Journal of Food Safety and Food Quality 75, Heft 5 (2024), Seiten 121–152

Arch Lebensmittelhyg 75,
124–134 (2024)
DOI 10.53194/0003-925X-75-124

ISSN 0003-925X

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Current innovations in three-dimensional food printing (3DFP) technology and food science: a review

Aktuelle Innovationen in der dreidimensionalen Lebensmittel Drucktechnologie (3DFP) und Lebensmittelwissenschaft: ein Überblick

İrem Kılınç, Berna Kılınç

Summary

Technology is constantly improving, enabling the creation and implementation of a wide range of new applications. Furthermore, growing populations, decreasing food supplies, and shifting environmental parameters lead to the creation of methods for generating food items fit for human consumption. Among these cutting-edge technologies with several benefits is 3DFP. The creation of food products with specialized nutrition, the decrease in food waste, and the efficient and dependable manufacture of nutritious food are just a few of the numerous benefits offered by 3DFP. Nevertheless, there are several limitations to adopting 3DFP, such as process, material, and method implementation challenges. Despite this strategy, it is anticipated that the research done will provide solutions to any issues that may arise and that the demand for foods made using cutting-edge 3DFP technology will rise. Soon, 3DFP is expected to gain widespread acceptance because of its novel technological advantages and the uniformity of generated foods in terms of food safety and engineering.

Keywords: 3D Food Printing, new applications in the food industry, food supply challenges

Introduction

Experts believe that a shift in dietary preferences will cause a move from vegan meals to meat products, as the use of meat is increasing quickly. Concurrently, there have been notable progressions in three-dimensional food printing (3DFP) for manufacturing food items, including meat products. It is anticipated that this novel strategy will lessen the risks associated with ongoing climate change and the careless usage of livestock (Tibrewal et al., 2023). Some remedies, including the use of new alternative protein sources, the use of agricultural ecology, the reevaluation of food loss waste, and the application of catch shares in fisheries management systems, have been put forth in response to these issues. It also involves other actions like creating new food products, educating people about healthy eating, or changing current unhealthy eating habits to good ones (Garcia-Oliveira et al., 2022). In the realm of meat and fish production, new food technologies like 3DFP and cellular agriculture present a wealth of opportunities, including tissue diversity, food waste reduction, animal welfare, and customized nutrition. Consumer opposition to them persists, nevertheless. For example, conventional meat and fish haven‘t been compared with other dietary options simultaneously up until now (Lanz et al., 2024). Despite this approach, 3DFP technology is a versatile maturing production technique that holds significant promise for the scalable production of structured cultivated meat cuts. In addition to this, bioprinting can deposit the material in a precise and programmable way in a customizable and predefined way. Additionally, bio-printing for cultivated meat adopts methodologies and design philosophies from both the emerging fields of 3DFP and tissue engineering. Moreover, it is based on the potential brought by 3DFP for the adjustability of nutritional and organoleptic properties as well as it borrows and expands knowledge from the more advanced field of tissue engineering in the construction of meso- and microstructures of complex tissues (DeSantis et al., 2024). Five main themes were determined, which depict 3DFP technology as creative, futuristic, healthy, sustainable, and efficient. These themes contributed to the sociotechnical imagination based on several contemporary preoccupations related to food cultures: effective production and distribution; leisure and entertainment activities; innovation; time-saving and convenience; environmental impacts and global food security; nutrition aspects and human health (Lupton, 2017).

Three major categories that have a stronger influence on humanity are sustainability, animal welfare, and human health. Because of rising water pollution, biodiversity loss, greenhouse gas emissions, and disease, the use of animal-derived foods like fish and seafood has put the ecosystem at risk. These foods also contain harmful metals. Customers are now more conscious of the need to switch to sustainable seafood options as a result of this (Tripathi and Agarwal, 2023). On the one hand, various innovative technologies and protein sources have been associated with more sustainable food systems and improved nutritional quality and safety. On the other hand, many digital advanced technologies (e.g. Artificial intelligence, Big data, Internet of Things, Blockchain, and 3D printing) are increasingly being applied in smart farms and smart food factories to improve food system outcomes (Hassoun et al., 2022). In response to changing dietary preferences and growing health awareness among consumers, the food industry is increasing rate of moving towards ever healthier and higher-performance edible bio-inks (Song et al., 2024). Due to the interest in sustainable foods, a new approach known as 3DFP is being used to make fiber foods for meat and fish substitutes (Lee et al., 2023). For this reason, significant research has been conducted on meat analogs obtained from various plant-based protein sources, such as nuts, soy, peas, and wheat (Tan et al., 2021) as well as 3D food printing offers numerous possibilities for the development of personalized animal protein-based products. For example; 3D printed muscle fiber models and scaffold/filling of salmon fillets (Zhu et al., 2023), fancy shaped 3D printed egg and cheese products as a new food segment were developed (Bhat et al., 2021). This process stands as a developing technology for food production, offering the opportunity to design new food products with improved nutritional value and sensory profile (Dick et al., 2019). 3DFP is a developing technology in the field of food engineering (Dasgupta et al., 2024). There is not only a growing interest in the use of 3DFP to fabricate foods. But also, this innovative technology can be used to create foods with customized geometries, compositions, structures and nutrient content using an additive manufacturing approach for children, aging populations as well as sick patients (Sun et al., 2018; Phuhongsung et al., 2020). For those with specific requirements, including patients with dysphagia, who like food that has good fluidity but can preserve the visible shape, this technology offers a unique tool for creating special and functional food (Yu et al., 2023). The most recent studies on 3DFP applications are indicated as not only in the form of personalized food applications but also they have been produced for fruit and vegetable-based, cereal-based, chocolate-based, hydrocolloid-based, insect-based, etc. (Çakmak and Gümüş, 2020). Consequently, material regarding 3DFP technology whose significance has been growing quickly in recent years as well as studies on its application to food and marine food products are included in this review study.

What is 3DFP technology?

Traditional printing is restricted to the two-dimensional plane (e.g., printing ink on paper, line by line), whereas 3DFP technology pushes the theory into the structure itself. In summary, the 3DFP exhibits exceptional efficiency and design freedom as it is manufactured layer by layer without the need for a conventional mold. Although the method involves less labor and makes sophisticated building possible, it presents greater hurdles for computer-aided intelligent design and the characteristics of printed materials (Garcia de Soto et al., 2018). 3DFP is changing the way 3D objects are designed and manufactured by transforming digital models into solid models. 3D printing, known as revolutionary additive manufacturing (AM), is also having an impact on catalysis with its continuous progress. At present, 3D printing technology is widely combined with some related catalytic reactions and processes. Unlike the traditional production mode, the computer-aided digital and intelligent manufacturer conducts research on monolithic catalysts, reactors, mixers, and excipients in greater depth. 3D printing provides more variety and provides wider applications for catalysis (Zhu et al., 2022). Personalization, digitization, and customization are benefits of 3D printing technology. While there have been notable advancements in the study of printable materials and the enhancement of printing precision in food 3D printing technology, a thorough assessment of the role that effective physical spaces play in altering the

Journal of Food Safety and Food Quality 75, Heft 5 (2024), Seiten 121–152

printing properties of materials and enhancing the quality of printed goods has not yet been conducted (Shen et al., 2023).

The demand for 3D printing technology has increased significantly in recent years, coming from both domestic and international markets. Rapid advancements in both research and practice have resulted from this surge in interest. Numerous industries, including healthcare, pharmaceutical manufacture, the textile and fashion sector, water treatment, medicine, dentistry, surgery, artistic creativity, aerospace, architectural embellishment, and food, have effectively incorporated 3D printing. Because of its beauty, no molds are needed during manufacturing, which leads to high production efficiency, cost-effectiveness, and unmatched structural design freedom (Diao et al., 2024; Gomez et al., 2024; Sharma et al., 2024; Sultana et al., 2024; Yang et al., 2024; Pan et al., 2024). Based on all this information, Figure 1 explains the principle of producing food with the 3D printing method.

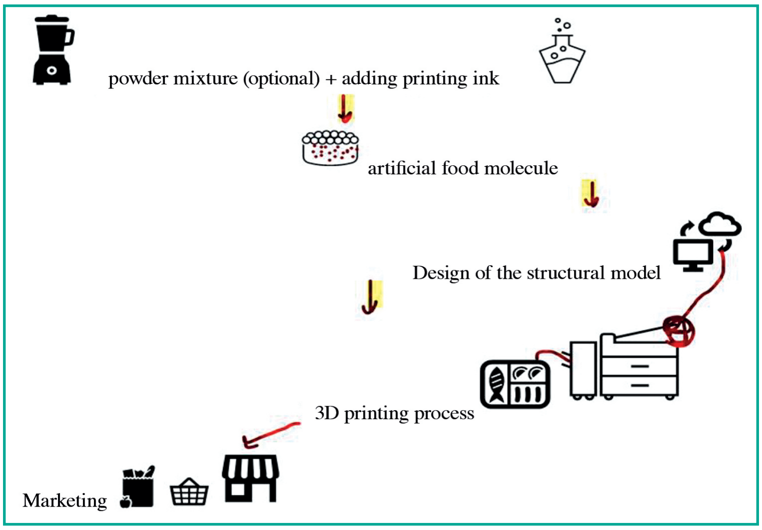

FIGURE 1: *The principle of producing food with the 3D printing method.*

The types of 3D printing machines

Current developments in 3D printing technology provide a wide range of printing methods, chemical substrates, and reaction processes for the creation of goods with several uses. The capacity of 3D printing to create a wide range of intricate shapes makes it particularly intriguing (Smith et al., 2018). Different 3D printing techniques can be used to print hydrogel-based inks, each of which has advantages and limitations. 3D printing of foods using hydrogel-based inks has the potential to develop customized food products (Sharma et al., 2024). Different 3DFP technologies have been found and indicated as follows: Binder jetting, Inkjet printing, Extrusion-based printing, Selective laser sintering (Topuz et al., 2018; Kozicki et al., 2024; Pan et al., 2024). Recent research indicates that the extrusion process, binder jetting, selective laser sintering, and inkjet printing are the most relevant techniques used in 3DFP. Figure 2 shows these techniques, which are explained in the sections that follow.

Table 1 shows reviews scientific sources that examine different types of food on different 3D printer samples tested for different purposes.

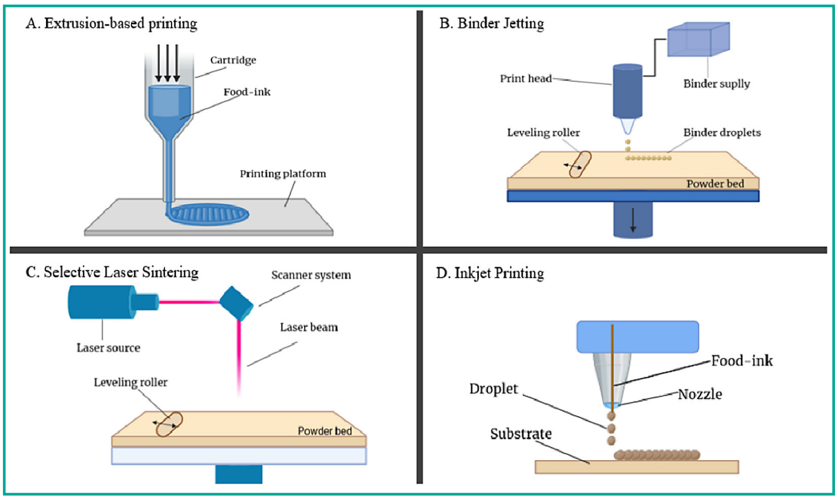

FIGURE 2: *Commonly used techniques for 3DFP Technologies by Varvara et al. (2020).*
A.: *Extrusion-based printing (EBP): The food type of the extrusion-based printer type was specified as soft foods such as meat puree, dough, chocolate, and cheese. The materials used were biofuels, hydrogels, and polymers (Topuz et al., 2018; Kozicki et al., 2024; Pan et al., 2024).*
B.: *Binder jetting (BJ): The food type of binder jetting was indicated as powdered materials such as flour, sugar, and starch. Sugar and starch mixtures are used as materials in this type of printer. (Topuz et al., 2018; Kozicki et al., 2024; Pan et al., 2024).*
C.: *Selective laser sintering (SLS): Powder materials are not sticky, and any agglomeration tendency has been used for Selective Laser Sintering. The type of food was categorized as powdered ingredients such as sugar, chocolate, and fat (Topuz et al., 2018; Kozicki et al., 2024; Pan et al., 2024).*
D.: *Inkjet printing (IJP): The materials used for inkjet printing were specified as solid/liquid phase (fruit juice, fruit concentrate, ink), which are low-viscosity materials such as pizza sauce and fruit puree (Topuz et al., 2018; Kozicki et al., 2024; Pan et al., 2024).*

3DFP materials and their usages on food products

The process of additive manufacturing, or 3DFP, is a well-known and innovative technique that has pushed the frontiers of materials science and has enormous potential for creating intricate geometries for the building, electronics, and medical industries. Nowadays, stimulus-responsive hydrogels (SRHs) and additive manufacturing (AM) technology works together to produce extremely precise dynamic and functional structures that can adapt their shape, mechanical properties, or functional attributes to various environmental stimuli, including light, pH, humidity, electric and magnetic fields, and heat (Arif et al., 2024). For the 3DFP process, the material must have enough fluidity to allow continuous and homogeneous extrusion, and the product must retain its shape after extrusion. Studies conducted on natural polymer hydrogels have shown their ease of use, as they usually exhibit non-Newtonian fluid behavior. At present, the availability of 3D edible gel printing materials is limited. The rheological properties of foods can be improved by optimizing food formulations to ensure easy extrusion of materials and minimal deformation after printing. The rheological and textural properties of 3DFP inks mainly depend on the components (Fan et al., 2024). Polysaccharide is a kind of natural macromolecular carbohydrate with complex and large molecular structure, which is obtained from multiple monosaccharides after dehydration and condensation. Food polysaccharide refers to the polysaccharide that is allowed as a food additive in the food processing process to control the sensory quality, and physical properties and improve the nutritional value of food (Liu et al., 2019). The rheological and mechanical behavior of soy protein-polysaccharide composite paste for extrusion-based 3D food printing were investigated by Wang et al., (2024a). The effects of the type and concentration of polysaccharides were evaluated (Wang et al., 2024a). The outstanding network assembly of natural polysaccharides/protein-based hydrogels offers suitable biological properties and adjustable physical properties, making them ideal candidates for food and biomedical applications. Rheological analysis can provide quantitative informational information about the combined network, which is critical for determining the hydrogel properties and their suitability for food or biomedical use (Fan et al., 2022). In addition, alginates are widely used as 3DP materials due to their good gelling properties due to many carboxyl and hydroxyl groups (Chen et al., 2019). Proteins and polysaccharides are two basic nutrients in the human food system that can change their structural and functional properties, such as emulsions through electrostatic forces and hydrogen bonds or the ability to form gels (Zhang et al., 2022a). Recombined food gels for 3D printing are complex systems that by their very nature consist of multiple components. The combination of basic food ingredients can improve the nutritional, rheological, and sensory properties of the printed gel through the interactions between the ingredients to achieve better ink printing properties and product quality. However, there is no systematic review evaluating the effect of the component interaction in recombined food gels on 3DP (Feng et al., 2024). Food-grade oleo gels can be used as edible inks in 3DFP applications. However, there is currently a lack of simple and robust methods for manufacturing oleo gel-based edible inks with adjustable printing properties (Miao et al., 2024). Among the most common materials are polysaccharides such as chitosan, methylcellulose, alginate, etc. To make bioink, different polysaccharides and proteins are used to make food inks. In addition, 3DP has found applications in the development of devices that can monitor food quality, help with food verification, and assess package integrity (Pan et al., 2024). Hydrocolloids are frequently used as a thickener to create tissue-modified diets for people with dysphagia (Yu et al., 2023). 3D printing of foods is an emerging technology that can be used to produce foods with an advanced nutritional, texture, functional properties as well as pre-designed shape (Huang et al., 2023). This additive technology is increasingly being used to produce plant-based meat analogs. However, there are several difficulties in producing meat analogs using this technology: (1) the protein content in the final printed product is too low to match the nutritional profile of real meat; (2) it is often difficult to accurately imitate the textural and structural properties of real meat using existing plant protein edible inks (Qiu et al., 2023). Sustainability and environmental concerns regarding animal protein production require urgency in dietary changes toward plant-based meat and seafood analogs (Tay et al., 2023). AM, especially 3D printing based on extrusion, offers unique opportunities to improve food‘s nutritional properties, structure, and texture (Bian et al., 2024). The flow characteristics of the original materials directly affect the shape customization of 3D printing. To improve the molding quality, 3D printing equipment has been developed, which is characterized by a variable pressure and temperature extrusion unit, an extrusion cooling unit, a numerical control transmission unit, and also a control box (Liu et al., 2023a). In addition to this, the finite element method (FEM) simulation has shown that the nozzle diameter affected the fluid properties (shear velocity, pressure, and velocity) in the flow area, as well as the residual stress and also deformation of the printed sample of the surimi pastes (Oyinloye and Yoon, 2022). To make

TABLE 1: *Advanced 3D Printing Methods for Producing Food and Their Using Advantages.*

3D Printing method	printer	food products	findings of the study	reference
Extrusion	OODINI	Fresh and frozen vegetables	Sorting different veggies based on their starch and water content in order to make them 3D printable and creating aesthetically appealing diets for patients with dysphagia.	Pant et al., 2021
Extrusion	ByFlow 3D printer	Tomato paste	Possible relationships between basic rheological characteristics and printability of formulations. As a model system, tomato paste was used.	Zhu et al., 2019
Extrusion	3D printer CARK	Rice starch	Effect of motor speed, print size, and nozzle size on rice starch printability, taking uniformity and extrusion ease into account. Additional factors that were examined included thread quality, binding property, finishing, texture, layer definition, shape, dimensional stability, and appearance.	Theagarajan et al., 2020
Extrusion – cold	Pneumatic Direct Ink writing (DIW) printer	Powdered milk	The printability of edible inks, such as milk ink, at room temperature without the addition of any ingredients.	Lee, 2020
Extrusion – hot	SHINNOVE-S2 printer	Potato starch	Examining the ways that differences in concentrations and printing temperatures affect the structure and rheological characteristics of potato-starch paste during hot-extrusion 3D printing	Liu et al., 2020
Selective laser sintering	–	Mixture of 50 % native wheat starch + 40 % maltodextrin + 10 % palm oil powder	Compression testing was used to determine the mechanical properties of 3D-printed samples. A constitutive model that explains the material's brittle failure and massive deformation behavior captures the observed events.	Jonkers et al., 2020
Extrusion	A FoodBot 3D-printer	Cookies	Examining the effects of various printing and product characteristics (hardness, microstructure, and structure) on the rheological characteristics of 3D-printed cookie dough	Varghese et al., 2020

better use of sturgeon meat (a by-product of caviar), surimi was investigated in this study as a potential 3D printing food ink for gel products. Colloid milling was investigated as a pre-printing process to improve the printability of SG paste, and then 3D printing was performed to produce surimi gel products with appropriate elasticity and stiffness (Wang et al., 2023e).

Pulse-based protein components have many applications in meat analogs, baked goods, pasta, beverages, and dairy alternatives. Beyond these applications, there is a need to explore new applications of pulse proteins in flavor enhancement and extruded snack products, infant and children‘s formulas, beverages, and breakfast cereals, to develop new applications such as personalized and sensitive bioactive peptides and nutrition as well as to use innovative technologies such as Artificial intelligence for pulse protein research, extrusion, and 3DP (Rajpurohit and Li, 2023). Direct ink writing (DIW) is a flexible technique that covers a number of substances in the form of ink, such as composites, ceramics, synthetic polymers (acrylonitrile butadiene styrene, polyvinylalcohol, polyurethane), natural polymers (chitin, carrageenan, silk, cellulose) (Antanitta et al., 2024). 3D-printed bio-based polymers, composites, and bionanomaterials have been used in many sectors such as water treatment. These 3D-printed biomaterials were used to purify water through size exclusion, absorption, or catalytic degradation (Fijol et al., 2022). Biopolymers and their derivatives are materials for which there is a growing interest in the industry and, in particular, in the development of sustainable engineering. Among such materials, carbohydrate polymer, such as highly deacetylated chitin (chitosan), is commonly used for a wide range of applications, including materials and biomedical developments. The prepared carbohydrate polymer is used for forming a hydrogel. The prepared gel was characterized to demonstrate the compatibility of the extracted chitosan with biomaterial application and was used for 3D printing (Godeau et al., 2022).

Smart biomaterials have numerous applications ranging from health (e.g. biosensors, tissue engineering, and drug delivery) to more recently researched environmental applications involving ecosystem restoration (e.g. coral reefs and environmental remediation). The use of 3DP technology opens up the vision for automated bio-production more precisely and clearly. With this wide range of applications, smart and intelligent biomaterials are used separately or in combination with 3D printing to enable the design of environmentally friendly and sustainable solutions that can be used to overcome challenges for both modern medicine and the environment (Leon et al., 2023; Berman et al., 2023). 3DP of food materials is a form of additive manufacturing, also known as computer-aided layer production, that has emerged in the last decade. It uses computer-aided design to create structured products from food "ink" ingredients and has the potential to create complex geometric shapes and patterns while enabling mass production of food products (Watkins et al., 2022). The nutritional composition of a dinner can not only be improved with the use of 3DFP but it can also be used as a therapy for individuals with nutrition-related problems, such as malnutrition. Among them, the inadequacy of the relevant study and the nutritional requirements of consumers emphasize the importance of improving the nutritional properties of 3D-printed foods. Natural food gels, which are completely new or consist of existing ones, have the potential to be created in the future, which will allow more nuanced diet customization for customers (Sharma et al., 2024). Therefore, 3D food printing is an emerging technology developed to facilitate the lives of consumers and food businesses. This technology allows all kinds of new foods to be obtained according to personal wishes. It is possible to develop a nutrient with the exact nutritional value necessary for the body, with the most beneficial nutrients humans want or without any ingredients that they are allergic to, and even to predict or personalize the taste, color, shape, and size of a food (Donn et al., 2022).

The 3D printability of surimi has been affected by water and rheological properties (Liu et al., 2022b). In one report, surimi was investigated as a promising 3D printed component, but its rheological properties were reported need to be identified in order to improve printing accuracy and gelling properties (Cao et al., 2022). However, the addition of food additives was indicated to improve the 3DFP properties of food hydrogel (Sharma et al., 2024). It was also stated in another report that 3DP technology could create a surimi dish. Therefore, microbial transglutaminase improved the extrudability of surimi, and the inclusion of microbial transglutaminase affected the 3D printability of surimi (Dong et al., 2020). The preparation and characterization of surimi-based imitation crab meat using coaxial extrusion 3DFP were also studied (Kim et al., 2021).

3D printing with fused deposition modeling (FDM) is an advanced additive manufacturing technology for making thermoplastic-based structures. Recently, many studies have investigated the 3D printing of polylactic acid (PLA) with biomass sources such as hemicellulose, cellulose, lignin, and whole biomass. Such biodegradable composites are better for the environment and can be used to replace non-biodegradable composites in various applications (Bhagia et al.,2021). Non-toxic poly (butylene adipate-cauterephthalate) -Chitin-based nanocomposite products were scaled by injection molding and 3D printing (Sadhasivam, et al., 2020).

Bioactive compounds can be extracted by conventional methods with solvents such as water, ethanol, methanol, chloroform, acetone, and others, but with some limits such as environmental contamination, human toxicity, and low extraction rate. For these reasons, it will be interesting to use emerging extraction technologies to recover bioactive compounds and use them in a 3D food printer to make functional foods that can provide a targeted health benefit to consumers (Donn et al., 2022). Functional foods, defined by their ability to provide health benefits beyond basic nutrition, have gained importance globally. Seafood, which is considered a functional food due to its nutritional richness, faces challenges related to ecological, ethical, and health concerns (Mahmud et al., 2024). 3D printing of animal-derived foods has also been investigated, as they are more suitable for protein-rich diets. Xanthan gum and guar gum can be used to improve the viscoelasticity and stability of cooked meat pastes, making them suitable for extrusion-based 3D printing. For this reason, the rheological properties and textures of garden peas and carrots can be replaced with xanthan gum, kappa carrageenan, and locust bean gum for 3D printing. Konjac gum/xanthan gum developed the textural quality of the fish paste, especially through hydrogen bonding (Yu et al., 2022; Yu et al., 2023) 3D printing has recently been investigated for the potential to create meat analogs using various plant proteins (Ko et al., 2021; Chen et al., 2021). Development and characterization of emulsion gels prepared with gliadin-based colloidal particles and gellan gum with adjustable rheological properties were performed for 3D 3D-printed dysphagia diet (Hou et al., 2023). In addition to this, the role of dietary fiber and flaxseed oil in changing the physicochemical properties and the 3D printability of cod protein composite gel (CPCG) were also studied. Therefore, the CPCG can be used to produce customized foods for the elderly and other need-based consumers (Xie et al., 2022).

Commercially, some Japanese companies could refresh pixelated sushi printing for the 3D printer. Its sushi consists of a renewable gel of a certain color and a data vessel. However, to date, the research on 3D printing of SPI-polysaccharide composite pastes has been limited. At the same time, caragenan and sodium alginate can be extracted from plants, and the authors are thinking of maintaining a plant-based property in the material properties that can be used as raw materials to support the future production of plant meat (Warner et al., 2019). The popularity of plant-based meat analogues produced with 3DFP technology has increased today (Dick et al., 2020). In one study, soy protein isolate (SPI), rice starch (RS) and xanthan gum (XG) were used food ink for 3D printing of fish analogues. Therefore, it has been shown that high-precision 3D printing on a micro scale can produce plant-based fish meat-like structures, providing a systematic approach to 3D-printed food analogues with appropriate mouthfeel (Shi et al., 2023). In another study aimed to develop plant protein-based salmon mimics through three-dimensional (3D) printing of plant protein-based food inks combined with the post-printing transglutaminase (TGase) process. HP (high-pressure) ink plus 3D printing with post-printing texturing makes a critical contribution to the development of a plant-based mimic with macronutrient content, physicochemical properties, and texture comparable to a real salmon fillet (Tay et al., 2023). These edible inks prepared with mixed protein were indicated to be useful for 3D printing of plant-based foods (Qiu et al., 2023). Currently, brown algae *Undaria pinnatifida* (UP) has been consumed by people in one way, and it is serious to process homogeneity. However, UP has not gained any traction in the 3D printing industry to date. The group containing guar gum and soy protein isolate was reported to have the best 3D printing results (Sun et al., 2024). Another study also showed that edible inks can be formulated from plant-derived ingredients, which could enhance their application in the development of plant-based foods with improved properties using additive manufacturing processes (Wang et al., 2023a). Carrageenan, obtained from red algae, is widely used in various food applications (Uda et al., 2023). The effect of κ-carragena on the quality improvement of the 3D printed *Hypophthalmitis molitrix*-sea cucumber (HM-SC) compound surimi product was investigated. 3D printing technology was used to make HM-SC compound surimi products. κ-Carrageenan improved the quality of the HM-SC compound surimi gel (Yu et al., 2022). Rapeseed oil as an extraction solvent motivated the preparation of high internal phase emulsion loaded with fucoxanthin for food 3D printing (Wang et al., 2023c).

With the increasing rate of seafood consumption globally, this industry is also creating a large amount of waste production, which is rising and often contains high-value substances. The by-product/waste production from harvest to the end of consumption represents about 50–70% of the total weight (Tümerkan, 2021). A strategy for the effective use of food waste is a major challenge today. Therefore, 3DFP is considered a promising strategy for developing healthy foods. On the other hand, many food enterprises release high amounts of waste from their processing activities. These wastes contain many bioactive components such as polyphenols, carotenoids, vitamins, minerals, fibers, and unsaturated fatty acids, which, among others, have physiological and health benefits. Similarly, several bioactive compounds have been identified in also algae (Donn et al., 2022). In one study, 3D printing technology was used to develop a suitable material based on salmon industry by-products. The most suitable biomaterial for 3D printing based on extrusion was reported to be 8% salmon skin gelatin gel (SGG) because the printed objects fit the designed 3D models and maintained their dimensional stability over time. This study provided insight into the appropriateness of using salmon gelatin for 3D food printing usages (Carvajal-Mena et al., 2022). In addition to this, a mixture of fish gelatin and gellan gum was made as edible ink for 3D printing. Gelatin obtained from fish skin and bones was obtained using sustainable methods, as well as the printed products have preserved their intended structure well. The method shown here allowed for the precise fabrication of target food structures through 3D printing (Bian et al., 2024).

A food-grade 3D printing ink not only can be provided a new method for preserving flavor substances under freezing conditions, but also it can be expanded the application range of flavor high internal phase emulsions (HIPEs) in the food industry (Hu et al., 2023). Recently, there has been a significant increase in interest surrounding the development of High internal phase aggregation emulsions (HIPEs) in the field of structural oils. The development and characterization of HIPE, which are spontaneously emulsified using endogenous phospholipids obtained from Antarctic krill oil, were evaluated. The HIPEs exhibited potential as structured fat for application in 3D printing food (Fu et al., 2023). In one research, HIPEs stabilized by oil-edible colloid particles in water have received great attention for three-dimensional (3D) printing and the delivery of a hydrophobic bioactive. The results of this study proved to be a new way to produce HIPEs with better performance and opened up new possibilities for the production of future foods and the delivery of hydrophobic bioactive molecules (Song et al., 2023). In another research, sea bass protein microgel particles were prepared to stabilize the HIPEs. They improved the stability and biological accessibility of astaxanthin. Astaxanthin-loaded HIPEs can be used as food-grade 3D printing materials (Zhang et al., 2022). The HIPEs developed were applied for 3D printing, and the objects printed in this way were able to maintain the designed shape and structure sufficiently. The 3D printable HIPEs developed have excellent potential applications not only in the food industries, but also in the medical, and cosmetic industries (Bi et al., 2022). HIPE of ω-3 fatty acids stabilized with fish scales gelatin particles: Lipid-enhanced surimi was applied to 3D printing. The inclusion of HIPEs in surimi products has not only led to an increase in the number of healthy lipids, which are useful for meeting the nutritional needs of consumers but also gave rise to addressing technical problems and difficulties in producing high-end surimi products (Wang et al., 2024b). Experimental printing further confirmed its suitability by confirming extrudability, printing performance, and self-supporting properties. In particular, low-fat surimi products based on medium internal phase emulsion gel showed better suitability for 3D printing in real food systems compared to traditional surimi products. This work was reported to significantly expand the development potential of edible bio-inks by introducing innovative approaches to produce medium internal phase emulsion gel with superior 3D printing properties (Song et al., 2024). The accuracy of 3D printing was indicated to be influenced by the extrusion property of food ink, which has been

Journal of Food Safety and Food Quality 75, Heft 5 (2024), Seiten 121–152

controlled by the ionic bond content. The stability of the 3D printing was influenced by food ink's self-supporting capacity, which has been controlled by hydrogen bonding and hydrophobic interaction ingredients. The results provided theoretical guidance for developing 3D printing of surimi components (Liu et al., 2022b). Other results of the study showed that rice starch/casein with a higher degree of gelatinization can be used to prepare high internal phase emulsions with good 3D printing properties. Moreover, the developed processing can be applied to the 3D printing of foods with personalized shapes (Liu et al., 2023b). Additionally, protein-enriched inks exhibited pseudoplastic behavior with viscoelastic properties. These pastes' apparent viscosity and storage modulus decreased with the increased proportion of rice protein, which improved 3D printing performances such as hardness, support strength, and plasticization (Qiu et al., 2023). The addition of carrageenan was reported to be improved the melting temperature and 3D printing performance of the gelatin system (Wang et al., 2023b). Pickering emulsions (HIPPEs) stabilized with sea bass protein-epigallocatechin-3-gallate (SBP-EGCG) complex were administered to increase the stability and biological accessibility of astaxanthin and delay algal oil lipid oxidation. HIPPEs could become a food-grade 3D printing material that acts as a delivery system for functional foods (Zhang et al., 2023). 3D printed fish analogs were gradually produced in place of real fish meat to increase environmental concerns related to personalized diet and food security, as well as marine biodiversity and seafood supply. However, preparing shaped fish oil imitations based on the precise structural and nutritional regulations of food 3D printing technology is still challenging (Li et al., 2023).

Practical food 2D/3D printing (such as bread and surimi) has shown high potential in food creation and food innovation (Wang et al., 2023d). These results suggest that in the future, there should be a focus on communicating the health and environmental-related benefits of 3DFP and cellular agriculture to facilitate their adoption (Lanz et al., 2024). Food printing, which includes 2D, 3D, 4D, and 5D printing methods, has attracted great attention due to rising living standards and higher consumer demand for innovative food. Printable biopolymers with a special structure hierarchy are particularly attractive for formulating edible inks for food printing, as they serve as basic structural components for forming an ink matrix and providing a supporting presence for the printed functions. Edible ink printing (such as 6D printing) and key challenges (multidisciplinary integrated rheology) are proposed and addressed for creative food production (Chen et al., 2021; Cheng et al., 2022; Liu et al., 2023a). Three-dimensional (3D) food printing is the technology of the future that can present creative, unique, and complex food items in an attractive format. The 3D food printer is potentially a 'print and eat' technology for future generations. The next few years will see an increase in the use of 3D printing technology in foods that will create unique new textured foods, healthy and smooth foods as well as easy-to-swallow foods for the elderly. In addition, technology will contribute to preventing food waste (Prakash et al., 2019).

The facts and gaps of 3DFP

3D printing is a convenient and efficient processing technology. Due to the bottom-up stacking approach, it can print and produce complex and intricate structures that traditional processing methods cannot create (Dankar et al., 2018). This novel technology has many advantages such as economical processing, high nutritional value, reduced waste, rapid design, customized products, and automated production (Çakmak and Gümüş, 2020). These benefits include less pollution, higher efficiency, fewer injuries, etc., directly because of reducing material waste and time consumption (Munoz et al., 2021). The application based on the principle of extrusion-based 3D printing is the most studied method in 3DFP. When it comes to equipment selection, Delta 3D printers are widely used for food printing, especially for applications. Although recent research has tried to develop a dual extruder and color food printing equipment development in this field is limited with these printers. The development of the multi-nozzle based on the Delta 3D printer faces limitations due to high cost because each nozzle requires a series of independent three-axis installations to achieve multi-nozzle simultaneous printing. In addition, the printing area is limited by the three-axis kinematic system, which leads to relatively low productivity for food 3D printers based on the number of printheads. In contrast, SCARA robots with 4 degrees of freedom (DOF) have been applied for component use in the industrial field (Pan et al., 2024). Based on the formation mechanism, the defects associated with BJ for the first time are methodically divided into quintuple classifications, including slitting defect, dust spreading defect, single-layer printing defect, multi-layer deposition defect and dedusting defect. Particular attention is paid to the anomalies caused by the interaction of the binder with the dust bed, which fundamentally distinguishes BJ from traditional AM methodologies. A combination of numerical algorithms and physical paradigms is introduced in each corresponding classification to arm researchers with a deep understanding of the mechanism behind these defects. In addition, various mitigation strategies for these corresponding defects are being further investigated, covering connector selection, procedural parameter improvement, post-process interventions, and the integration of hybridized techniques (Zhao et al., 2023).

Taking advantage of developments in information communication technology and advanced manufacturing (such as robotics, the Internet of Things, augmentation and virtual reality, blockchain, big data, artificial intelligence, and 3D printing) will inform creative disruptions such as quality, security, safety, packaging and advanced online delivery in the food supply chain (Rowan, 2021). With the development of 3DP technology and nanotechnology, cells fixed to a 3D biosensor or a 3D microenvironment have shown great improvement over the traditional application of cell-based biosensors (CBBs) in sensitivity and detection originality (Li et al., 2022). 3D printing is also positioned as a new technology in the field of food science, which has the potential to design complex internal and external structures that would be quite impossible with traditional applications such as molding while providing unique nutritional experiences and the opportunity to meet specific nutritional needs for healthy people and sick patients (Lupton, 2017; Dick et al., 2019; Watkins et al., 2022; Huang et al., 2023; Yu et al., 2023; DeSantis et al.,2024). A wide variety of mixers are available for a large number of mixing applications. Defines the molding and forming equipment used for bread, pie, biscuit and confectionery products and 3D food printing (Fellows, 2022). 3DFP has a number of benefits compared to traditional cooking techniques, it can be difficult to get used to at first. Cocoa powder, powdered sugar, etc. just a small number of food items, for example., can be used directly for 3D printing with food. Most materials need to be processed in a certain way before they can be used for printing. This is done to ensure that the printing materials have the appropriate rheology, thus facilitating easy extrusion, which forms the nozzle with better mechanical properties, thus maintaining the shape of the printed product (Sharma et al., 2024). However, this technology is still under development some difficulties in processing, and the suitability of new foodstuffs such as methodologies, formulations, and printers, among others, is constantly being investigated (Qiu et al., 2023; Lanz et al., 2024). Recent advances in 3D printing technology have provided a new way for food production. However, one of the challenges in 3D printing food is the limited availability of printable materials that can mimic the properties of real food (Sharma et al., 2024). This is because most natural food systems cannot be printed directly. However, a wide variety of printing materials and excellent printing properties are important conditions for the rapid growth of 3DFP technology (Sharma et al., 2024).

Due to its minimal equipment and infrastructure requirements, additive manufacturing, often known as 3D printing, is becoming more and more popular for producing prototypes, customized goods, and quick tooling. A few benefits of 3D printing include the capacity to create intricate components that are easy to utilize, incredibly flexible, precisely dimensioned, and require little upkeep or operation. However, new printable polymer composites must be developed immediately for high-performance applications because virgin polymers have restricted mechanical characteristics and functionalities (Singh et al., 2022).

Various scaffold technologies have been adopted and developed to support the cultivation, expansion and differentiation of cells using edible, low-cost and sustainable materials and methods. Cytoskeleton structures can take advantage of different processing strategies, which include structuring approaches and additives, to produce the final cultured meat products (Levi et al., 2022). Scaffolds can solve the problems of proliferation and differentiation of cells (slow and small in volume), which can occur in a single layer and have the advantage of being able to produce many cells at the same time. Many types of scaffolds have been created, such as hydrogel, fiber scaffolds, and microcarriers, and manufacturing methods have also been developed to allow cells to better adhere to and grow on them (Lee and Choi, 2024). In addition to this, scaffolds are produced by mixing various materials using methods such as 3D printing, electrospinning, and spraying, molding and deceleration. Collagen extracted from animal skin or tendons is most commonly used, but vegetable proteins such as soybeans, corn, alginate, and wheat as well as edible microorganisms such as mold, are also used in scaffolding construction. The production of cultured meat for consumption should not only focus on awareness and mass production but also complement the sensory properties of meat, such as texture and flavor. Therefore, scaffold production must contain components similar to that of meat, and further research will be needed to develop cultured meat with a scaffold similar to that of meat (Lee and Choi, 2024). Moreover, post-processing feasibility refers to the examination of the integrity of the desired interior and exterior designs of 3D printed products. Because of the physical and chemical changes that occur during cooking, it is necessary to take into account the formulation design, printing settings and post-processing conditions, among other factors, in order to obtain both the expected structure and textural properties of the food. Limited information on the post-processing applicability of 3D-printed products, including meat products, is currently available (Dick et al., 2019).

Extrusion-based, inkjet, selective laser sintering, and binder printing methods have been applied in 3D food printing (Topuz et al., 2018; Sharma et al., 2024; Pan et al., 2024; Kozicki et al., 2024). Due to the limitations of printers, most studies use a single blended mixture of food ingredients, such as pizza and pasta batters, fruit and vegetable mixes, seafood products, meat products, cheese, chocolates, and more, which are usually deposited using a single nozzle. extruder type 3D printer (Dick et al., 2019). However, device design takes advantage of both the open-source hardware methodology and the paradigm developed by the open-source self-replicating rapid prototyper (RepRap) 3-D printer community. RepRapable Recyclebot: Open source 3D printable extruder was made to convert plastic into 3D printing filament (Woern et al., 2018). The different 3DFP techniques and reinforcement of natural food gel for enhancement of printing characteristics in 3D printed food should be some special characteristics like heat characteristics, the rheological role of additives, modification of printing rheological qualities, modification to boost electrostatic qualities, flow properties, and modulus properties (Sharma et al., 2024). While there are challenges to overcome, such as improving the printability and mechanical properties of hydrogel-based inks, the potential benefits of this technology make it an exciting research area (Sharma et al., 2024).

Conclusion

The improvement of technology every passing day enables the development and implementation of many new applications. In addition to this, factors such as decreasing food resources, increasing population, and changing environmental conditions give rise to the development of techniques for producing food products suitable for human needs. 3DFP is one of these novel technologies that have many advantages. The many advantages provided by 3DFP can be summarized as follows: the production of food products containing personalized nutrients, the reduction of food wastes, and reliable and healthy food production economically and quickly. However, there are also several drawbacks to using 3DFP including difficulties in implementing methods, materials, and processes. Despite this approach, it is believed that the problems that may be experienced will be solved with the studies conducted, and the foods produced with advanced 3DFP technology will increase in consumption. It is foreseen that 3DFP will be widely preferred soon with the standardization of the produced foods in terms of engineering and food safety will provide innovative technological advantages.

Author Statement

Irem Kılınç:
Writing the original draft, content, and design of the study.
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Conflict of interest

The authors have no conflict of interest to declare.

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