analysis, the reduced-fat printed cheese analog's micro-biosurfactant ratio notably fluctuated and was mostly connected to instrumental texture characteristics. High-quality sensations, especially those concerning the spatial perception of mouth coating, richness, or fatty aftertaste, revealed the feasibility of employing low-fat 3D-printed objects, which were regarded as a feasible cheese analogue commodity. This offers the prospect of manufacturing low-fat 3D-printed things with the practical or sensory features desired by the specific consumer, such as personalized nutrition or increased understanding of texture [57]. The printing parameters of the 3D-printed foods are summarized in Table 2.

3.6. 3D Printing of Hydrocolloid-Based Products. The foundation of the particles and the particle content are the major factors that govern the printability and rheological features of food ink systems in which the particles were spread in a hydrocolloid matrix. The use of powdered components in hydrocolloid-based food ink preparations, where the moisture is reduced through drying techniques, may improve the product's printability. Increasing the amount of food powder used can also increase the percentage of nutrients in 3D-printed foods. Exacerbating factors include the origin of the powder, the volume of the powder, the swelling of the particles, and the distribution of particle size in mixtures made up of dispersed particles in a hydrocolloid matrix. In particular, the volume fraction of powder, which is related to particle swelling and could be regulated by the addition of hydrocolloids to prevent swelling, has a substantial effect on rheological characteristics [48]. Three crucial criteria, printability, application, and postprocessability, must be addressed by the hydrogel, hot melt, or soft materials used in extrusion-based food printing [60]. A widespread disease known as dysphagia is estimated to affect up to 40% to 50% of elderly people in nursing homes and 14% to 15% of the population over the age of 50. Dehydration, malnutrition, aspiration pneumonia, risk of choking, and a decline in quality of life are some of its symptoms. Texture-modified diets (the Royal Australian College of General Practitioners (RACGP) (2006)), which include thickened fluids, pureed, and minced or bite-sized foods, among others, while being unpleasant and stressful to consume, are one way to minimize the risk of choking and aspiration. With the use of 3D printing technology, a delectable substitute may be created with precise layering or deposition to create a 3D model based on a CAD design that retains desired textural characteristics while resembling the food's original form. The addition of hydrocolloid mixtures of xanthan gum or guar gum to 3D-printed cooked pork pastes altered the textures, making them appropriate as transition foods for those who have difficulty chewing and swallowing [61]. Some foods, such as grains, meat, fruits, and vegetables, are difficult to print on one's own. In these cases, we can use food hydrocolloids, transglutaminase, and other agents to increase the extrusion capacity and structural stability. Soy protein has been successfully printed to create porous shells that could be used as biomaterial implants for regenerative medicine applications. Soy protein has a good number of necessary as well as nonessential amino acids and reasonable physicochemical or functional qualities. By gelling, the soy protein and sodium alginate comixing method aids in the formation of a stable structure [59]. Phase angle or relaxation exponent

Table 2: Printing parameters of 3D-printed foods.

Type	Macronutrients used for printing		Printer parameters				
	Material	Shape printed	Nozzle speed (mm/s)	Nozzle diameter (mm)	Extrusion speed (cm3/s)	Temperature (°C)	Reference
Primarily carbohydrate	Gelatin, xanthan gum, agar	Spider web, maple leaf, cylinder	20	1.1	—	20	[58]
	Baking dough	Mickey mouse	25	2	0.118	24.8	[41]
	Carrots, pears, kiwi, broccoli, avocado	Pyramid	15.87, 20.77	1.2	—	Room temp	[44]
Primarily protein	Soy, gelatin, alginate	Cylinder	10	1.55	—	35	[59]
	Fish surimi gel		28	2	0.0028	Room temp	[60]
	Egg white protein, gelatin	Snowflake, square	70	2.5	0.003, 0.004	40	[49]

could be utilized to understand the solid or liquid behavior of the paste during the cold extrusion 3D printing process, according to the results of the viscoelastic behavior and printability of food-grade hydrocolloid pastes, including their thixotropic behavior and rheological parameters. The findings indicate that paste materials are printable or able to support their weight when printed if the phase angle is between 3° and 15° and the relaxation exponent is between 0.03 and 0.13. The phase angle could be utilized as a rapid and efficient way to examine the printability of the formulation because the measurement of the phase angle in the viscoelastic area is straightforward. To create novel feedstocks for 3D food printing, the knowledge retrieved could be utilized as a design rule for food (hydrocolloid) printing procedures [62].

3.7. 3D Printing of Protein-Based Products. Proteins are typically preferred for the development of inks used in 3D printing because of their ability to serve as a vital structural component of living systems, support cells, and promote tissue function. They serve as the foundation for numerous crucial ex vivo hidden structures found in nature. These inks bridge the gap between technology and biology by supporting implant-host integration and playing a beneficial function in vivo due to their mechanics, chemical and physical fit to the specific tissue, and full degradability. Through their chemical, biological, and physical characteristics, protein-based inks can offer crucial possibilities to meet the requirements of tissue engineering or regenerative medicine [63]. Plant protein-based polymers have unique thermomechanical characteristics, making them potential 3D printing materials. The material characteristics of the substitute feed proteins are also examined, and potential protein sources are found for 3D extrusion printing. The use of plant proteins presents some difficulties, such as the high moisture absorption of the materials, the peculiarities of 3D printing, and the choice of plasticizer. Protein-based materials can be 3D printed and utilized for packaging, food production, or medication design. Animal proteins can be replaced with plant proteins, which have received a great deal of attention in recent years. They are part of a rapidly expanding new market for meat substitutes and have a good amount of nutritional protein that is more sustainable than animal proteins, has health advantages, and can be used in a variety of diets (vegan and vegetarian). For those who only have difficulty swallowing and dislike foods high in protein, getting enough protein is crucial. The technology used in 3D printing allows for the modification of food nutrition, making it particularly useful in this context. Consumers have been shown to prefer and have more faith in printing inks made from peanut protein isolate over other inks. In addition to creating a novel printing material, peanut protein isolate raises awareness for the creation of other proteins and protein composite ink systems. A feasible technique is to incorporate fruit and vegetable powder into a 3D printing ink mixture that uses peanut protein isolate as a matrix. Furthermore, protein matrix technology has a broad range of applications and is designed to adapt nutrition programs for common or unique populations (such as children and people with dysphagia) [64]. The food industry produces a tremendous amount of by-products that can be recycled for sustainable management. As an illustration, consider (1) porcine plasma protein (PPP), a by-product of slaughterhouses that can be made from blood; (2) soy protein isolate (SPI); and (3) pea protein concentrate (PPC), which are surpluses of pea crops and by-products of the industrial extraction of soy oil, respectively. These three protein sources (PPP, SPI, and PPC) are frequently utilized as thickeners or emulsifiers in the food sector. During the 3D printing process, the rheological characteristics of protein-based doughs made from blood plasma, peas, and soy were evaluated for their impact on the process's effectiveness. In the end, the designs generated products that were conveniently formed or that mimicked the desired pattern. Rheology methods were used to assess the printability of dough with various concentrations of porcine plasma protein (PPP). It was discovered that dough with a PPP content between 42.5 and 47.5 weight percent were successful in printing. The remaining portion of the PPP was then replaced with either a pea protein concentrate (PPC) or a soy protein isolate (SPI), maintaining the overall biopolymer content of the dough at 45 wt. 36%. Mixed doughs were successfully printed, displaying identical textural profiles for all printable dough up to a PPC or SPI concentration of 10 or 15 37 wt% within the biopolymer fraction, respectively (low firmness, high adhesion). Building printability maps for the protein-based dough under study reveals how important it is to manage their rheological qualities [65]. When considering the manufacture of 3D-printed meat products, it is vital to consider minimization of particle size and weakening of the meaty and savory flavor, which is frequently linked to a decrease in value. This will make it more difficult to construct meat products using 3D printing from lower-quality, harder pieces of meat. However, the manufacture of cultured meat products and the successful meeting of the needs of those on specific diets may have a brighter future for 3D printing. These foods may be available to some unique groups in society, such as those who need omega-3-enriched foods for their developing brains, women who need iron-enriched products, celiacs who need gluten-free products, and those who need calcium-enriched products because they have a dairy allergy [66]. It could provide unique solutions to the complex problems associated with the creation of cultured meat, focusing primarily on controlling the level of fat, protein, and other nutrients, as well as providing the proper texture [35]. The DFPI (Digital Food Processing Initiative) has concluded several 3D printing initiatives of food, with a focus on the development of a customized military diet based on the demands and preferences of each soldier. By 2025, 3D-FP sales are predicted to increase by approximately 20%, with more applications in the meat, chocolate, and pastry industries [67].

3.8. 4D Printing Inks. Among the manufacturing technologies which were used for 4D printing, the direct ink writing (DIW) technology shows dominance because of its open source for several types of material, as shown in Figure 3. The DIW method refers to a printing process based on

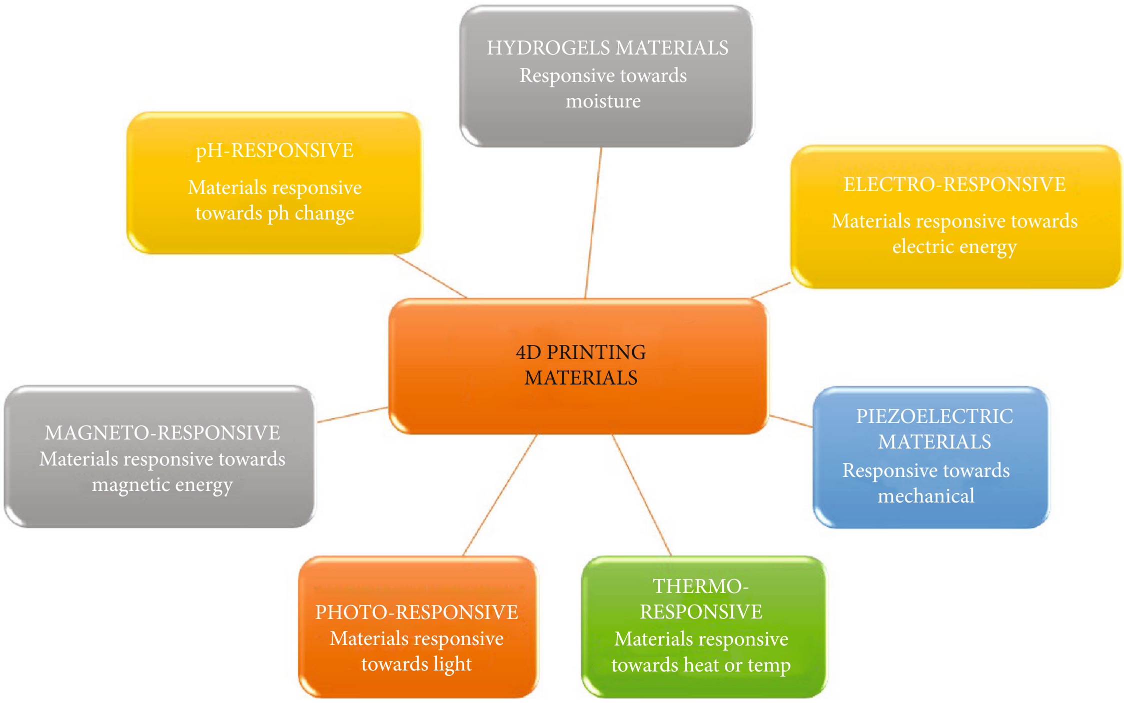

Figure 3: Schematic representation of the types of materials used for 4D printing.

extrusion through a nozzle under pressure that transfers a dispenser filled with printed ink while being controlled by a computer to form geometries layer by layer. High printing resolution could be achieved using DIW micronozzles, which is encouraging given the potential of radio frequency and unconventionally powered microdevices [68]. The ability to utilize a standard 3D printer to manage material placement is made possible by the invention of a submissive composite cellulosic hydrogel that contains a sizable amount of cellulosic material without sacrificing the cellulose's approachability to hydration. The composite was given a cellulosic hydrogel, which resolved the issue of the composite's shear thickening, which was frequently clogging the print nozzle due to the strong natural hydrogen bonding among cellulose fibers, and enabled the composite to be extruded precisely. In addition to introducing the necessary shear thinning qualities, the detachment of pulp fibers in the hydrogels also helped to induce distortion and circulation of pulp fibers through optimized mixing techniques. Cellulose is made up of β-1,4-linked anhydrous D-glucose units, each of which is 180° reversed from its nearest units. Hydrogen bonds form between molecules as a result of the presence of hydroxyl groups (OH) in cellulose. In the cellulose structure, this hydrogen bonding produces crystalline and amorphous segments and results in the creation of fibrils, which are further subordinate to form fibers in a genuinely hierarchical manner [69]. Uchida and Onoe [70] proposed a new way to fabricate 4D objects made of stimulus-responsive hydrogels utilizing viscous liquid that functions as a backup material when printing. A slower stage speed and a nozzle with a smaller diameter should be used to perfectly create 4D structures. Liquid carboxymethylcellulose (CMC) with UV-polymerized printed ink can respond repeatedly to external stimuli. By printing several hydrogels with cross points and inner gaps, complex 4D structures with a variety of distortions in response to external stimuli might be created [70]. The utilization of a hydrogel system in soft robotic products has many benefits, such as low cost, straightforward designs, processability at low temperatures and in aqueous settings, or the ability to emulate bioinspired function. For instance, isotropic volume expansion or contraction of similar hydrogels, or the bending/unbending tactic, which exemplifies an anisotropic distortion or frequently involves the construction of a hydrogel structure having two layers of diverse materials with varying swell-ability values, can be used to achieve a directed program of hydrogels. When the expandable material was in contact with water, it formed a hydrogel, and as the experiment progressed, the printed gel demonstrated a significant volume growth of up to 200% [71]. To achieve a quick, reversible shape change, liquid crystal elastomers (LCEs) switch between the liquid crystal (nematic) state and the isotropic state in response to stimuli. These were initially noted by de Gannes in 1975, and their potential uses have been thoroughly investigated. After being 3D printed at room temperature to create LCE, the object could be immediately stimulated. A box with reversible opening and closing, a soft robotic gripper for pick-and-place operations, and a hand with five reversibly actuating fingers to create American Sign Language were made using the simple concept. Using simple preparation, printing, and activation techniques, 4D printing of two-way shape memory LCE can enable an inventive group of quick manufacturing for flat-pack smart structures or implanted medical devices [72]. Applications in optics, such as structural color creation colorimetric pressure sensors, as well as temperature-sensitive passive labels, which all need sub-micrometer resolution and accuracy, are indeed driving the push to increase print resolution. A conclusion may be reached from the observation of nanoscopic-scale 4D printing of shape memory polymers with the proposal for multicolor unseen inks using two-photon polymerization lithographic of the specifically designed photoresist. Multiple colors can be easily recognised by adjusting the printing settings, such as diode lasers, write rate, or nominal grid height, due to the flexibility of the design and manufacturing application's design factors. By using software design, printed structures can quickly and firmly wander in color [73]. The color filter impact is eliminated by programming and arranging the lattice in a compressed shape, resulting in transparent structures. All colors reappear when the eternal shape is recovered [74].

3.9. 4D Printing of Starch-Based Products. Most consumers choose food based on food qualities such as taste, cost, nutritional value, texture or convenience. Perhaps the hardest and most important aspects to change in food are its structure and texture. Furthermore, consumer preferences, demands, and choices are varied and essentially limitless. For a very long time, different processing techniques have been used to create foods that are dense in nutrients, economical, flavorful, and practical [75]. To combine the distortion of 4D-printed food items outfitted with purple sweet potato particles (PSPP) and mashed potato, the bending angle may be evaluated by simply implementing the proportions of edible salt as well as the butter content of the printing materials (MP). As a result, a printed object/support sheet bilayer combination may withstand instinctively directed bending deformation during microwave dehydration. The combination of the printing components had a significant impact on the bending inclination of the printed products. Purple sweet potato purees were examined for their rheological characteristics, water distribution behavior, and dielectric characteristics [76]. When salt is added, the relaxation time of the purees increases, but the yield stress, loss modulus, storage modulus, and viscosity decrease. Fructose syrup addition produced the opposite effects. The inclusion of salt or syrup decreased the dielectric constant while raising their dielectric loss, respectively. The rates of dehydration and deformation increased with improvement in microwave power and salt concentration, whereas the highest degree of distortion of the printed models decreased because salt addition, which hastened the temperature rise and dryness, boosted the samples' capacity to transform MW into heat. Consequently, the surface case hardened once again, postponing the deformation. Additionally, the syrup reduced the maximum degree of deformation. The use of the infill parameters could potentially result in a desirable deformation design. When the composition of the printed material and the stimulation conditions are adjusted, the distortion properties of the printed samples can be precisely regulated. The intended strategy is expected to become a popular alternative to improve the consumer's experience when eating food if the deformation of intricate printed objects, such as butterflies or flowers, can be successfully managed [77, 78].

In a study by He et al. [79], they observed that the coloration of printed samples of potato flakes gradually altered in response to pH values in a different investigation. The potato flake content (15%, 19%, 23%, and 27%) and the pH values (pH 2.5, 6.8, and 7.8) significantly affected moisture distribution, printing performance, rheological properties, and textural characteristics. The amount of potato powder added was shown to be inversely associated with tan and relaxation time, while being positively related to mechanical properties, loss factor, bulk modulus, and texture characteristics. The addition of more potato flakes allowed the printed product to regulate its shape. As a result, at 23% and 27% of the potato flake concentration for the printed samples, the mashed potatoes showed good shape fidelity and neutral mashed potatoes. Additionally, it was possible to direct the printing of PSPP and MP using multiple materials and to change the color of the samples on demand. Acid MP turned red as a result of anthocyanins, neutral MP appeared blue-purple, or alkaline MP turned green. As the concentration of potato flake increased, the percentage of color change decreased [79].

4. Effect of Food Printing on Physical Properties

4.1. Color. The most deliberate assertion made by 4DFP is that the color changes over time, caused by many inputs. According to the findings of numerous studies, the diffusion rate of anthocyanins was changed by tempering the width of both the purple sweet potato puree (PSP) layers and the printed mashed potato (MP), leading to a variety of color modifications [80]. The colors produced depend on the change in pH level, since the molecular structure of anthocyanins changes with a change in pH. It investigated how a 3D-printed lotus root compound pigment gel responds to pH using a novel technique. Customers were given a different pictorial understanding after scattering the $NaHCO_3$ solution, since the color of the printed sample quickly changed from reddish/yellowish to green in 1 minute. A stronger color change resulted from a higher solid/liquid ratio, although the interior color change was slowed [81]. After being microwave-treated, the printed sample's color changed from yellow to red. Due to the heat generated by microwaves, which encouraged water molecules to flow around, as well as improve the alkalinity of the area around curcumin lotus root gel, treatment noticeably improved textural characteristics. Snacks made using interesting 4D printing technology can change their properties (color, texture, etc.) with the simple use of a microwave, giving consumers a unique sensory experience [81–83].

4.2. Shape. According to results from scanning electron microscopy, spinach that has been combined with xanthan gum was investigated for a food-ink dispersion system. Higher particle sizes (307 m and 259 m) were found to have a slender as well as cellular structure and to be more permeable than the smaller particles (up to 26-172 m). The bulk density and composition of the spinach powder were both considerably impacted by the increase in particle size. The water solubility index was not affected by the reduction in particle size, suggesting an increase in the capacity to store water and oil. A systematic increase in the storage modulus and loss modulus values was facilitated by a larger particle size [11, 82, 83]. The aspects of electrical constants, water management, and young's modulus of oleogel and purple potato mashed showed the impact of numerous purple potato puree formulas on deflection success or failure, as well as its printability and the effect of shape change caused by microwave treatment. By adjusting the microwave duration, the model can produce various levels of deformation (0 s, 15 s, 30 s, 45 s, 60 s, 75 s, 90 s, 105 s, 120 s, and 135 s) or the power (0 W, 30 W, 60 W, 90 W, 20 W, 150 W, and 180 W) [84]. As suggested by the interplay among material characteristics, heating mechanism, and structure behavior, a solid groove of the grasp of the printing materials is necessitated to grab the planned shape change of printed samples. The amount of water evaporation and shrinkage ratio is found to be proportional to the bending degree; however, the dielectric constant loss factor is found to be inversely related to the bending degree. The dielectric microwave dehydration rate and internal heating simulation did not allow the samples to be bent. Although the greater contraction ratio and the "bending stacking effect" caused by the ground dryness process during air dehydration (AD) have a positive effect on the bending of the sample [23, 58].

4.3. Flavor. Most food production methods primarily focus on mass production, ignoring human control over shapes, structures, and flavors, as well as food innovation. Consumers have a fantastic opportunity to experiment with food flavors and forms thanks to food printers. Previously, this customization procedure was performed manually using specialized talents with a high cost and a low output rate. Food printing technologies can eliminate these limitations by giving more flexibility in food customization design in shapes, colors, and flavors for home users. Moreover, design options could result, such as individualized full-color pictures in solid food formats and customized chocolate sculpting [17].

4.4. Nutrition. For the first time, 3D printing technology was used to generate a fruit-based food composition with 5-10% of the needed resources, iron, potassium, or vitamin D, for kids aged 3 to 10. This technology allowed the creation of edible things in the required shape and size. The use of this visual technology, which was well liked by children and adolescents, in particular, increased the possibility of nutritional intake [85]. To improve health characteristics, minor elements that have been modified, such as vitamins, natural colorants, plant extracts, and substances based on fats or proteins, can be added to food printing. These will impart various colors, tactile characteristics, and nutritional information to the printed food items [86, 87].

5. Conclusions and Future Prospects

Food printing is a popular method for producing complicated shapes and customized foods. The primary goal of food printing is to achieve nutritional completeness or customisation. These responsibilities allow stringent product quality control and correct nutrition control. This technology has a significant influence on food production, since it may customize consumer needs based on their tastes. For 3D food printing, only a small number of food ingredients can be utilized directly for printing such as cocoa powder and powdered sugar. Most materials need to be properly pretreated in accordance with their states and characteristics so that the materials used for printing have the right rheology to be easily extruded from the nozzle and the suitable mechanical properties to maintain the shape fidelity of the printed product. The postprocessing involved in 3D printing food should not be undervalued in comparison to material pretreatment. It is frequently important to dry or freeze the printed product in order to retain the stability of the printed product's structure. To ensure maximal safety procedures and, ultimately, provide wholesome products, sterilisation of each constituent in the vicinity of food ink at preprinting processing and excellent overall processing procedures should be ensured, during printing and postprinting processes. The appealing appearance of the food of printed fermenting and malted food items may provide a novel consumer experience, increase healthier food choices and healthy nutrition, and improve food security. Intense research in the field of additive manufacturing is currently under way, and it is producing the new trends in 3D printing with the development of 4D, 5D, and 6D printing.

Data Availability

All data are available upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Irtiqa Shabir wrote the original draft. A. H. Dar contributed to the conceptualization, supervision, and editing. S. Manzoor wrote the original draft. V. K. Pandey wrote and edited the original draft. S. Srivastava wrote, reviewed, and edited the manuscript. R. Shams wrote and edited the original draft. K. K. Dash contributed to the conceptualization, supervision, and editing. I. Bashir wrote, reviewed, and edited the manuscript. Ufaq Fayaz wrote the original draft. V. Prithviraj wrote the original draft. Punit Singh wrote the original draft. Sarvesh Rustagi wrote the original draft. Seema Ramniwas wrote the original draft. R. Pandiselvam provided the resources, contributed to the conceptualization and supervision, and wrote and edited the original draft.

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