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Advances and prospective applications of 3D food printing for health improvement and personalized nutrition

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Abstract

Three-dimensional food printing (3DFP) uses additive manufacturing concepts to fabricate customized designed products with food ingredients in powder, liquid, dough, or paste presentations. In some cases, it uses additives, such as hydrocolloids, starch, enzymes, and antibrowning agents. Chocolate, cheese, sugar, and starch-based materials are among the most used ingredients for 3DFP, and there is a broad and growing interest in meat-, fruit-, vegetable-, insect-, and seaweed-based alternative raw materials. Here, we reviewed the most recent published information related to 3DFP for novel uses, including personalized nutrition and health-oriented applications, such as the use of 3D-printed food as a drug vehicle, and four-dimensional food printing (4DFP). We also reviewed the use of this technology in aesthetic food improvement, which is the most popular use of 3DFP recently. Finally, we provided a prospective and perspective view of this technology. We also reflected on its multidisciplinary character and identified aspects in which social and regulatory affairs must be addressed to fulfill the promises of 3DFP in human health improvement.

KEYWORDS

3D food printing, additive manufacturing, bioinks, health, nutrition

1 | INTRODUCTION

Additive manufacturing (AM), commonly referred to as three-dimensional printing (3DP) technology, was introduced in 1986 and is defined as a process of adding materials to fabricate objects from a computerized 3D model in a layer-by-layer fashion (C. Feng et al., 2019). AM is also known as rapid prototyping and rapid manufacturing (S. Li, 2016). It has the advantage of constructing volumetric complex models without using molds, dies, fixtures, or cutting tools (Pitayachaval et al., 2018). It also prevents material wastage.

In 2007, Cornell University researchers presented the first low-cost 3D printer compatible with food matrices, the Fab@Home Model 1, which is a syringe-based deposition-printing device. The Model 1 version was similar to traditional Solid Freeform Fabrication (SFF) devices, but it can use a wide array of materials for printing (J. Lipton et al., 2011). Two years later (2009), Fab@Home Project released Model 2 to reduce the cost and increase the access to this technology (Malone & Lipson, 2007; Manstan & McSweeney, 2020). Early 3DP concepts can be traced back to 1977, followed by the first patent for 3D food object fabrication in 2001. In recent years, several developments in 3DFP as microencapsulation and coaxial extrusion had stood out. A more detailed chronological information about 3DP development and 3D food printing (3DFP) is shown in Figure 1.

Food printing starts with raw materials and pretreatment of food ingredients. It is a crucial phase because the

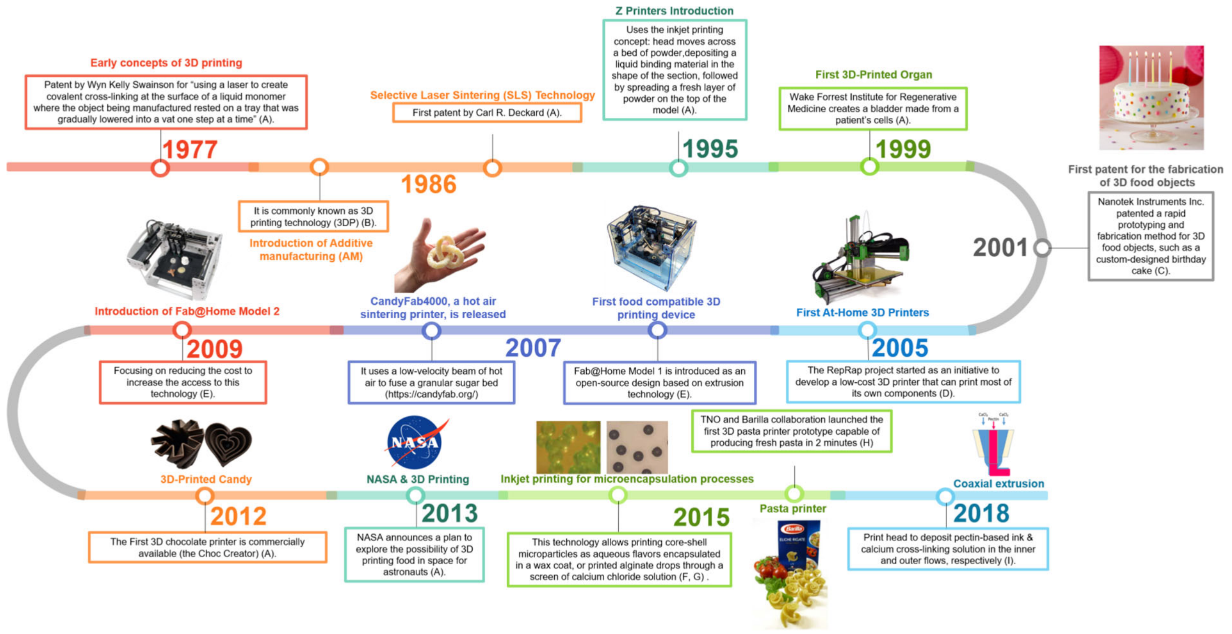

FIGURE 1 Chronological breakthroughs in the development of three-dimensional food printing (3DFP) technologies. (a) Museum of Arts and Design (n.d.); (b) C. Feng et al. (2019); (c) Sun, Zhou, Huang, et al. (2015); (d) IMRC (2012); (e) J. I. Lipton et al. (2009); (f) Godoi et al. (2019); (g) TNO (2015); (h) Di Leo (2016); (i) Vancauwenberghe et al. (2018)

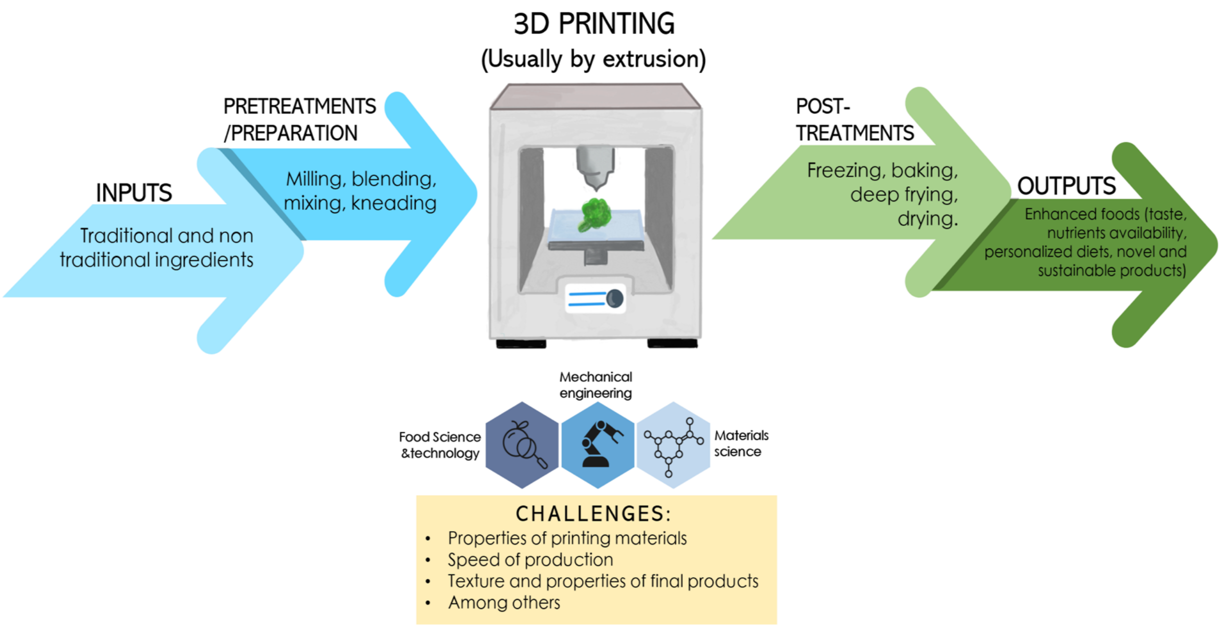

FIGURE 2 General stages of three-dimensional food printing (3DFP)

ingredients must be printable as a powder, liquid, dough, or paste, and they must be formulated with additives during the pretreatment (see Section 2) to improve the food ink rheology (Manstan & McSweeney, 2020). Some of the unit operations to give the printability of the food ingredients are milling (to produce flours), cooking (to prepare potatoes or starchy materials), and blending (meat-based products).

The second stage is 3DP itself (Figure 2). Several techniques are available, generally involving material extrusion from a printing head layer-by-layer on a bed. The head and bed distance and temperature can be adjusted to control the consistency, crosslinking, and cooking of the products, depending on the ingredients and desired results (Sun, Zhou, et al., 2015). In this step, the merge of different disciplines is needed, as discussed in Section 4. The third phase is the postprinting treatment to set the final structure and form of the product or to make it edible. Freezing, baking, or deep-frying are the common examples.

The interest in 3DFP has grown remarkably in the last decade due to the associated expectations of supply chain simplification, better use of existing food materials, food shelf-life extension, food design customization, and personalized nutrition (Holland et al., 2018). Personalized nutrition is one of the most exciting promises of 3DFP technology. It refers to a diet that can be applied to individuals or specific population groups, such as athletes, pregnant women, or older adults. An example of this application is the project "PERFORMANCE" (Development of Personalized Food using Rapid Manufacturing for the Nutrition of elderly consumers), which was founded by the European Union to develop and validate a holistic, personalized food supply chain for elderly persons with swallowing and/or masticating problems (C. Feng et al., 2019). Moreover, 3DFP technology can potentially solve some health problems associated with nutritional deficiencies, such as vitamin D deficiency (Azam et al., 2018).

Among the advantages and future opportunities of this technology are (a) personalized nutrition, as food can be specifically printed to meet the nutritional needs of an individual; (b) nutrient enrichment to solve health problems and malnutrition; (c) food waste reduction using underappreciated food ingredients and through expanding the use of existing ingredients (helps in fighting climate change); (d) customized food design by offering personalized and high-value products to consumers (exploiting the advantage of low-volume fabrication) and leaving in the own hands of consumer food design and production; (e) cost reduction in food preparation and transportation associated with low-volume manufacturing and straightforward supply chain; (f) innovation, as printing technologies are evolving to control food architecture from a macroscopic to microscopic level (some 3D bioprinters allow working on a microscopic scale by depositing living materials in a cell-by-cell matter); and (g) process digitalization, as consumers can preview their products during the process by allowing changes or modifications in a print-ready model (Dick et al., 2019; H. Jiang et al., 2019; Portanguen et al., 2019; Skartsaris & Piatti, 2019; Sun, Peng, Zhou, et al., 2015; Wan et al., 2015).

Despite its promising benefits, 3DFP still has significant challenges to overcome, such as (a) printing complex foods with multiple ingredients, pieces, or textures (e.g., burgers) that require sophisticated food processing and (b) the use of high-intrinsic variability of food ingredients, which exhibit a narrow range of physicochemical properties (e.g., viscosity or thermal conductivity) to be 3D printed (Skartsaris & Piatti, 2019).

This review describes basic 3DFP and 4DFP concepts, advantages, possibilities, and challenges. It presents recently published information about food printing, bioink formulations, and raw material treatments, emphasizing the use of this technology from space and military missions to human health improvements and aesthetic enhancements. Finally, we discussed the need for the integration of multiple disciplines to solve the challenges this technology faces nowadays.

2 | INKS IN 3DFP

Inks in 3DFP can be classified according to their easiness to print, main components associated with nutrition and health, such as protein, starch, fat, fiber, and functional compounds, such as vitamins and antioxidants, and based on the origins of the materials, such as dairy-, meat-, vegetable-, or fruit-based inks. The most popular printable edible inks are chocolate and mashed potatoes, which are rich in fat and starch but are good vehicles to integrate bioactive compounds and other functional ingredients to improve their printability. These vehicles can help increase fruit, vegetable, and protein consumption derived from nontraditional food or nonnatively extrudable materials, such as insect flours, algae derivatives, plant-based ingredients, and meat. The "natively extrudable materials" are those with rheological and mechanical properties that can be directly extruded without adding materials, such as gums (Voon et al., 2019). Additives applied to edible inks play a significant role in improving the flow behavior, sedimentation, and lubrication properties of the material to be printed. It can also improve the nutritional properties of food by adding vitamin C or cranberry powder to milk chocolate (Hao et al., 2019), plant sterol powder to dark chocolate (Mantihal et al., 2019), mealworm powder or probiotics in cookie dough (Azzollini et al., 2018; Zhang et al., 2018), and low-gluten flour to produce printed doughs (Yang, Zhang, Prakash, et al., 2018; Yang et al., 2019). Moreover, some additives optimize the process and postprocess of 3DFP and increase the nutritional value (protein content) of the final products by adding calcium caseinate and pea protein (Chuanxing et al., 2018; Zhang, 2018).

Fish collagen has been used as a thickener by Severini et al. (2018) to formulate fruit and vegetable (blends of carrots, pears, kiwi fruit, broccoli, and avocado) edible inks. Kouzani et al. (2017) also reported the use of canned tuna with beetroot and butternut pumpkin to produce printed tuna fish chunks (14 × 14 cm with 1 cm in thickness). The printing process did not modify the phenolic content, sensory, and antioxidant characteristics of the fruit and vegetable blends, maintaining their nutritional properties.

Regarding meat printing, J. Lipton et al. (2010) printed a multi-material structure of turkey meat and celery with the addition of transglutaminase (as an enzymatic binder agent), whereas Hertafeld et al. (2019) used shrimp or ground chicken pastes with other ingredients, such as egg whites. Post-printing, the products were either slowly cooked (using *sous-vide* methods) or deep-fried. The result was a successfully cooked 3D-printed material than can maintain its shape.

Moreover, 3DFP technology can potentially increase the acceptability of certain food ingredients that are highly nutritious, such as insects (rich in protein), seaweeds (rich in dietary fiber), fruits, and vegetables (rich in fiber and bioactive compounds), because of the change in the form and presentation, yielding a more attractive product for consumers. This advantage is related with one of the main uses of the 3DFP technology: aesthetics improvement, increasing the consumer acceptability. The use of insect fractions has a broad potential as printing materials; they can provide 3D-shaped food products supported by protein crosslinking. Additionally, its fractionation enables production of food ingredients with different functional and nutritional characteristics from the same raw material (Azzollini & Fogliano, 2017). Ingredients, such as seaweed and plant-based products, are alternative sources of protein and fiber. These underappreciated and novel food sources may ease the growing demand for sustainable food production, reducing the food crisis. Furthermore, using alternative ingredients significantly expands the existing portfolio of food printing materials (Sun, Peng, Yan, et al., 2015).

There are reports about the use of fruit-based mixes (banana, beans, mushrooms, or lemon juice) to produce printed snacks (Derossi et al., 2018). In addition, L. Feng et al. (2021) used carrot pulp, potato starch, xanthan gum, and water to print carrot-based gels in a cylindrical shape to evaluate rheological properties, while Lee et al. (2019) used spinach powder with xanthan gum to print spinach dispersion, increasing the possibility of using vegetable by-products to have more attractive vegetable presentations for kids and other population groups.

3 | NOVEL USES AND APPLICATIONS OF 3DFP

The global population will grow to an estimated 9.6 billion people by 2050, and some analysts project that food production will need to be raised by 50% to match this increased demand (Singh & Raghav, 2018). Food security is a term introduced by the Food and Agriculture Organization of the United Nations (FAO) that states that "food security exists when all people have physical and economic access to sufficient, safe, and nutritious food at all times to meet their dietary needs and food preferences for a healthy and active life" (FAO, 2016). Indeed, the assurance of food security is a global challenge of our time. Moreover, it is an imperative to favor and ensure a healthy society (Augustin et al., 2016), and 3DFP may significantly contribute to address these challenges. Several printing technologies have been developed, and the use of different edible materials has been explored to achieve well-accepted products. Nevertheless, some problems in the printing process still needs to be solved, and aspects related to ordinance and guidelines, food shelf life, ingredient restrictions and stability, and postprocessing should be addressed soon (Dankar et al., 2018).

Fortunately, many researchers are continuously working on solving the mentioned issues, and more studies about printing materials and their characteristics besides process optimization are being conducted. As a result, the number of publications related to 3DFP exhibited a positive exponential trend from 2015 to 2019. This research focuses on printing materials and formulation development, technologies and techniques, process optimization (including ink printability), and characterization studies (Chua, 2020).

In this regard, food industry research encompasses more than 60% of published papers, whereas related gastronomic documents constitute the rest. This research area includes molecular gastronomy, culinary transformations, and sensory perceptions associated with 3D-printed foods (Otcu et al., 2019). These reports should be used to develop or evolve food processing models assisted by 3DFP that consider design, production, and nutrient composition. Furthermore, by creating interactive user interfaces, 3D printers may enable a sustainable ecosystem to solve food supply and food quality challenges in the future. For instance, this 3D-printing-assisted network can be used to order new and detailed ingredients, prepare favorite food on demand, promote user's creativity, and even collaborate with nutritionists to develop healthier diets for all types of populations (Sun, Peng, Yan, et al., 2015).

The food-related fields of production, transformation, distribution, and consumption contribute massively to a nonsustainable feeding and environment. Technological advances in food production alone are unlikely to generate significant conversions required to build more sustainable food landscapes (A. R. Davies, 2014). Prospective studies mentioned that by 2050, one-third of the world would not be considered an urban area. Thus, humans should be looking forward to adapting those urban spaces to increase food production to avoid a more severe food crisis, expanding the need to reinforce the links among food, water, energy, and nutrition (F. T. Davies & Garrett, 2018). According to López-Galdeano (2015), the sustainability necessary for 3DFP and 4DFP technologies has five essential areas to be considered: (1) water waste, (2) food waste, (3) energy consumption (preferably renewable), (4) social acceptation, and (5) food hazards.

One of the multiple possibilities offered by 3DFP technology is its capacity to reduce food waste by reusing materials that would otherwise be discarded. It can also provide alternative ways to process and prepare more cost-efficient foods. Thus, 3D food fabrication devices could help people reduce food wastage while increasing the nutritional value of the food they eat. Furthermore, in the future, the widespread availability of 3D food printers would be helpful to improve environmental sustainability (Lupton & Turner, 2016). In this sense, shifting agricultural practices to accommodate 3DFP ingredients would be more sustainable and environmentally friendly (Tran, 2016).

The production of 3DFP must be considered as a zero-waste technique to reduce the environmental impact. Thus, the development of bioinks should focus on using low-carbon and low-water footprint food ingredients, leading to the introduction of a new market of novel and edible composites (Gholamipour-Shirazi et al., 2020). A more specific approach to be discussed is the cartridge materials. Bioinks will be sold as a packaged ingredient inserted into the printer to obtain 3DFP. The packaging material must be recyclable or biodegradable and innocuous to fit in with the sustainable technology and food safety concepts.

According to FAO (2019), food losses occur along the food supply chain from harvest, slaughter, or catch to the retail level. In contrast, food waste occurs only at the retail and consumer level. Therefore, losses and residues of cereals, meat, dairy, fruit, and vegetables should be harnessed to be processed and produce 3D-printed foods with added value. This is another main potential of 3DFP, reducing food wastage by re-utilizing food materials or ingredients and simplifying the food production chain. Besides, streamlining the supply chain would help produce equal distribution of foods by using this technology (Gholamipour-Shirazi et al., 2020).

The trimmings and off-cuts from meat markets are usually sold as low-value by-products. Such food losses could be considered an unconventional source of proteins of high nutritional value to customize meat by-products using 3DFP. For example, if only 7.2% of cattle carcass is deemed suitable for high-value steaks, the remaining cuts and viscera could produce a significant number of protein-rich products (Dick et al., 2019).

Improving the utilization of seafood by-products could be an opportunity to develop 3DFP. Surimi, for example, a high-protein raw material, could be made from fish and also from fish by-products and can be utilized to form different formulated seafood meals. Moreover, 3DP opens the possibility of developing new shapes and textures, increasing the convenience, likability, and food security of this type of food (Dong et al., 2019; Gudjónsdóttir et al., 2019).

Upprinting Food is a new company that develops 3D-printed foods exclusively from food waste in the Netherlands (Upprinting Food, 2020). This group decided to produce delicious-looking foods based on the premise that high amounts of bread, vegetables, and fruit are discarded because they are visually unattractive or too ripe. Blends and combinations of different ingredients from residual flood flows are converted into 3D-printed purees or unique products, especially desserts.

Finally, the actual impact of 3DFP on sustainability is still being studied. According to Bedia Octu et al. (2019), there is a lack of methodologies to evaluate all previous aspects and establish specific conclusions. Until now, the state-of-the-art sustainability of 3DFP has only been studied from a qualitative and decision-based view with an incomplete basis.

4 | NUTRITION, HUMAN HEALTH IMPROVEMENT, AND FOOD PERSONALIZATION

A practical application of 3DFP technology is food customization for an individual's health-nutritional needs, including medicinal and nourishment requirements. In the last decade, personalized medicine, nutrition control, and some therapeutic approaches have been changing. The evolution of technological developments associated with food engineering, food processing, and consumption patterns is evolving. Moreover, 3DFP is developing an enormous market potential with a customized approach of tailoring food to individual needs and for personalized nutrition. The organoleptic acceptability and neurotherapeutic possibilities offered by 3D products are related to their geometric complexity, extended shelf life, and mass customization. These are critical areas that provide the advantages of 3DFP over other techniques (Baishakhi et al., 2019).

For the entire creation of customized foods, it is necessary to use materials that are large enough to satisfy all consumer requests or small materials that can be combined at varying proportions. Consequently, food printing is a method that requires food distribution in a personalized way to satisfy nutritional needs (L. Liu, Yang, et al., 2020).

4.1 | Treatment of swallowing disorders

Dietary illnesses, such as digestive problems (from mouth to anus), allergies, and intolerances, lead to unnecessary hospitalizations due to the lack of adherence to dietary and pharmaceutical treatments (J. I. Lipton, 2017). The personalization of 3DFP could meet the nutritional recommendations related to restricted food regimens, probably reducing the complications and hospitalizations.

In addition, 3DP technology has also been applied to design foods for people with swallowing disorders (Gudjónsdóttir et al., 2019; Hemsley et al., 2019). It can help people with dysphagia and those who support them. It also represents a new area for collaboration between food engineering and health. The development of these products for populations with specific disorders such as dysphagia should contemplate the provision of safe and enjoyable meals. Individually tailored food to cover special nutritional needs must consider the consumers' age, health status, allergies or intolerances, comorbidities, among others (Hemsley et al., 2019). Perhaps, food consistency and texture are the most crucial issues to consider while developing 3D-printed foods for patients with dysphagia. Inappropriate food textures can cause choking and death in people with swallowing diseases due to an unsupervised consumption (Hemsley et al., 2015).

In the same context, the improvement of inks to produce 3D-printed foods to treat dysphagia disorders was studied by Pant et al. (2021). Garden pea, carrot, and bok choy were pureed and mixed with different gums to develop personalized 3D-printed foods that meet the International Dysphagia Diet Standardization Initiative categories. The main idea consisted of using dehydrated vegetables and carbohydrates to print aesthetic and palatable 3D-printed foods, preserving their nutritional components and flavors. These 3D-printed foods can be distributed or prepared in hospitals, nursing homes, and daycare centers that attend elderly populations and patients with related pathologies. Promising results were obtained; above all, textural properties and qualitative measurements are helpful tools to specify 3D-printed foods models because they involved evaluations of objective parameters and also from individuals with dysphagia.

Pereira et al. (2021) reviewed some critical aspects of food texture design during 3DP. Due to the complexity of the process and the nature of bioinks, it is challenging to achieve desired textures from the original design. However, researchers are working on these issues by incorporating new features, such as 4D printing, to increase their sensory properties to handle specific pathologies.

4.2 | Highly nutritious 3D-printed foods for toddlers and children

A beneficial and innovative application of 3D-printed food for domestic applications with dietetic purposes was described by Rubio and Hurtado (2019). The food habits of toddlers and children could be improved using 3D food printer devices to catch and increase their interest in consuming fruits, vegetables, and legumes. The creation of natural, balanced, and attractive snacks with desired textures and shapes adapted to their nutritional needs could be prepared directly by the kids with bio-functional inks produced with natural ingredients. This technology can create dinosaurs, pirates, superheroes, fairies, boats, and spaceships, among other shapes.

4.3 | The use of 3DFP with pre- and probiotics for the treatment of digestive disorders

Another attractive application of 3DFP is the improvement of digestibility and gastrointestinal health. The gastrointestinal microbiome contains about 10^{14} bacteria that are mainly located in the large intestine. This microbiome prevents the colonization of potentially pathogenic microorganisms (Bischoff, 2011; Mai & Glenn Morris Jr., 2004). Some efforts have been made to produce 3D-printed food with probiotics to improve the digestive problems related to gastrointestinal disorders. The feasibility of incorporating *Bifidobacterium animalis* subsp. Lactis BB-12 into 3D-printed smashed potatoes was studied by Z. Liu, Bhandari, et al. (2020). This probiotic strain is involved in gastrointestinal health and immune function. It was concluded that the fabrication of food structures enriched with beneficial microorganisms was feasible; their best treatment showed a bacteria viability of above 9.773 log CFU/g, which was higher than the recommended dose in probiotic foods (6 log CFU/g).

Technically, insoluble fibers cannot be used as raw materials for 3DP despite their benefits for human health because they do not usually show plasticity nor adequate structural properties (H. Jiang et al., 2019). Nevertheless, dietary fibers are incorporated as additives in different products with distinct rheological and textural features related to their ability to absorb water. These characteristics can be developed depending on the type of fiber used (nonstarch polysaccharides and other plant components). Consequently, nutritional performance will be different depending on the consumer. Patients suffering from gastrointestinal diseases, such as diarrhea, constipation, and irritable bowel syndrome (highly prevalent in the adult population), could potentially benefit from 3D-printed foods as a part of their treatment.

Some efforts have been made to improve gastrointestinal health by designing a core-shell multi-drug using 3DFP. Zhu et al. (2020) evaluated the effectiveness of drug release and its improvement effects on *Bifidobacterium* and inhibitory effects on *Escherichia coli* in vitro in a

3D-printed membrane. The modulation of drug release (proteoglycan) was successfully controlled via the membrane geometry of a composite containing stachyose as prebiotic and excipient materials (cellulose acetate and polyacrylic resin II). The proliferation ratio of *Bifidobacterium bifidum* increased by up to 294.2%, and its inhibitory effects on *E. coli* was up to 37%. This study should be explored further in humans to evaluate the real impact of specific pathologies on gastrointestinal health.

An interesting approach was done by Kewuyemi et al. (2021), introducing concepts such as fermentation and malting during 3DFP. Although there were no studies that relate to these topics, it would be interesting to evaluate the effects of fermented or malted inks on 3DFP printability and their potential influences on nutritional values.

4.4 | Nutraceutical and functional 3DFP

Recent approaches in 3D food design include functional and nutraceutical ingredients to obtain foods with health improvement potential. Such products may be used to promote public health benefits or to decrease the high incidence of non-communicable diseases (Portanguen et al., 2019; Zhao et al., 2020). In this regard, fruit juice (Azam et al., 2018; Yang, Zhang, Bhandari, et al., 2018), insect powder (Azzollini & Fogliano, 2017), vitamins (Azam et al., 2018), and plant-based powders (An et al., 2019; Southey, 2019) have been studied.

The moisture content of food ingredients is considered a critical factor that affects their printing performance. Furthermore, powdered food materials in manufacturing food ink formulation control the material properties and nutritional values (Lee et al., 2019). Thus, the design of meals containing specific ingredients, foods, or food groups for a particular treatment of an illness should be studied.

Some sugar substitutes, such as maltitol and xylitol, are commonly consumed by patients with diabetes mellitus. Therefore, chocolate-based 3D-printed foods with these synthetic sweeteners and a complex mix of functional polysaccharides were produced. The formula for polysaccharides includes an extract of *Ganoderma* fungus, goji, and liriope. All these ingredients possess some benefits, including immune regulation, tumor inhibition, antioxidant activity, and antiaging properties. In addition, 3D-printed samples of healthy sugar-free chocolate were obtained with acceptable texture characteristics, making this product a good alternative for these patients (P. Li et al., 2014; Zhao et al., 2020).

An assessment of the use of vegetables as a source of bioactive compounds to produce inks for 3D-printed foods was performed by Kim et al. (2018). A mix of broccoli, spinach, and carrot powders (in different percentages, 10 and 30%) with hydrocolloids was used to develop printable materials. The printability performance and rheological properties of the material were reported as "good." The obtention of vegetable powders by freeze-drying probably changes the functional properties of bioactive compounds. The main objective of this study was to produce suitable inks and to characterize their rheological and textural performance. However, the assessment and evaluation of its antioxidant capacity in vitro and in vivo are also necessary to design 3D functional meals. A group of researchers evaluated the antioxidant capacity and total phenolic content of printed smoothies produced from fruits and vegetables during storage. Carrots, pears, kiwi, broccoli rabe leaves, and avocado were blended; then, the solid phase was used to prepare smoothies using a 3D printer under different process parameters. The results showed that their antioxidant capacity did not change after 8 days of storage, but there was a significant reduction in the total phenolic content. It was concluded that (1) the analysis of the visual aspects of foods depicted poor results and (2) the sanitization procedures of 3D printers must be studied (Severini et al., 2018).

In a recent report, powdered flowers from the fungus *Cordyceps militaris* was mixed with vegetable oil and gums to produce an optimized printing ink with bioactive components (Teng et al., 2019). This fungus has several properties that enhance the function of the immune system and macrophages. It also contains a high amount of proteins, cordycepin, superoxide dismutase, and other beneficial ingredients. After performing all the experiments and analyzing the results using response surface methodology, the cordycepin content of the samples was not affected, maintaining its potential health benefits.

A novel approach to produce "vegetable" food printing materials is to incorporate plant cells into the ink formulation to obtain a printed food product that resembles plant tissues (Vancauwenberghe et al., 2019). In a recent study, lettuce leaf cells were embedded in a low-methoxylated pectin gel, and the composite was extruded under specific conditions (Vancauwenberghe et al., 2019). Then, bovine serum albumin was added to increase the air fraction in the printed gel matrix. The 3D-printed objects showed encapsulated plant cells with viability of 50%–60%. It is crucial to notice that assessing organoleptic characteristics, target consumers, and nutritional goals should be well-defined when developing these products.

Moreover, 3DFP can also be a useful and customizable tool to obtain edible objects from fruits and vegetables for those who do not eat or have difficulties consuming this food group. This includes the children, adolescents, and elderly who will greatly benefit from a frequent inclusion of vegetables in their diet (Ricci et al., 2019).

Finally, preserving these 3D functional foods should be carefully explored since their main ingredients are very susceptible to microbial spoilage. Such contamination compromises the food safety of the products and undoubtedly diminishes their nutritional and functional effects. Processing temperatures and light exposure may also negatively affect the concentration of phenolic compounds, polyunsaturated fatty acids, bioactive peptides, and other chemical components in 3D-printed foods. Therefore, further studies are needed to preserve these properties by evaluating technologies that could be useful (Tomaŝević et al., 2021).

4.5 | High-protein content using different sources in 3DFP

Lille et al. (2018) explored the application of food pastes made of protein, starch, and fiber-rich materials in extrusion-based 3DP for the customization of functional snacks. The ingredients used for the pastes preparation were modified food starch (from waxy maize), finely ground rye bran, oat and faba protein concentrates, skimmed and semi-skimmed milk powders, and cellulose nanofiber (from bleached birch Kraft pulp). The study demonstrated that the 3D-printed foods obtained from these materials could be further processed by oven-drying to produce low-energy healthy snacks.

Fiber-enriched and high-protein snacks produced by 3DP were evaluated by Anukiruthika et al. (2020). Freeze-dried mushroom powder, wheat flour, and water were mixed at different proportions to produce bioinks injected into an extrusion-based 3D printer. The postprocessing treatment consisted of microwave (MW) exposure of the samples at various power levels and durations to improve the snacks' palatability and shelf life. Finally, a sensory analysis was done on microwaved 3D-printed snacks flavored with sugar and spiced salt, and the last snack had a better acceptance for the panelists.

In the same research line, alternative and nontraditional ingredients for 3DFP to produce healthy snacks have increased. For example, a composite flour made of barnyard millet, green gram, fried gram, and ajwain seeds was processed by extrusion-based 3DP to obtain a high-fiber and high-protein food (Krishnaraj et al., 2019). The evaluation of three postprocessing methods, deep-frying, hot-air drying followed by deep-frying, and MW drying, indicates that structural changes occurred in the 3D-printed samples. Even if the snack obtained from the second postprocessing technique had the best performance in the sensory analysis for overall acceptability, the product's oil must be reduced to be considered healthy and be promoted for daily consumption.

Ingredients contained in dairy products have been often evaluated due to their potential applications in 3DFP. Milk proteins, milk fats, and lactose possess technological functions to produce printable dairy structures (Ross et al., 2019). Therefore, understanding the challenges and opportunities at different industrial levels is important when tailored 3D-printed foods are produced. In this regard, food printing designed to address specific diseases, such as lactose intolerance or cow milk protein allergies, could significantly increase the potential market of this technology.

With regards to the production of 3D-printed foods containing animal proteins, an investigation performed by Le Tohic et al. (2018) showed the use of commercially available processed cheese as a printing material. Cheese samples were processed by melting, extrusion, and solidification to be used as ink to produce tailored structures with potential applications in 3D manufacturing. The materials showed exceptional flexibility in geometries, textures, and flavors. However, the bioavailability of these proteins should be assessed to rationally offer personalized nutrition to customers.

Egg white protein (EWP) is an ingredient with high nutritional and functional values. These properties make EWP a promising material for the development of 3D-printed foods. A new formulation of EWP, gelatin, cornstarch, and sucrose was optimized to obtain complex 3D-printed objects (L. Liu, Yang, et al., 2020). Aside from characterizing this blend, developing formulations was proposed to produce complex-shaped food objects with high-protein content and high bioavailability.

Anukiruthika et al. (2020) reported that egg yolk blends have better printability properties than the EWP fraction combined with rice flour in a ratio of 1:2. These attributes were due to the complexity of the interaction between starch and protein fractions, causing higher binding properties. Then, egg yolk could be considered as a key ingredient for 3DFP with improved nutritional formulations. Nevertheless, studies on protein efficiency ratio (PER), relative PER (RPER), and net protein ratio may be helpful to tailor formulations in high-protein 3D-printed foods.

Azzollini and Fogliano (2017) reviewed the inclusion of nonconventional proteins as ingredients of 3D-printed foods to improve their nutritional properties and cover specific protein requirements. It was observed that the elaboration of yellow mealworm flours for use in 3DP possesses some advantages: (1) it was more appealing than the whole insect, (2) it can improve the food-carrier nutritional value, and (3) it can provide little or no technological functionality.

The Spanish startup NovaMeat created a mix of vegetable proteins extracted from rice, pea, and seaweed to obtain a 3D-printed steak with chicken or beef sensory characteristics. The idea was born as an alternative containing a high concentration of amino acids for vegetarian consumers (López et al., 2015; Vialva, 2018).

4.6 | Treatment and control of food allergies or intolerances with 3DFP

Customized 3D-printed foods may find an important niche in the treatment of food allergies and intolerances. Approximately 220–520 million people worldwide suffer from food allergy or intolerance (WAO, 2011). Lactose, casein, gluten, egg, peanut, sesame, fructose, soy, tree nuts, fish, and shellfish allergies or intolerances constituted the most common allergic reactions in most countries worldwide. Today, there is no cure for food allergies other than allergen avoidance and prompt treatment of allergic reactions; therefore, the development of practical solutions is necessary (Loh & Tang, 2018).

To help patients with celiac disease plan their diets, the company WASP conducted a project to develop a 3D printer to prepare gluten-free foods inside a traditional restaurant kitchen. The use of a 3D DeltaWASP 2040 printer allows the production of pastries using a recipe book. This device needs little space, controls specific calorie portions, and produces no waste during the preparation process (Moretti, 2017).

In the future, a 3D food printer could be used as a personal device; each person would own their capsules containing specific food materials free from cross-contamination. For this purpose, domestic, clinical, and hospitality scenarios should consider introducing 3D printers to support diet management and control meal preparations (Rubio & Hurtado, 2019). The convergence of several fields (food technology, mechatronics engineering, nutrition, etc.) is needed to make this scenario a reality. Personalizing nutrition using 3DFP is within the reach of developed societies, but it is still distant from developing countries.

4.7 | Food design and nutritional profile customization using 3DFP

Sun et al. (2018) published a specific analysis of formulation innovation and advanced nutrition profiles. An analysis was also done on extrusion-based food printing techniques and digitalized food designs and nutritional control. Briefly, 3D printers will be controlled digitally to produce tailor-made meals with preferred nutritional and sensory characteristics.

In a digital gastronomy vision, computers and other dispositives will allow users to control the structure, texture, flavor, odor, and aesthetics of each dish by providing a local control over the ingredients of the meal. Digital devices could also advise or suggest the best way to include food elements in meals to satisfy consumer preferences (Zoran, 2019).

In 2014, Chloé Rutzerveld developed a new concept related to the potential use of AM in food production. The development of high-tech, natural, healthy, and sustainable food was combined with a very original design. First, the use of a 3D printer allowed the elaboration of an edible breeding ground matrix (agar-agar) containing the spores (*Schizophyllum*) and seeds (cress) of living organisms. Then, an underlying support structure made from carbohydrates covered the entire matrix as a shell. This 3D-printed edible structure must be placed within the reach of sunlight for photosynthesis. From 3 to 5 days, plants and mushrooms were fully grown (Figure 3a). The consumer can eat this healthy snack directly from the culture dish (Rutzerveld, 2014). The main objectives of this study were to introduce and engage the consumers in the elaboration of their foods using 3DP technology, in the use of alternative ingredients with functional properties, and in food production with zero waste.

4.8 | Application of 3DFP as a drug vehicle

In pharmaceutics, 3DP has produced complex forms of different sizes and structures, dose variations and combinations, and release characteristics, which are not possible to fabricate using actual manufacturing procedures. In 2016, the Food and Drug Administration (FDA) approved for the first time the use of a 3D-printed drug for oral consumption for the treatment of epilepsy. The tablet offered an instantaneous disintegration of the active ingredient (1000 mg of levetiracetam) (Zidan, 2017). Today, there are six leading 3DP technologies that manufacture materials with pharmaceutical applications (Vithani et al., 2019). Tablets are the most common type of dosage form produced by 3DP, and soft materials with biological applications are the most used. More specifically, lipids and lipid-based drug delivery systems are broadly utilized as transporters to carry poorly water-soluble lipophilic drugs. Lipids are also more appropriate in biological terms to increase their physiological effects. A detailed evidence is also described in a study of Vithani et al. (2019).

The utilization of natural substances to produce 3D-printed pharmaceutical formulations is still under study. The trend of using biodegradable and biocompatible compounds, such as chitosan, alginate, pectin, gelatin, sodium hyaluronate, snake gourd, *Astragalus* roots, and chocolate, offers a significant advantage against the use of synthetic materials. These substances can be used in

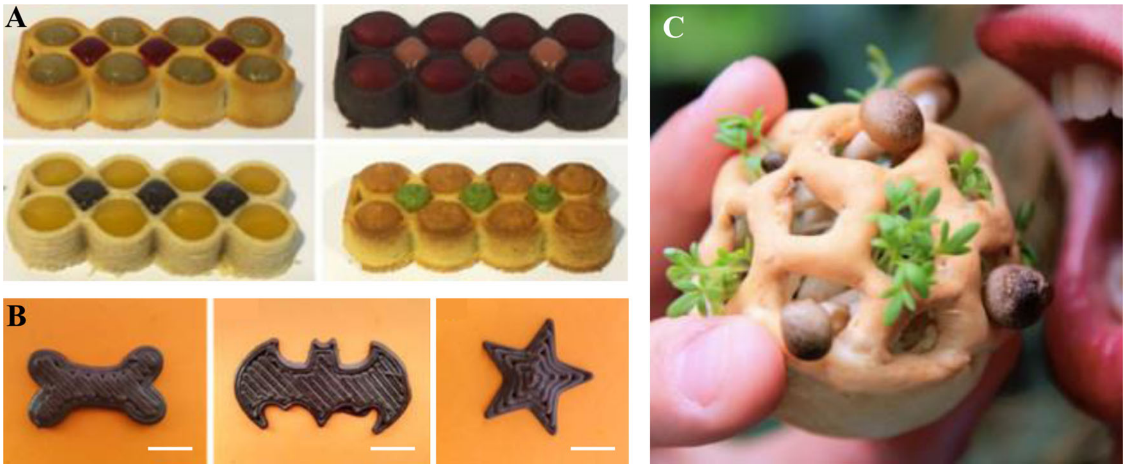

FIGURE 3 Examples of three-dimensional food printing (3DFP) pursuing different aims. (a) 3D-printed snack bars with different flavors and textures to evaluate the consumers' acceptance (Caulier et al., 2020). (b) 3D-printed chocolate: corn syrup mixtures were used as lipophilic and hydrophilic drug carriers for pediatric patients. Scale bar: 20 mm (Karavasili et al., 2020). (c) Improvements in food aesthetic, sustainability, and nutrient content of 3D-printed foods (Rutzerveld, 2014; https://www.chloerutzerveld.com/edible-grow)

different printer platforms (Aguilar-de-Leyva et al., 2020). Many studies are currently focusing on developing 3D-printed objects to be used as pharmaceutical carriers; however, incorporating drugs into 3D-printed foods is now causing a revolution, and only limited information is available in the scientific literature. Combining lipophilic (ibuprofen) and hydrophilic (paracetamol) drugs with chocolate for oral administration of pediatric patients was recently assessed to increase their treatment adherence (Karavasili et al., 2020). Bitter chocolate was used as a blank ink, and a mixture of melted bitter chocolate and corn syrup in a 1:1 ratio was used as a carrier to administer paracetamol and ibuprofen at a final concentration of 22.9 and 19.6 mg/g, respectively. A 3D-printed chewable chocolate-based dosage form showed an elevated release of both drugs in a simulated salivary fluid. Striking shapes were printed to increase the acceptance of the patients (Figure 3b). A texture profile analysis and an in vitro drug digestion were performed. The results showed that employing extrusion-based 3DP to produce drug carriers substantially enabled the flexibility in dose adjustments for specific populations and purposes. Therefore, their mouth-feel properties were also acceptable. These reports suggest that 3DFP is a cost effective and convenient method to be applied in pediatric patients in particular.

The addition of some substances to develop healthcare products by 3DP has also been studied. For example, vitamin C, lutein, and cranberry extract were successfully blended with chocolate to produce functional 3D-printed foods; however, some performance issues still need to be resolved. For example, some properties, such as the degree of fineness, viscosity, and flowing performance, brought some difficulties in forming chocolate geometries (Hao et al., 2019).

4.9 | The role of 3DFP in personalized nutrition of astronauts during space explorations and soldiers in military missions

Through its Advanced Food Technology program, the National Aeronautics and Space Administration (NASA) has started to explore the possibility of using 3DFP on space missions. Personalizing the diet of astronauts and its versatility could significantly improve their food variety and quality during space journeys (Hall, 2013; Steenhuis et al., 2018; Thangavelu et al., 2013). Using progressive 3DFP and inkjet technologies, the Systems and Materials Research Corporation is designing, building, and testing a complete nutritional system for long-duration missions beyond the low Earth orbit (Irvin, 2013); undoubtedly, this is one of the most outstanding future applications of 3DFP.

In this sense, the "3D-Printed Food System for Long-Duration Space Missions" project has potential NASA commercial and non-NASA commercial applications. The first one focused on developing a 3DP system (i.e., a 3D printer for space missions) that prepares flavored and textured foods. The designed device must include a long/short storage system for macro- and micronutrients, a mixing system to formulate pastes, and a system to dispense the final product with an increased shelf life. The device should also generate zero waste. The second approach focused on meeting the food demand of the future large population; the development of 3D food technologies could avoid food shortage, inflation, starvation, famine, and food wars. This device could also be helpful for military and aeronautic missions by reducing downtime in refilling supplies (Irvin, 2013).

The microbiological safety of space foods is a significant concern in the human Mars mission in 2030. Thus, food technologists specialized in 3DFP have a critical task in developing safer, nutritious, acceptable foods produced by a long-duration space flight system to ensure food safety (Kim & Rhee, 2020).

To develop nutritious and safe foods for Chinese astronauts, J. Jiang et al. (2020) evaluated the application of radiofrequency (RF) combined with a natural preservative to produce Chinese yam/chicken semi-liquid paste. RF heating was used as an alternative to traditional sterilization, increasing the product's sensory characteristics, nutritional value, and aseptic effects. The paste was produced by mixing chicken, yam, and Chinese chestnut, and an equal volume of chitosan/ε-polylysine solution as a thickener/conservative was added. As a result, shelf life was extended, and acceptable sensory properties were improved, making this type of paste suitable for 3DFP.

The startup BeeHex (https://www.beehex.com/) introduced a project to create a new 3D printer to produce various food options for astronauts during their travel to Mars. They are still developing a device capable of producing fresh and edible cheese pizza, creating foods faster and safer than a human chef (Gohd, 2017).

In 2019, an Insider magazine's report described how Russian astronauts used a 3D food printer to produce meat in space for the first time in history. Aleph Farms' food-tech startup extracted cow cells in its laboratory and placed them into a growing media that simulated the animal's body. This "broth" was poured in closed vials and sent into the Soyuz MS-15 spacecraft to the International Space Station. Then, the astronauts processed the content using a magnetic printer designed by 3D Bioprinting Solutions (https://bioprinting.ru/en/). Finally, the printer replicated the cells to produce muscle tissues, and the samples were returned to Earth to complete the 3DP in microgravity proof of concept (Bendix, 2019).

In an annual meeting of the American Association for the Advancement of Science in a recent online session, Professor Reinhold Ewald exposed some issues related to the astronauts' food habits and their relationship with 3DFP. He focused on their vitamin needs during their long voyage to Mars and the development of nutrient-enriched 3D-printed foods. In the same session, Professor Szcewczyk argued that vitamin C-rich foods, such as fruits and vegetables, are the most desired foods to be shipped for the astronauts. Vitamin A was also an essential compound for long-term colonization-type missions and for its fortification in 3DFP (Wylie & PA, 2021).

Regarding the impact and application of 3DFP technologies during military missions, Caulier et al. (2020) conducted a pilot study in a military setting in the Netherlands to evaluate the acceptance of 12 male soldiers on 3D-printed foods. For 4 weeks, the soldiers consumed and evaluated different samples of snack bars. During the first week, the soldiers consumed a conventionally manufactured baked snack bar. In the second, third, and fourth weeks, the soldiers ate snack bars produced with 3DFP in a lab-scale Fused Deposition Modeling printer where the customization choices increased every week (Figure 3c). At the beginning and end of the study, the attitudes of the consumers toward 3D-printed foods were evaluated. Although this study exhibited some limitations, such as the limited group of 12 male and nutrition-conscious soldiers, exciting findings were obtained. The authors concluded a disconnection between consumer knowledge and product development and that the simultaneous progress in these two avenues should significantly improve the acceptance of 3D-printed foods.

The US Army Natick Soldier Research, Development & Engineering Center is currently exploring 3DFP and its application for tailored military rations on battlefields. Research areas are focused on performance nutrition, joint foodservice equipment, and mission-tailored rations for soldier/squad performance optimization. The operational concept of the project includes (1) real time monitoring of nutritional needs using biosensors and (2) biometric data transmission to a 3DFP on or near the battlefield to provide ready-to-eat foods on demand. The project should be operating in 2025–2035 (Scerra, 2018).

5 | FOUR-DIMENSIONAL FOOD PRINTING

Incorporating a fourth dimension (the temporal dimension) to 3DP in health science focuses on imitating biological functions (bioinspiration and biomimicry). Four-dimensional objects are 3D structures fabricated with stimuli-responsive materials (e.g., heat or moisture) that trigger shape changes (Mandon et al., 2017). Moreover, 4D printing has also been proven helpful in various healthcare applications, including tissue engineering and biobot manufacturing (Choi et al., 2015).

The application of 4D printing has been rapidly involved in food developments. According to Teng et al. (2021), the main factors that determine the quality of four-dimensional food printing (4DFP) are printing, simulation, modeling, and slicing software. Thus, the principal applications of 4DFP are color changes, shape changes (by different hydration mechanisms), nutrition, and flavor changes. Due to the importance of 4DFP on nutrition, the remarkable aspects that should be considered are the biocompatibility of food matrix components (hydrogels), the ability to continue the transfer of nutrients and oxygen to cultured cells, and the particle size of foods used as inks. For example, when vegetables are used, the fibers should be dried and milled at nanometer levels. This increases the printability of 3DFP and affects the perfusion, bioavailability, and nutrient absorption levels in the intestine.

For example, color changes have been reported by Ghazal et al. (2021), who produced a 4D-printed potato-starch-based meal, where a color shift was developed over time due to the response of anthocyanins to different pH stimuli.

He, Zhang, and Guo (2020) also evaluated the spontaneous color changes in a 4D-printed puree made from mashed potato and purple sweet potato produced by a dual-extrusion printer. Its potential application was to provide new views about foods that spontaneously change their color using 3D-printed multi-material products and 4D printing. This innovative area of study is growing significantly; however, further studies are still needed to evaluate the bioactivities of some molecules in foods.

Ghazal et al. (2021) assessed the 4D changes on 3D-printed healthy foods responding to external and internal pH stimuli. Red cabbage, orange, lemon, apple juices, food-grade vanillin powder, and potato starch were mixed in different proportions to produce bioinks. A dual-extruder 3D printer was used to make 3DFP samples, which were exposed to the stimuli. To evaluate the external stimulation, the 3D samples were sprayed separately with solutions with different pH levels that varied from 2 to 12. Color changes were evaluated after 1.5 h. The results indicated that anthocyanins from the red cabbage contained changed chemical forms due to their reactions and structural transformations at different pH levels from colored flavylium cations to an anionic structure, such as chalcone.

To evaluate the internal stimulation, multilayered 3DFP samples were prepared with a layer inside (at different positions, up and down) of apple, orange, and lemon gel. Observations were done after 1, 2, and 3 h, and the results demonstrated that the diffusion of hydrogen ions occurred following the Fick's first law because of the differences in the juices' pH levels. Thus, the hydrogen ions diffused from high concentration to low concentration regions, causing the same color changes in anthocyanin molecules caused by different pH levels.

It will be interesting to study new methods to synthesize 4D-printed materials that could be incorporated in food science. This includes shape memory, self-heating, and metamaterials, including the responses of food components to stimuli, such as light, electric or magnetic fields, heat, pH, and humidity (Ryan et al., 2021). The formulation and production of intelligent foods could also be considered essential for functional properties and food safety purposes, since color changes could indicate the decomposition of food products (Le-Bail et al., 2020).

Recently, Phuhongsung et al. (2020) evaluated MW heating as an external stimulus for flavor development on 4DFP based on soy protein isolates (SPI). Those authors irradiated by microwaves (MW irradiation at different intensities was done on 3DFP samples made using materials, such as SPI, *k*-carrageenan, vanilla flavor, and an extrusion-based 3D printer. MWs are supposed to increase the temperature, affecting the sensory properties, such as smell, oral, and taste sensations, to produce higher intensity. Gas chromatography-mass spectrometry (GC-MS) analysis showed that four newly generated flavor compounds were developed after the 3DP and microwaving process. Rheological and low-field 1H nuclear magnetic resonance spectroscopy with low-field pulsed NMR analysis demonstrated that samples made with 3% (w/v) carrageenan showed the best combination to produce 4D-printed samples with high-protein concentrations. These types of products could be promptly directed to the nutrition and dietetic fields.

Changes in the shape of 4D-printed purple sweet potato starch induced by MW analysis were assessed by He, Zhang, and Devahastin (2020). Initially, 3DFP samples were obtained from bioinks produced with gelatinized purple sweet potato, sodium alginate, edible salt (NaCl), and fructose syrup at different concentrations. To induce spontaneous changes in the 3DFP samples, MW power was applied at 2, 5, and 8 W/g. The results showed that MW irradiation is an excellent alternative to induce morphological changes in 4DFP samples produced with simple materials.

In the same context, color changes by MW stimulation were studied in 4DFP composites from curcumin lotus roots (C. Chen et al., 2021). Natural materials, lotus roots, and curcumin were used to evaluate their printability features and antioxidant and nutritional characteristics. For 3DP, emulsions were prepared using different lotus root powder, water, and curcumin concentrations. Coacervates were stimulated at 280 W for 1–3 min, which was a considerably shorter time compared to a previous research (He, Zhang, & Devahastin, 2020; Phuhongsung, Zhang, & Bhandari, 2020). Changes in the composites, which turned from yellow to red, because of the alkalinity increased during the MW effect and chemical environment. It was interesting how MW affected the rheological and textural properties of the samples. The uniformity of MW irradiation (dielectric properties), changes in electromagnetic field, and control during MW drying could be future research perspectives.

A study fusing a dual change effect in color and aroma in 4DFP coacervates triggered by MW was conducted by Guo et al. (2021). First, microcapsules were produced using a mixture of corn oil as a core material, red pepper pigment, and cinnamaldehyde essential oil in a ratio of 8:1:1 (v:v:v). The wall material was a solution of gelatin and Arabic gum (1% w/w). Then, a bioink was prepared with buckwheat flour and freeze-dried yellow flesh peach powder. Different microcapsule concentrations were added, and it was processed into a SHINNOVE-D1 3D food printer. The results showed that only cinnamaldehyde increased by more than double, but the flesh peach aroma remained unchanged after the MW stimulus.

Moreover, in red pepper, the pigments lose their color during MW heating by isomerization and oxidation at shorter times (< 5 min). However, even when the microcapsules' morphology exhibited a fusiform structure, their functionality was acceptable. Thus, it was demonstrated that this technique could be applied as another alternative to produce 4D-printed foods.

The first report about spontaneously induced shape changes by dehydration was developed by Liu et al. (2021). An edible 3DFP gel made from flakes and potato starch was studied to evaluate the relationship between material properties, MW heating, traditional air dehydration mechanisms, and shape change behaviors. Significant differences in the bending degree of samples were found since this parameter was proportional to water evaporation and shrinking. Air dehydration showed the best performance to induce shape changes in the composites, increasing the bending accumulation effect and bending degree. These findings lead to more investigation related to the materials' dielectric properties, water diffusion, and MW stimulation to improve the performance of 4D-printed foods.

In summary, 4DFP technology has some unique and auspicious features over 3DFP until today: (1) during 4DFP performance, suspended structures that react earlier could be a stimulus to attract all kinds of consumers; (2) enhancement of flavor, odor, and color during eating or storage; (3) 4D-printed foods, such as snacks, could be dehydrated to increase their shelf life; and (4) this technology facilitates the distribution logistics because it is compatible with "flat packaging," making the products more sustainable in a certain way by reducing logistics issues and packaging material (Teng et al., 2021).

Regarding health monitoring devices, 4D printing technologies could be useful to develop dynamic monitors with different applications, including some biomedical uses. The control of drug delivery and the measurement of the nutritional needs of patients with specific illnesses in real time are future approaches that should be considered (Ryan et al., 2021; Seoane-Viaño et al., 2021).

6 | INTEGRATION OF MULTIPLE DISCIPLINES TO SOLVE THE CHALLENGES OF 3DFP AND 4DFP TECHNOLOGIES FOR HEALTH IMPROVEMENT AND PERSONALIZED NUTRITION

It is crucial to consider all the factors involved in accomplishing a virtuous circle of 3D- and 4D-printed food production and its consumption (Figure 4). Some of the main topics to be resolved are tailoring ingredients to develop specific formulations (recipes) for individuals with specific nutritional needs, associated comorbidities, development of molecular and digital gastronomy visions, legislation regarding nutrition labeling, and the study of nutrigenomics and nutrigenetics. In addition, the accessibility/availability of 3D printers for most of the population is also a relevant topic to be resolved in the years to come. In this sense, integrating different disciplines is necessary to achieve and embrace 3DFP technology.

Regarding the customization of ingredients in 3DFP, Severini and Derossi (2016) introduced the concept of "personalized food formula." This involved aspects that consider supplying specific nutrients to individuals based on their physiological state, and it could also include dietary components that can diminish some comorbidities. Thus, the assurance of adequate nutrients in a diet could reduce the risk of developing non-communicable diseases and health care costs. In this scenario, 3D-printed functional foods should be developed. For example, the design of inks with customized formulations that specifically affect target functions can improve the nutritional status of consumers. To achieve these desired effects, interactions between physicists, dietitians, and food technologists are expected.

Some approaches considering nutritional opportunities and challenges, such as the potential clinical uses of 3DFP, are texture-modified diets. Its nutritional applications are the addition of dietary components that improve health recovery (Burke-Shyne et al., 2021). For example, the design of 3DFP with functional properties includes specific types of slowly absorbed carbohydrates that could be used for glucose control in patients with diabetes. The addition of unsaturated fatty acids has potential benefits in the risk reduction of coronary illnesses. Likewise, the addition of protein isolates or concentrates with customized amino acid profiles are the potential applications of 3DFP to improve the nutritional status of hospitalized or ambulatory patients. Furthermore, exclusive biomolecules with

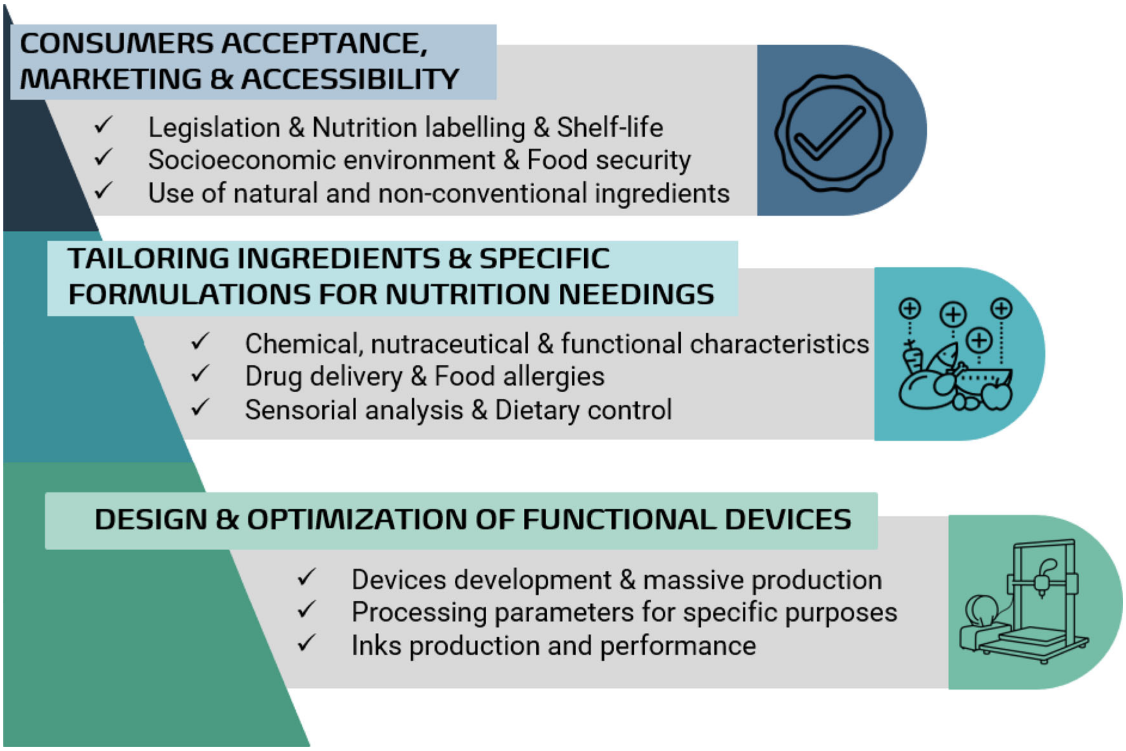

FIGURE 4 Involved factors in accomplishing a virtuous circle of three-dimensional (3D)- and four-dimensional (4D)-printed food production and consumption

antiproliferative, antioxidants, and antimutagenic properties (nutraceuticals) would be included in high concentration formulas to produce 3DFP for patients with cancer or other non-communicable diseases.

The evaluation and measurement of consumption responses, such as acceptance, perceptions, and adoption, of this new technology to produce 3D-printed foods are complicated. First, it will significantly depend on the region and their economic development since this technique requires innovative and expensive equipment and research centers that develop next-generation technologies. Second, novel foods and technologies are usually mistrusted and rejected, especially in emerging countries due to their attachment to traditional foods. On the contrary, developing countries tend to consume more ultra-processed foods; however, a new growing sector is looking forward to produce and consume organic foods, mainly in Europe and Asia. Thus, the diffusion of such innovative technology in all global nutrition and feeding fronts should not be expected to arrive without many economic and societal changes (Skartsaris & Piatti, 2019). These polarized scenarios make the study and analysis of the trends in this issue difficult. In this sense, a study done by Brunner et al. (2018) evaluated the attitude of 260 consumers toward 3D-printed foods in Switzerland. The results suggested that the participants showed minimal knowledge related to 3DP and 3D-printed food. In addition, negative perceptions and attitudes were initially found among the consumers. These findings could be linked to the fear of eating unknown food and some aversion to ultra-processed products. This study concluded that the acceptance and adoption of 3DFP would increase by convincing them that 3DFP are fun to use, convenient, have health benefits, and can enable personalized nutrition. Because of the rapid increase of 3D-printed foods in markets, food safety and nutrition labeling are critical topics that need to be revised and actualized continuously. The safety of 3D-printed food has been discussed by Tran (2019), including aspects of adulteration of 3D-printed food as a factor that may lead to an increment of food poisoning cases and the lack of specific regulation for its production inspection and commercialization. Until now, there are no detailed reports about the digestibility and bioavailability of those products. Further research is still needed to assure 3D-printed food safety and other biological and nutritional aspects in this scenario.

Some other aspects to be highlighted include the labeling issues since there is no legislation about it. To our knowledge, the FDA has not published information related to 3D-printed foods. According to Tran (2016), 3D-printed foods labeling legislation would have the same issue as genetically modified organisms' meals because of its potential long-term effects. It should consider safety issues related to changes in a human body, such as modifying eating habits to strictly consume 3D-printed foods and subsequent reject them physiologically to consume traditional food. Besides, 3D-printed products could be considered as imitation food. The author hypothesized four possible scenarios to be considered during the elaboration of laws. Thus, there are many legal issues to commercialize 3D-printed foods in the first world that need to be attended promptly. Therefore, this technology could be considered a feasible strategy to resolve the long-term low food availability in developing countries.

During the last 10 years, 3DFP technology has increased rapidly, and it will probably grow exponentially in the next 10 years (Prakash et al., 2019). Therefore, technological, scientific, economic, and social perspectives should be prepared to support the 3D-printed food production and consumption massively to ensure food security for the world population.

7 | CONCLUSIONS

To meet the needs for personalized nutrition for the general population, particularly for space and military missions, 3DFP technology holds high expectations to surmount nutrition- and food-related production problems. To reach the full potential of 3DFP and close the gap between technology development and adoption, it is necessary to focus on the opportunity areas of scientific, technological, economic, and social ambiances. The development of 3DFP calls for the integration of multiple disciplines, such as economy, law, labeling, food safety, marketing, consumer preferences, and food science, to develop printing materials and textural property studies, mechanical engineering, information technology, and software development. Through this, it will be possible to have a 3D printer at home, where foods will be printed according to our specific necessities and preferences, taking out most of the available ingredients and reducing food waste and environmental footprint. The use of this technology for space missions is one of the most promising scenarios of 3DFP. In this review, we made a complete overview of the most recent studies about the novel applications of 3DFP, including its use to reduce food waste, improve human nutrition as a pharmaceutical vehicle, and accompany space missions. Despite the multiple studies about 3DFP, integrating different disciplines seems the most critical area of opportunity for this technology.

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AUTHOR CONTRIBUTIONS

Anayansi Escalante-Aburto contributed to conceptualization, writing the original draft, reviewing, and editing the manuscript. Grissel Trujillo-de Santiago was involved in writing and reviewing. Mario M. Álvarez contributed to writing and reviewing. Cristina Chuck-Hernández contributed to conceptualization, writing the original draft, reviewing, and editing the article.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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