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3D Food Printing: Technical and market perspectives

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Abstract

3D food printing is an emerging technology with the potential to transform the food industry, offering benefits such as customization, decreased food waste, and the creation of intricate structures. Extrusion-based food printing and binder jetting has emerged as a notable technology in recent years, garnering interest for its potential in personalized nutrition, sustainability, and innovative food design. In this article, we will explore the technical approaches, material properties, printing stability, and post-processing of extrusion-based 3D printing and binder jetting along with consumer acceptance, market trends, future outlook and opportunities in 3D food printing.

Keywords: 3D food printing technology, material properties, printing stability, technical approaches

Introduction

Over time, 3D food printing technology has seen significant progress, with experts and professionals in the field investigating its possible uses and advantages within the food industry. The early phases of 3D food printing involved a general understanding of the technology and its potential in food production (Sun *et al.*, 2015) [51]. As the technology progressed, researchers shifted their focus to the latest developments in 3D food printing, studying its potential for large-scale customization in food production (Yang *et al.*, 2017; Sun *et al.*, 2015) [60, 51]. Alongside technological improvements, researchers also started examining the crucial factors involved in 3D food printing, such as material characteristics, printing settings, and post-processing methods (Derossi *et al.*, 2019) [16]. The field continued to grow with the release of extensive books and reviews on the topic, like "Fundamentals of 3D Food Printing and Applications" (Godoi *et al.*, 2018) [23] and "Review of 3D Food Printing" (Sher & Tutó, 2015) [48]. As the technology became more sophisticated, researchers started concentrating on printing precision and its relevance in the food industry (Liu *et al.*, 2017) [34]. Moving forward, the future prospects of 3D food printing appear bright, with researchers investigating new materials, methods, and applications to further enhance the technology's capabilities.

Advantages and challenges in food fabrication

Advantages

1. Customization and Personalization: One of the significant benefits of 3D food printing is the ability to create customized and personalized food products (Zhang *et al.*, 2022) [61]. This technology allows for precise control of ingredients, shapes, textures, and flavors, enabling the creation of unique and tailored food items for individual preferences and dietary needs (Le-Bail *et al.*, 2020) [29]. For instance, 3D food printing can be used to produce meals for people with specific dietary restrictions, such as gluten-free or low-sodium diets (Escalante-Aburto *et al.*, 2021) [18].
2. Health Improvement and Personalized Nutrition: 3D food printing has the potential to improve health outcomes by enabling the production of food items with specific nutritional profiles (Escalante-Aburto *et al.*, 2021) [18]. By controlling the composition of ingredients, it is possible to create food products that cater to individual nutritional needs, such as those with specific vitamin or mineral deficiencies. This technology can also be used to produce functional foods with added health benefits, such as incorporating probiotics or bioactive compounds (Zhao *et al.*, 2021) [63].
3. Sustainability and Resource Efficiency: 3D food printing can contribute to more sustainable food production by reducing waste and optimizing resource use (Zhang *et al.*, 2022) [61]. The precise control of ingredients and portion sizes allows for the minimization of food waste, while the ability to create complex structures with minimal material use can lead to more efficient use of resources (Sun *et al.*, 2018) [52].

4. Additionally, 3D food printing can potentially reduce the environmental impact of food production by enabling the use of alternative protein sources, such as plant-based proteins or insect-based ingredients (Le-Bail *et al*., 2020) [29].
5. Novel Food Structures and Textures: 3D food printing enables the creation of innovative food structures and textures that are difficult or impossible to achieve through traditional food processing methods (Zhao *et al*., 2021) [63]. This technology allows for the precise control of internal structures, such as porosity and layering, which can influence the mechanical properties, mouthfeel, and overall sensory experience of food products (Zhang *et al*., 2022) [61].

Challenges

1. Limited Range of Printable Materials: One of the significant challenges in 3D food printing is the limited range of printable materials, as not all food ingredients are suitable for printing (Zhang *et al*., 2022) [61]. The rheological properties of food materials, such as viscosity and gelation, play a crucial role in determining their printability (Le-Bail *et al*., 2020) [29]. Developing new formulations and processing techniques to expand the range of printable materials is an ongoing area of research (Zhao *et al*., 2021) [63].
2. Printing Speed and Scalability: The current printing speed of 3D food printers is relatively slow, which can be a limiting factor for large-scale production and commercial applications (Zhang *et al*., 2022) [61]. Improving the printing speed and scalability of 3D food printing technology is essential for its widespread adoption in the food industry (Le-Bail *et al*., 2020) [29].
3. Food Safety and Regulatory Issues: Ensuring food safety and meeting regulatory requirements are critical challenges in 3D food printing (Escalante-Aburto *et al*., 2021) [18]. The use of novel ingredients, such as alternative protein sources, and the creation of complex structures may raise concerns about food safety and require thorough evaluation and testing (Sun *et al*., 2018) [52]. Additionally, the development of appropriate regulations and standards for 3D printed food products is necessary to ensure their safety and quality (Le-Bail *et al*., 2020) [29].
4. Consumer Acceptance: Consumer acceptance of 3D printed food products is another challenge that needs to be addressed (Zhang *et al*., 2022) [61]. Factors such as taste, texture, appearance, and perceived health benefits can influence consumer acceptance of 3D printed foods (Escalante-Aburto *et al*., 2021) [18]. Educating consumers about the benefits and potential applications of 3D food printing, as well as addressing any concerns or misconceptions, is crucial for the successful integration of this technology into the food industry (Sun *et al*., 2018) [52].

3D Printing technologies for food fabrication

Extrusion-based printing

Extrusion-based 3D food printing has emerged as a notable technology in recent years, garnering interest for its potential in personalized nutrition, sustainability, and innovative food design. This method utilizes a printer head that dispenses food materials layer by layer, forming intricate food structures with precise control over shape, texture, and composition. In this essay, we will explore the technical approaches, material properties, printing stability, and post-processing of extrusion-based 3D food printing, drawing from the provided references.

Technical Approaches

Extrusion-based 3D food printing employs a printer head that releases food materials in layers, constructing complex food structures with exact control over their shape, texture, and composition. The printer head typically features a nozzle that can be adjusted to regulate the size and shape of the dispensed material (Hussain *et al*., 2022) [27]. Various parameters, such as extrusion rate, temperature, and pressure, can be manipulated to achieve the desired food structure and texture (Sun *et al*., 2018) [52].

Material Properties

The rheological characteristics of food materials are crucial in determining their suitability for extrusion-based 3D food printing (Ma & Zhang, 2022) [61]. Factors such as viscosity, elasticity, and gelation properties can impact the extrusion rate, shape retention, and stability of the printed food structures (Wang *et al*., 2022) [56]. Consequently, it is vital to choose food materials with appropriate rheological properties for extrusion-based 3D food printing.

Printing Stability

Maintaining printing stability is essential in extrusion-based 3D food printing, as it influences the quality and uniformity of the printed food structures (Agunbiade *et al*., 2022) [1]. Stability can be affected by factors like extrusion rate, temperature, and pressure, as well as the properties of the printing substrate (Hussain *et al*., 2022) [27]. Therefore, optimizing printing parameters and substrate properties is crucial for achieving stable and consistent extrusion-based 3D food printing.

Post-Processing

Post-processing plays a significant role in extrusion-based 3D food printing, as it can alter the final quality and sensory attributes of the printed food structures (Sun *et al*., 2018) [52]. Techniques such as drying, baking, and frying can enhance the texture, flavour, and appearance of printed food products (Hussain *et al*., 2022) [27]. Moreover, post-processing can be used to improve the nutritional value of printed food products by incorporating functional ingredients like vitamins and minerals (Ma & Zhang, 2022) [61].

Applications

Extrusion-based 3D food printing has various applications in the food industry, including personalized nutrition, sustainability, and innovative food design (Wang *et al*., 2022) [56]. This technology enables the production of customized food products tailored to individual preferences and dietary requirements (Sun *et al*., 2018) [52]. Furthermore, extrusion-based 3D food printing can contribute to sustainable food production by minimizing waste and optimizing resource utilization (Wang *et al*., 2022) [56]. This technology also allows for the creation of unique food structures and textures that are challenging or impossible to achieve through conventional food processing methods (Agunbiade *et al*., 2022) [1].

Binder Jetting

Binder jetting is a 3D printing technique that has gained significant attention for its potential in food production (Shahrubudin *et al*., 2019) [47]. This method involves selectively applying a liquid binder to a powder bed, resulting in the formation of solid objects layer by layer (Ziaee & Crane, 2019) [64]. One of the main benefits of binder jetting in food production is its ability to create intricate and complex structures that are difficult to achieve using traditional manufacturing methods (Holland *et al*., 2019) [26]. This technology allows for the customization of food items in terms of shape, texture, and nutritional composition, catering to individual preferences and dietary needs (Le-Bail *et al*., 2020) [29].

Various materials, such as carbohydrates, proteins, and fats, can be used in binder jetting for food production (Ziaee & Crane, 2019) [64]. The choice of material depends on the desired characteristics of the final product, including taste, texture, and nutritional value. Additionally, binder jetting enables the incorporation of functional ingredients like vitamins and minerals into food items, enhancing their nutritional content (Le-Bail *et al*., 2020) [29].

Numerous applications of binder jetting in food production have been explored, such as creating food structures for specific dietary requirements and developing innovative food products with unique textures and flavors (Holland *et al*., 2019) [26]. For instance, binder jetting has been utilized to fabricate food structures with controlled porosity, which can be beneficial for individuals with dysphagia or other swallowing difficulties (Le-Bail *et al*., 2020) [29].

Materials and Ingredients for 3D food printing

Edible inks and food-grade materials

In recent years, there has been growing interest in edible inks and food-grade materials for their potential applications in 3D food printing and packaging (Pulatsu & Lin, 2021) [66]. These materials are designed to be safe for consumption and can be used to create personalized food items with distinct shapes, textures, and flavors (Chen *et al*., 2022) [12].

Developing edible inks for 3D printing involves creating materials with suitable rheological properties to ensure printability and shape retention after printing (Pulatsu & Lin, 2021) [66]. Various strategies have been explored to transform edible food materials into 3D printable inks, including the use of starch, proteins, and hydrocolloids (Chen *et al*., 2022) [12].

For example, starch has been investigated as an edible ink for 3D food printing applications due to its abundance, affordability, and biodegradability (Chen *et al*., 2022) [12]. Starch-based inks can be customized to achieve the required rheological properties and can be used to create intricate food structures with controlled textures and nutritional profiles.

Another example is the screen printing of catechu (Senegalia catechu) and guar gum-based ink for food printing and packaging applications (Hakim *et al*., 2023) [24]. This ink formulation offers a sustainable and environmentally friendly alternative to conventional inks, with potential uses in the creation of edible packaging materials and printed food products.

Hydrolyzed collagen has also been studied as an edible material for 3D food printing, specifically for generating scaffolds in bio manufacturing cultivated meat (Koranne *et al*., 2022) [28]. This material possesses unique properties, such as biocompatibility and biodegradability, making it a promising option for developing alternative protein sources and sustainable food production.

In addition to edible inks, edible films and coatings have been extensively researched for their potential applications in food packaging and preservation (Han, 2014) [25]. These materials can be formulated from various food-grade components, including proteins, polysaccharides, and lipids, and can be used to improve the shelf life, safety, and quality of food products. Edible inks and food-grade materials offer promising opportunities for the creation of innovative food products and packaging solutions. As research in this field continues to advance, these materials are expected to play an increasingly important role in the future of food production and packaging (Pulatsu & Lin, 2021) [66].

Nutritional considerations and customization of materials and ingredients

3D food printing is a groundbreaking technology with the potential to transform food production and consumption. This technology enables customization of food in terms of shape, texture, flavor, and nutritional content, addressing various dietary needs and preferences (Sun *et al*., 2015) [51]. Nutritional considerations and the customization of materials and ingredients are crucial aspects of 3D food printing.

A key advantage of 3D food printing is its capacity to generate personalized nutritional profiles for individuals. By modifying the composition of printed food, it can accommodate specific dietary requirements, such as food allergies, intolerances, or particular nutrient needs (Attarin & Attaran, 2020) [5]. This customization is also advantageous for individuals with medical conditions necessitating specialized diets, like diabetes or celiac disease (Sun *et al*., 2015) [51].

Besides catering to specific dietary needs, 3D food printing can also improve the overall nutritional value of food. For instance, by integrating nutrient-dense ingredients like vitamins, minerals, and proteins into the printing process, it can produce visually appealing and nutritionally balanced food products (Attarin & Attaran, 2020) [5]. This can be especially helpful in addressing malnutrition and encouraging healthier eating habits.

Customizing materials and ingredients in 3D food printing also enables the creation of innovative food products with distinct textures and flavors. By blending various ingredients and adjusting their ratios, it can produce food products that appeal to individual taste preferences and cultural backgrounds (Sun *et al*., 2015) [51]. This can foster a more diverse and enjoyable eating experience and inspire the discovery of new and inventive food combinations.

Nonetheless, challenges exist in customizing materials and ingredients for 3D food printing. Ensuring the safety and quality of printed food products is a primary concern, as using novel ingredients and printing processes may pose potential risks (Attarin & Attaran, 2020) [5]. Moreover, developing appropriate materials and ingredients for 3D food printing demands extensive research and testing, as well as the establishment of suitable regulatory frameworks to guarantee their safe and effective application (Sun *et al*., 2015) [51].

Applications of 3D food printing

Personalized nutrition and dietary needs

3D food printing has emerged as a promising technology with the potential to revolutionize the food industry by offering personalized nutrition and catering to specific dietary needs.

This innovative approach allows for the customization of food in terms of shape, texture, flavour, and nutritional content, enabling the creation of tailored meals for individuals with unique dietary requirements (Escalante-Aburto *et al*., 2021) [18].

One of the primary applications of 3D food printing in personalized nutrition is the ability to create meals with precise nutrient compositions. This can be particularly beneficial for individuals with specific dietary restrictions, such as those with food allergies, intolerances, or chronic conditions like diabetes (Varvara *et al*., 2021) [54]. By controlling the ingredients and their proportions, 3D food printing can help ensure that individuals receive the necessary nutrients while avoiding potentially harmful substances (Burke-Shyne *et al*., 2021) [9].

Another application of 3D food printing in personalized nutrition is the potential to address the needs of the elderly population. As people age, they may experience difficulties in chewing and swallowing, leading to a reduced intake of essential nutrients. 3D food printing can be used to create soft, easily digestible foods with customized textures, making it easier for older adults to consume a balanced diet (Escalante-Aburto *et al*., 2021) [18].

Furthermore, 3D food printing can contribute to the development of personalized diets for athletes and individuals with specific fitness goals. By adjusting the macronutrient composition of printed foods, it is possible to create meals that support muscle growth, recovery, and overall performance (Varvara *et al*., 2021) [54].

In addition to addressing specific dietary needs, 3D food printing can also play a role in promoting healthier eating habits among the general population. By using this technology to create visually appealing and appetizing foods, it may be possible to encourage the consumption of nutrient-dense, plant-based ingredients, ultimately contributing to improved public health outcomes (Burke-Shyne *et al*., 2021) [9].

Creative food design and gastronomy

3D food printing has opened new possibilities in the realm of creative food design and gastronomy, allowing chefs and food enthusiasts to explore innovative culinary techniques and artistic presentations. This technology enables the creation of intricate shapes, textures, and flavours that were previously unattainable through traditional cooking methods (Chua *et al*., 2022) [14].

One application of 3D food printing in creative food design is the reinterpretation of heritage foods. By using 3D printing technology, chefs can recreate traditional dishes with a modern twist, preserving cultural heritage while introducing new and exciting culinary experiences (Antlej *et al*., 2017) [3]. This approach can also be employed in museum maker spaces, where visitors can engage with the history of food and participate in the creation of unique, culturally inspired dishes (Antlej *et al*., 2017) [3].

Digital gastronomy, a concept that combines computational design, digital fabrication, and culinary arts, is another area where 3D food printing plays a significant role (Zoran *et al*., 2021) [65]. This interdisciplinary field aims to transform the way we perceive, create, and consume food by integrating technology into the cooking process. Through digital gastronomy, chefs can experiment with novel ingredients, textures, and flavours, pushing the boundaries of traditional culinary practices (Zoran *et al*., 2021) [65].

Furthermore, 3D food printing can be used to create visually stunning and intricate food presentations, elevating the dining experience and engaging the senses of the consumer (Ross *et al*., 2021) [45]. By manipulating the shape, color, and arrangement of printed foods, chefs can craft visually appealing dishes that not only taste delicious but also provide a memorable and immersive dining experience (Ross *et al*., 2021) [45].

In addition to its applications in high-end gastronomy, 3D food printing can also be utilized in educational settings to teach students about the science of food and the creative possibilities of culinary arts (Chua *et al*., 2022) [14]. By incorporating 3D food printing into the curriculum, educators can inspire the next generation of chefs and food scientists to explore innovative approaches to cooking and food design.

Critical variables in 3D food printing

Printing precision and accuracy

Printing precision and accuracy are critical factors in 3D food printing, as they directly influence the quality, appearance, and functionality of the printed food products. Achieving high precision and accuracy in 3D food printing depends on several factors, including the properties of the printable edible inks, the printing parameters, and the technology used (Liu *et al*., 2017) [34].

The properties of printable edible inks play a significant role in determining the printing precision and accuracy of 3D food printing. The rheological properties, such as viscosity and shear-thinning behavior, as well as the solid content and particle size distribution, can affect the printability and resolution of the printed food products (Feng *et al*., 2019) [20]. For instance, inks with appropriate viscosity can maintain their shape during the printing process, resulting in better precision and accuracy (Feng *et al*., 2019) [20].

Printing parameters, such as printing speed, layer height, nozzle diameter, and temperature, also have a considerable impact on the printing precision and accuracy of 3D food printing (Liu & Zhang, 2019) [67]. Optimizing these parameters is essential to ensure that the printed food products have the desired shape, texture, and structural integrity. For example, a slower printing speed may result in higher precision, while a larger nozzle diameter may lead to lower resolution (Liu & Zhang, 2019) [67].

The choice of 3D food printing technology can also affect the printing precision and accuracy. Different printing technologies, such as extrusion-based, inkjet, and selective laser sintering, have varying levels of precision and accuracy, depending on their inherent characteristics and limitations (Liu *et al*., 2017) [34]. For instance, extrusion-based printing is suitable for printing materials with high viscosity, while inkjet printing is more appropriate for low-viscosity materials, each offering different levels of precision and accuracy (Liu *et al*., 2017) [34].

Printing speed and scalability

The importance of printing speed and scalability in the development and application of 3D food printing technology cannot be overstated, as they directly affect the efficiency and feasibility of producing printed food products on a larger scale (Chua, 2020) [13]. Printing speed is determined by factors such as food ink properties, printing parameters, and the printing technology used, while scalability refers to the ability to produce food products on a larger scale, such as in mass production or industrial settings (Ma & Zhang, 2022) [61].

To enhance printing speed and scalability, researchers and industry professionals are working on optimizing food ink properties and printing parameters, as well as developing new printing technologies and techniques (Ma & Zhang, 2022) [61]. For instance, formulating food inks with suitable rheological properties can help achieve faster printing speeds while maintaining print quality (Ma & Zhang, 2022) [61]. Additionally, the use of multi-nozzle 3D food printers and parallel printing techniques can significantly increase printing speed and scalability, allowing for the simultaneous production of multiple food products (Chua, 2020) [13].

Consumer acceptance and market trends

Consumer perception of 3D printed food

The perception of consumers towards 3D printed food is a critical aspect in determining its acceptance and integration into the food industry. Research has delved into different facets of consumer perception, such as attitudes, information, and the impact of food neophobia and food technology neophobia (Feng *et al*., 2022; Brunner *et al*., 2018; Caulier *et al*., 2020; Lee *et al*., 2021) [21, 8, 10, 31].

Labels and information about 3D printed food can significantly affect consumer perception. According to Feng *et al*. (2022) [21], sharing information about the advantages of 3D printed food, like customization and sustainability, can positively shape consumer perception and acceptance. However, the study also indicated that explicitly labelling food as 3D printed might result in negative perceptions, emphasizing the need for effective communication strategies to encourage consumer acceptance.

Consumer attitudes towards 3D printed food can differ, with some individuals showing curiosity and interest, while others may display scepticism or apprehension (Brunner *et al*., 2018) [8]. Factors such as taste, texture, appearance, and nutritional value can impact consumer attitudes, as well as the perceived novelty and technological aspects of 3D printed food (Baiano, 2022; Gayler *et al*., 2018) [6, 22].

Food neophobia, or the reluctance to try new or unfamiliar foods, and food technology neophobia, or the reluctance to accept food produced using new technologies, can also contribute to consumer perception of 3D printed food (Lee *et al*., 2021) [31]. People with higher levels of food neophobia and food technology neophobia may be less likely to accept 3D printed food, underlining the significance of addressing these concerns through education and exposure to the technology (Lee *et al*., 2021) [31].

In the food service industry, overcoming obstacles to consumer acceptance of 3D printed foods may involve addressing concerns related to taste, texture, and nutritional value, as well as highlighting the potential benefits of customization, sustainability, and convenience (Ross *et al*., 2022) [45].

The market potential and growth of 3D Printed Food

The market potential and growth of 3D printed food have garnered considerable interest in recent years. This emerging technology holds the potential to transform the food industry by offering innovative solutions for food production, customization, and sustainability (Baiano, 2022; Lee, 2021) [6, 31].

One of the primary drivers of market growth for 3D printed food is the increasing demand for personalized nutrition and customized food products (Baiano, 2022; Charlebois & Juhasz, 2018) [6, 11]. 3D food printing enables the creation of tailored food items catering to individual dietary needs, preferences, and health conditions, which is particularly relevant in the context of an aging population and the rise of lifestyle-related diseases (Lee, 2021) [31].

Additionally, 3D printed food has the potential to address some sustainability challenges faced by the food industry, such as reducing food waste and optimizing resource use (Attaran, 2017; Baiano, 2022) [4, 6]. The additive manufacturing process used in 3D printing allows for precise control of ingredients and portion sizes, contributing to more efficient food production and consumption (Attaran, 2017) [4].

Consumer attitudes towards 3D printed food also play a crucial role in influencing market growth. While some studies have reported positive consumer perceptions of 3D printed food, others have highlighted concerns related to taste, texture, and safety (Baiano, 2022; Charlebois & Juhasz, 2018) [6, 11]. As the technology continues to advance and address these concerns, it is expected that consumer acceptance will increase, further driving market growth (Baiano, 2022) [6].

The regulatory framework surrounding 3D printed food is another critical aspect that will shape the market's development. Since this technology is relatively new, regulations and standards are still being established to ensure the safety and quality of 3D printed food products (Baiano, 2022) [6]. The development of a robust regulatory framework will be essential for fostering consumer trust and promoting market growth (Baiano, 2022) [6].

The regulatory aspects and challenges of 3D printed food

The regulatory aspects and challenges of 3D printed food are vital for guaranteeing safety, quality, and consumer approval of this innovative technology (Baiano, 2022) [6]. As 3D printed food becomes more prevalent, it is crucial to create a strong regulatory framework that considers the distinct features and potential risks associated with this novel food production method (Portanguen *et al*., 2019) [40].

A primary regulatory challenge for 3D printed food is the absence of specific guidelines and standards tailored to this technology (Baiano, 2022) [6]. Current food safety regulations may not sufficiently cover the unique aspects of 3D printed food, such as the utilization of new ingredients, personalized formulations, and the additive manufacturing process (Portanguen *et al*., 2019) [40]. Consequently, there is a demand for new regulations and standards explicitly designed for 3D printed food products (Baiano, 2022) [6].

Additionally, potential liability issues may arise from employing 3D food printing technology (Beck & Jacobson, 2017) [7]. As consumers and other stakeholders participate in the manufacturing process, assigning responsibility for product flaws or safety concerns may become challenging (Beck & Jacobson, 2017) [7]. This underscores the necessity for unambiguous guidelines regarding liability and accountability in the realm of 3D printed food production (Beck & Jacobson, 2017) [7].

Moreover, the worldwide nature of 3D printed food technology requires international collaboration and the harmonization of regulatory frameworks (Rogers & Srivastava, 2021) [43]. Since 3D food printing can disrupt traditional supply chains and generate new business models, it is vital to establish consistent regulations across various countries and regions to ensure fair competition and encourage the safe and sustainable expansion of this market (Rogers & Srivastava, 2021) [43].

Future outlook and opportunities

Advances in 3D food printing technology

Progress in 3D food printing technology has been swiftly advancing, presenting new possibilities and uses in various fields such as space travel, senior nutrition, and the integration of plant-based and algae-based functional components (Enfield *et al*., 2022; Xie *et al*., 2023; Thakur *et al*., 2023) [17, 59, 53].

A breakthrough in 3D food printing is its potential use in space missions (Enfield *et al*., 2022) [17]. This technology can supply astronauts with personalized, nutritious, and appetizing food choices, addressing the issues of limited food variety and shelf life in space (Enfield *et al*., 2022) [17]. This progress could greatly enhance astronauts' quality of life during extended missions and contribute to the success of future space exploration efforts (Enfield *et al*., 2022) [17].

Another important development is the application of 3D food printing to improve the nutritional intake of the elderly (Xie *et al*., 2023) [59]. This technology enables the creation of tailored food products that meet the specific dietary requirements and preferences of older adults, addressing challenges such as dysphagia, malnutrition, and decreased appetite (Xie *et al*., 2023) [59]. This advancement has the potential to enhance the overall health and well-being of the elderly population and decrease healthcare expenses related to age-related health problems (Xie *et al*., 2023) [59].

The inclusion of plant-based and algae-based functional components in 3D food printing ink formulations is another area of progress (Thakur *et al*., 2023) [53]. These components provide numerous health advantages and can contribute to the creation of sustainable and nutritious food products (Thakur *et al*., 2023) [53]. The incorporation of these functional components in 3D printed food can help meet the increasing demand for plant-based and eco-friendly food options (Thakur *et al*., 2023) [53].

Additionally, the development of sustainable supply chain models for 3D food printing has been recognized as a critical advancement in the field (Rogers & Srivastava, 2021) [43]. These models aim to optimize resource utilization, minimize waste, and support circular economy principles, contributing to the overall sustainability of the food industry (Rogers & Srivastava, 2021) [43].

Potential applications in healthcare and space exploration in 3D printing

3D printing has demonstrated remarkable potential in various sectors, including healthcare and space exploration, presenting inventive solutions and possibilities for these fields (Wong, 2016; Liaw & Guvendiren, 2017) [58, 32]. In healthcare, numerous applications of 3D printing have been explored, such as the development of tailored prosthetics, implants, and surgical guides (Liaw & Guvendiren, 2017; Ahangar *et al*., 2019) [32, 2]. These custom medical devices can significantly enhance patient outcomes by offering improved fit and functionality (Liaw & Guvendiren, 2017) [32]. Moreover, 3D printing has been employed in the production of tissue engineering scaffolds, which can help regenerate damaged or diseased tissues and organs (Ahangar *et al*., 2019) [2]. This technology holds the potential to transform regenerative medicine and decrease the demand for organ transplants (Ahangar *et al*., 2019) [2].

In addition, 3D printing has been used in the creation of biomimetic materials and structures in healthcare, which can replicate the properties and functions of natural tissues, leading to more effective and biocompatible medical devices and implants (Zhu *et al*., 2021) [63]. 3D printing has also been successfully applied in various healthcare areas, such as drug delivery systems, dental restorations, and medical training models (Mishra *et al*., 2021; Cornejo *et al*., 2022) [68, 15].

Regarding space exploration, 3D printing provides numerous benefits, including the capacity to produce parts and components as needed, reducing the necessity for extensive inventories and decreasing spacecraft weight (Wong, 2016) [58]. This technology also allows for in-situ resource utilization, enabling astronauts to manufacture tools, spare parts, and even habitats using local materials found on extra-terrestrial surfaces (Wong, 2016) [58]. Furthermore, 3D printing has been suggested for creating customized food for astronauts, addressing the challenges of limited food variety and shelf life in space (Enfield *et al*., 2022) [17].

Sustainability and environmental impact

3D food printing is an emerging technology with the potential to transform the food industry, offering benefits such as customization, decreased food waste, and the creation of intricate structures. However, it is crucial to consider the sustainability and environmental impact of this technology (Baiano, 2022) [6].

A significant aspect of sustainability in 3D food printing is its ability to reduce food waste. According to Rogers and Srivastava (2021) [43], 3D food printing can contribute to sustainable supply chain models by minimizing waste through accurate portion control and using ingredients that might otherwise be discarded. This approach conserves resources and lessens the environmental impact of food production.

Another vital aspect of sustainability in 3D food printing is the utilization of eco-friendly materials. Nyika *et al*. (2022) [39] explore the environmental consequences of 3D printing materials processing and suggest that adopting environmentally friendly materials and implementing mitigation measures can help decrease the negative effects on the environment. Whenish *et al*. (2022) [57] propose a framework for the sustainability implications of 3D bio printing, stressing the importance of employing nature-inspired materials and structures to minimize environmental impact.

Integrating 3D food printing into sustainable food supply chains also faces several obstacles. Verma *et al*. (2022) [55] identify these challenges and offer a model to address them, emphasizing the necessity of a comprehensive approach to ensure the successful incorporation of 3D food printing into sustainable food systems.

Besides environmental advantages, 3D food printing can also contribute to the social and economic aspects of sustainability. Baiano (2022) [6] presents an extensive review of 3D printed foods, covering not only technological aspects but also nutritional value, safety, consumer attitudes, regulatory frameworks, and economic and sustainability issues. By addressing these factors, 3D food printing can contribute to a more sustainable food system.

Finally, Nadagouda *et al*. (2020) [38] review the application of

3D printing techniques to environmental applications, including water treatment, air purification, and waste management, further showcasing the potential of 3D printing to contribute to sustainability and environmental protection.

Conclusion

In summary, 3D food printing is an emerging technology with the capacity to bring about significant changes in the food sector. It presents various advantages, such as personalization, waste minimization, and enhanced productivity. Nonetheless, certain technical obstacles must be overcome, including the creation of food-grade materials, and refining the printing techniques. Furthermore, the 3D food printing market is currently in its infancy, characterized by limited adoption and high expenses. As the technology advances and becomes more widely available, it is expected that its adoption and innovation will grow. Ultimately, 3D food printing holds the promise of altering the way we manufacture and consume food, making it intriguing to observe its progress in the years ahead. The potential of 3D food printing to revolutionize food production and consumption is significant. To fully realize this potential, it is crucial for all parties involved to collaborate and address the current obstacles. With adequate backing and funding, 3D food printing could play a pivotal role in promoting a more sustainable, individualized, and imaginative culinary environment.

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