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A Review on 3D Food Printing Technology in Food Processing

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Abstract

The review's objectives were to discuss the understanding of 3D food printing technology, a new way of manufacturing foods, and how this technology can be applicable in the food processing industry. The 3D food printing provides a wide domain of food and nutrition-based applications. The different three-dimensional shapes of a food can be developed without the utilization of any mold by using 3D printing technology. Many industries use this technology to manufacture many distinct products. However, utilizing this technology in food processing to manufacture new foods, such as plant-based meat analogues, represents a new trend. So, it is important to understand the principle of the 3D food printing technology for applying this technology in the food processing industry properly. In this review, the mechanism of 3D food printing, evolution of this technology, ingredients compatible for this technology, pros and cons of this technology and the quality evaluation of the 3D printed foods were discussed in detail. Also, the study provided details regarding the available 3D food printers, specifications, and their price. Achieving the exact texture of the 3D printed foods prepared by conventional cooking methods is a steep challenge for this technology. 3D food printers can produce complex food models, and this technology can design unique food patterns. Selection of a printing method is important because a 3D food printing technique can be an extrusion-based printing, selective sintering printing (SLS) method, inkjet printing and binder jetting and each method has its advantages and disadvantages. Pizzas, cookies, chocolates/candies, plant-based meat/fish analogues and many more customized food products can be manufactured using a 3D food printer. Overall, 3D food printing technology has great potential as a cooking method in the food industry.

Keywords: 3D food printing technology, operational principle of 3D food printer, evolution of 3D food printer, plant-based meat analogue, quality evaluation of 3D printed foods

1. Introduction

The advent of 3D printing technology has revolutionized various industries, from aerospace to healthcare, by offering unprecedented levels of customization, prototyping, diverse fabrication methods, and complex geometries (Iftekar et al., 2023). Among these revolutionary functions, the utilization of this technology in customized food product development has piqued researchers' curiosity. The 3D food printers enable the precise fabrication of desired food items by depositing layers of edible materials, which can be customized for their nutritional content, flavor, shape, and texture (Anandharamakrishnan et al., 2022). Furthermore, the utilization of food printing technology enables the digitization and customization of a person's nutritional needs and energy intake based on their current physical and nutritional state (Liu et al., 2017). "Imagination into reality" is made possible by 3D food printing, which transforms the way food is customized based on sensory-acceptable genetic and biometric data. Food printing using a 3D food printer eventually has the potential to have a significant economic impact since this technology opens up opportunities for small as well as large-scale businesses to collaborate, giving customers more freedom to choose how they prefer to eat their foods (Anandharamakrishnan et al., 2022).

The fundamentals of 3D food printing involve a computerized procedure that is regulated and involves building a product layer by layer using a Computer Aided Design (CAD) software by accessing 3D frameworks from various internet sources (Dankar et al., 2018). After the 3D structure is produced, the printer receives the design data and uses it to cut the model into layers that are then assembled in the desired sectional pattern (Dankar et al., 2018). Utilizing a 3D model that is converted into an STL (stereolithography) file, the model building technique helps to realize each section's shape while also allowing the model to construct its layers through slicing activity (Guo et al., 2019). Furthermore, creating a 3D model includes more than just using CAD; it also involves scanning and other methods. In addition to being tailored to specific food printing needs, 3D models also need the G-code for model slicing in addition to variables like layer elevation nozzle pace, extrusion rate and filling (Agunbiade et al., 2022). The numerical methods for 3D printing may be used for both extrusion analysis and simulation activities related to the examination of 3D models and printed items (Guo et al., 2019).

The 3D printing technology has a number of drawbacks and restrictions, including the printing size and the weak firmness and durability of the materials used to create structures (Praveena et al., 2022). Additionally, several studies have examined for printing foods through different perspectives. However, a little is still known about the link between crucial printing process factors and material composition to produce the intended printed product (Dankar et al., 2018). Thus, an extensive summary of the state of food 3D printing technology is what this review article attempts to offer. This review discussed the variety of 3D printing processes that were used to make foods, what ingredients and materials worked well for desired food products and how 3D printed food would be employed in food industries. This review also goes over the advantages and disadvantages of this technology, recent advancements and research and speculates on the future paths and possible effects of food 3D printing on the food sector. The study presented in this paper aims to demonstrate the revolutionary potential of 3D food printers, while also noting the obstacles that must be overcome for this technology to reach its full potential.

2. Mechanism of Printing Foods with a 3D Food Printer

A 3D food printer shown in Figure 1 is being used to develop plant-based meat analogue at the University of Wisconsin-Stout. The operative principle of 3D food printers is identical of conventional 3D printers. The blends of food ingredients are placed in a food-grade injector or cartridge, which uses a food-grade orifice to precisely apply fractionated layers of the food materials and additively onto a plate or other surface. Hardware and software have to work together for 3D printing to be functional (Kakuk, 2019). The most advanced 3D food printers include intuitive user interfaces and already configured recipes and designs that can be accessed via a computer, mobile device, or printer itself in certain situations (Kakuk, 2019). Three phases such as creating the 3D model, printing goods and following post treatments are involved in printing the desired foods. The extrusion-based printing process is involved in designing a virtual three-dimensional model. The 3D design is translated into individual layer layouts by the software, which subsequently creates the 3D printed products (Agunbiade et al., 2022). Notably, the real food printing procedure would start after selecting a recipe and putting the codes onto a 3D food printer. Following the layer patterns produced by the 3D model, the extruded product is released by either shifting the stage beneath the nozzle or by moving the nozzle over a mechanized stage in order to construct a layer. When each successive layer adheres to the preceding layer, a three-dimensional structure has been built on layers on stage (Sun et al., 2015). The items that are printed could undergo post-discharge preparation such as baking, grilling or frying (Kakuk, 2019).

Both the food ingredients and the printer's specifications are needed to be considered in order to improve a particular 3D printing process for developing desired quality final products. The process parameters of 3D food printers such as print/extrusion speed, product's pressure and flow level on the quality of materials being printed, rate of deposition, size of the printing nozzle, nozzle's height or distance from the printing bed, infill layer and layer height, extruder or printing bed temperature (which are present on certain 3D printers) are needed to be considered for desired quality products (Dankar et al., 2018).

Table 1 summarized four major types of 3D food printing methods used in food processing. Extrusion-based printing, selective sintering printing (SLS), inkjet printing and binder jetting are the four main types of 3D printing methods that are being used in the food processing. Each 3D food printing method has its benefits and drawbacks because variables and their parameters are influencing the printing accuracy and precision as well as the variations in the processes of the various 3D printing methods.

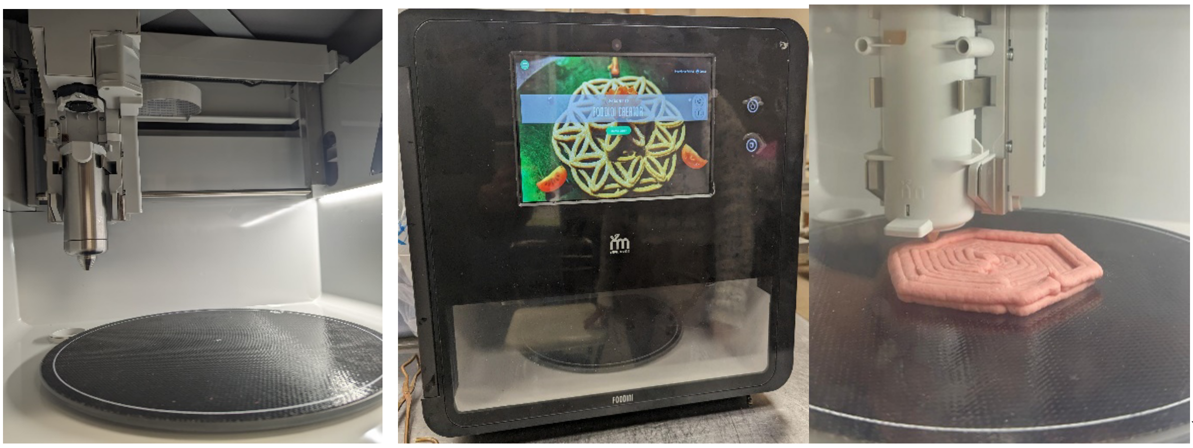

Figure 1. Foodini 3D food printer and a customized printed food product

Table 1. Different 3D food printing methods used in food processing

Printing methods	Mechanism and applications	Reference
Extrusion-based printing	Fused deposition modeling/extrusion-based printing is a process that uses a moving nozzle to continually extrude molten material or a paste-like slurry that cools and joins with previously printed layers. Three extrusion methods are available: air pressure-based which is best for low viscosity materials; syringe-based which is best for high viscosity materials but not for continuous feeding; and screw-based which is good for continuous printing but not for high viscosity slurries.	Sun et al., 2015

Selective sintering printing (SLS)	A strong laser is used for selective laser sintering (SLS) which fuses powder particles layer by layer to create three-dimensional structures. Before adding a new layer, the laser scans each cross-section of the layer, fusing the powder; this procedure is repeated until the object is created. Although it is currently restricted to certain powdered materials like sugar, fat, or starch, the SLS produces high-resolution and free-standing structures. The SLS necessitates exact control over material qualities and processing parameters.	Varvara et al., 2021
Binder jetting	A binder jetting selectively fuses each layer according to the design of the items as powdered materials are deposited layer by layer in binder jetting printing which is also known as inkjet 3D printing (3DP). The unfused powder is removed and recycled after supporting the structure during production to enable the creation of complicated and detailed structures. This technique may produce multicolored 3D edible food products; however, it can only work with powdered ingredients and needs post-processing to improve mechanical strength and accuracy.	Varvara et al., 2021
Inkjet printing	Inkjet printing for food involves dispensing droplets from a thermal or piezoelectric head to decorate surfaces like cookies, cakes and pizzas. It consists of drop-on-demand printing which ejects ink under pressure and offers greater resolution but slower printing speeds. The continuous jet printing which ejects ink constantly. Inkjet printing works well with 2D graphics rather than 3D structures and is typically used with low viscous materials.	Godoi et al., 2016

3. Evolution of 3D Food Printing Technology Over the Years

Although the history of food 3D printing is brief, it is distinguished by quick advancement and creativity. The idea of additive manufacturing, or 3D printing, first emerged in the 1980s, specifically in 1984 when Charles Hull invented stereolithography (Hull, 1996). Originally, this technique was used in the aerospace and automotive sectors, where it was highly appreciated for its capacity to generate intricate geometries and prototypes. The first 3D printer was found in the 1980s by Hideo Kodama under the name of rapid prototyping. This invention was never implemented to the industry due to failure of filling the patent at designated time (3DSourced, 2024). Initially, 3D printers were used for developing multi-layer structures of plastic, ceramic, and resins (Bogue, 2013).

In the early 2000s, the first significant attempt was taken for 3D printing of foods.

Researchers and inventors began investigating the possibility of producing food products using 3D printing methods (Malone & Lipson, 2007). The creation of the Fab@Home model by the Cornell Creative Machines Lab in 2005 was one of the first and most significant efforts towards development of 3D printed foods (Malone & Lipson, 2007). More specialized food printers were made possible by this open-source 3D printer's ability to print with a variety of materials including food pastes (Lipson & Kurman, 2013).

A syringe-based extrusion method was used by Cornell University's researchers in 2007 to print cookies and other basic food products (Malone & Lipson, 2007). This was a noteworthy achievement because it demonstrated that it was possible to 3D print intricate food structures from simple components (Lipson & Kurman, 2013). After these breakthroughs, there was a steady increase in the development of 3D printers as shown in Table 2. 3D food printers could earlier develop chocolates, pancakes and food items which had semi-solid consistency raw materials. In recent advancement, 3D printers can make complex food products like pizza and confectioneries including cake and pastries (Sun et al., 2015).

In the early 2010s, 3D food printers started to become commercially available. Natural Machines was one of the first businesses to market the Foodini printers. The Foodini was created to print a broad variety of foods utilizing fresh ingredients, ranging from savory dinners to complex sweets. It placed a strong emphasis on convenience and customization in an effort to close the gap between digital production and home cookery (Godoi et al., 2016). At about the same time, a number of other businesses with distinctive inventions joined the market. 3D Systems created the ChefJet, a printer that can use chocolate and sugar to create intricate culinary patterns (Attarin & Attaran, 2020), which demonstrated the benefit of 3D printing in the confectionery and dessert processing industries.

As technology advanced, so did its applications and the sophistication of the machines. A project called Cornucopia Digital Gastronomy was unveiled by MIT Media Lab researchers. They investigated how to combine 3D printing of food with other recipes (Zoran & Coelho, 2011). This project displayed 3D printers' structural capabilities as well as their ability to improve tastes and textures by precisely controlling ingredients and cooking methods (Zoran & Coelho, 2011).

The emphasis has shifted in recent years to cover the sustainability and nutritional elements of 3D printing foods. The utilization of alternative proteins (i.e. those derived from plants or insects) and optimizing ingredient consumption to reduce waste have emerged as important research topics (Sun et al., 2015). Customizing nutritional profiles for particular communities or people is an interesting new future for this technology, with the potential to solve global food security challenges (Godoi et al., 2016).

Table 2. Chronological development of 3D printer over years

Company	Year of Invention	Applications	Reference
Evan Malone and Hod Lipson invented Fab@Home at Cornell University	2006	Chocolate	Malone & Lipson, 2007
Choc Edge	2012	Chococlate-milk, dark and white cholate	Goehrke, 2015
NASA	2013	Pizza	Bauer, 2016
Biozoon Food Innovations GmbH	2012-2015	Easily swallowable foods for elderly	Research and Technology Development Services Group, n.d.
Coco Jet	2014	Chocolates	Shandrow, 2015
Natural machine company (Foodini printer)	2012	Bakery products, meat analogues and chocolates	(Mlot, 2014)
Novameat	2018	Plant-based steak	Carlota, 2019
Revo Foods	2023	Vegan Salmon	Boudreau, 2023

The state of food 3D printing today is defined by ongoing developments in materials research, printer technology, and culinary inventiveness. Researchers and businesses are attempting to lower the cost, increase the reliability, and speed of food 3D printers so that they may be used in homes and businesses more widely (Derossi et al., 2018). Additionally, there is a significant interest in using machine learning and artificial intelligence (AI) to further improve food production efficiency and personalization (Sun et al., 2015). Future developments in food 3D printing show potential for completely changing the food sector. Potential uses include customized diet plans, on-demand food manufacturing in isolated or resource-constrained locations, creative eating establishments, and fresh business concepts in the food service industry (Godoi et al., 2016). With the advancement of technology, it is probable that it will become a crucial component of the food chain, facilitating more environmentally friendly, productive, and customized methods of producing and consuming foods (Derossi et al., 2018).

4. 3D Food Printers in the Market

Initially, 3D food printers created only chocolates. After almost half of a decade, NASA was the first one to make pizza successfully using a 3D food printer. The advancement of developing different food products started after 2012, which included preparation of nutrition-monitored food for elderly, confectioneries and plant-based meat in various parts of world. There are many companies that manufacture several types of food printer as per distinct functions and accuracy to cater in the food industry with a specific instrument they are looking for. Table 3 serves as a crucial tool for guiding readers to the possibilities for use “at home” or in “research” if scientists or laymen intend to create 3D printed foods for personal or professional purposes.

Table 3. 3D food printers applicable in food processing

Company	Model	Applications	Price (USD)	Source
FoodBot	S2 Multi Ingredient Food 3D Printer Product Code: 3DPO-489	Mashed potatoes, biscuits, chocolates, cream, meat paste and jam	3499	(3D Printer Online Store, n.d.)
Mmuse	Delta model desktop food 3D printer	Chocolates, salt, sauce and pancakes	1999	(3D Printer Online Store, n.d.)
FoodBot	D2 Multi ingredient dual head 3D printer Product code: 3DPO-490	Candies, pastries, mashed potatoes, chocolate blocks and designed chocolates	7499	(3D Printer Online Store, n.d.)
Mmuse	New touchscreen chocolate 3D printer	Chocolates	6499	(3D Printer Online Store, n.d.)
Naturanl Machines	Foodini	Pancakes, chocolates, vegan-meat, biscuits and cookies	6000	(3D Printer Online Store, n.d.)

Mycusini	Mycusini 2.0	Chocolates	522	(Mycusini, n.d.)
Procusini	3D Choco printer	Chocolates	2723	(Procusini, n.d.)
Procusini	Research 3D food printer	Plant-based meat, chocolate and cookies	3639	(Procusini, n.d.)

5. Ingredients Used in 3D Food Printer

Often 3D printers are used to make chocolates, cheese and plant-based meat. The food that a 3D printer is capable or incapable of creating is decided by the raw materials required for a specific food aimed to be developed. The printability of raw materials plays a crucial role in 3D food printing. There are four types of technologies used for 3D printing, namely inkjet printing, binder jetting, selective laser sintering and melting capable material extrusion/simple material extrusion (Steenhuis et al., 2018). The companies mentioned in Table 4, use these four technologies (Attaran & Attaran, 2020) broadly to develop various kinds of foods. Different technologies are used as per the physical state of raw material as shown in Table 4.

Table 4. Technology is used for different raw materials

Technology used	Physical state of raw material	Raw material
Inkjet printing	Low viscosity liquid state	Pizza sauce
Binder jetting	Liquid and powdered state	Starch, sugar and protein
Selective laser sintering	Powdered texture	Sugar, chocolate
Extrusion-based printing	Soft texture	Meat dough, puree and chocolate

Note. Source (Attaran & Attaran, 2020; Steenhuis et al., 2018)

6. Challenges & Prospects

6.1 Challenges

Although the challenges are not limited, the study takes a focused approach to identifying the key obstacles essential for the future success of 3D food printing technology. The challenges associated to 3D food printing technology include:

6.1.1 Ingredients and Material Safety

A very crucial limitation of 3D food printers is that limited number of ingredients are compatible for 3D food printing. Thus, food choices are extremely limited when it comes to 3D food printing technology. 3D printers involve usage of edible food-safe materials like food grade plastics, edible gels, and pastes. According to Jaiswal and Wanjare (2024), it is important to ensure safety and quality of these materials to avoid leaching of chemicals and cross contamination leading to allergen transfer or microbial contamination.

6.1.2 Overall Cost

The modern technology offers a viable option in terms of automation and innovation, while one of the biggest challenges is the cost. The 3D food printers and their maintenance involve a huge amount of monetary investment which makes the path forward a huge challenge. However, according to Lee (2021), the production costs for 3D printed foods can be brought down by developing cost friendly alternatives for raw materials or ingredients, modifying the ingredients to simplify the design of 3D printers and designing efficient parts for manufacturing can lower production costs. (Claus, 2022)

6.1.3 Designing of Customize Foods

The 3D printer can create various shapes, structures, and varieties of foods. But some of the complex foods do require human interference because the understanding of compatibility of cooking process with the printers is crucial (Kamble, 2022). Food printers should not only print various shapes but also work on the texture of the food products (Nachal et al., 2019).

6.1.4 Training and Education

3D food printers are complex equipment which require proper handling, training sessions, and expertise. The solution to this challenge requires one of two approaches: Hire an engineer or someone with technical expertise to operate the instrument or train an individual to operate the machine efficiently. Both the approaches involve spending extra money and immense number of hours (Das, 2021).

6.1.5 Cleaning, Hygiene and Safety Aspects

The 3D printers are a system consisting of complex arrangement of components, sensors, and nozzle system. The leftover food materials remaining in these components are often difficult to clean and serve as a source for microbial growth (Jaiswal & Wanjare, 2024). According to Attaran and Attaran (2020), the temperature changes occurring in food during extrusion process in the 3D food printer can make the food susceptible to microbial growth. Thus, it can also be an upstream challenge for the 3D food printing technology to overcome in future.

6.2 Future Prospects

6.2.1 Customized Food Products

The rising trend of personalized food product creation that is customized according to consumers' needs and attributes in 3D food printing along with catered dietary needs is expected to revolutionize the food industry by offering unique dining experiences and tailored nutritional solutions (Eswaran et al, 2023; Xie et al., 2023).

6.2.2 Nutritional Control

3D food printing will provide an explicit control over the type of ingredients, amount of ingredients and the nutritional profile, The 3D food printing technology also allows the customization of food products according to health-specific considerations that aligns with the individuals' nutritional expectations. Thus, the technology is expected to hold the potential to conquer malnutrition and improve overall health and wellness (Mudau & Adebo, 2024; Waseem et al., 2024).

6.2.3 Diverse Food Ingredient Sources

3D food printing technology can broaden the spectrum of accessible food materials like pasta, cheese, chocolate, also including unconventional sources like high-fiber plant-based components, cultured meats, insects, and animal byproducts. This wide range of ingredients drives culinary innovation and encourages sustainable food production practices (Das, 2021; Jackson, 2024).

6.2.4 Market Growth and Innovation

The global 3D food printing market has displayed constant growth in the market with an average annual growth rate of 31.5% in the last three years (Lee, 2021). This is a consumer-friendly market in terms of uniqueness and food safety which drives the future of the 3D food printing technology market in food processing. As technology advances, the market is predicted to expand to 1.65 billion USD by the year 2030 (Zion Market Research, 2022).

6.2.5 Diverse Functions and Environmental Sustainability

The uses of 3D printing in the food business are growing, ranging from restaurants and liquid diets to battle and space foods. 3D food printing possesses the potential to provide significant contributions to address global food security issues and decrease the food wastes by embracing different food ingredient sources and sustainable manufacturing processes (Derossi et al., 2024, Waseem et al., 2024).

6.2.6 Transition into the New Normal Era

Following the COVID-19 pandemic, it is anticipated that the demand for tailored food solutions and non-contact production techniques would increase even further (Lee, 2021). With its capacity to provide creative, hygienic, and customized food products, 3D food printing is set to have a significant impact on how the food sector develops in the future (Attaran & Attaran, 2020).

7. Quality Evaluation of 3D Printed Foods

Some quality characterizations of the 3D printed foods are summarized in Table 5. Depending on the type of a 3D printed food, different quality parameters are evaluated.

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Derossi et al. (2021) studied the physical and textural properties of 3D printed cereal-based snacks. The physical and textural properties were the dependent variables of the products, and which were achieved by controlling the porosity fraction during 3D food printing. The properties measured for the cereal-based snack foods included loss in weight of sample, water activity and the moisture content of prepared products. Quality evaluation of 3D printed confectioneries (i.e. cookies) includes assessing parameters like color, shape retention and texture. Moisture content was analyzed using a gravimetric method. The water activity of the products was measured using a dewpoint system with an Aqualab water activity meter. The colorimetric values were determined using a colorimeter. The texture analyzer is used to determine the textural properties such as hardness, springiness, cohesiveness, gumminess and chewiness of the 3D printed foods. Sensory properties such as color/appearance, texture. flavor, taste, overall acceptability and etc. of 3D printed foods are commonly determined using a 9-point hedonic scale (from 1= extremely dislike to 9= extremely).

Table 5. Effect of raw materials/food types on the quality of the 3D printed foods

3D printed food products	Evaluated quality parameters	Effect on quality	Reference
Cereal-based snacks	Moisture content, water activity, color (L, a and b values), internal pores and morphology	Significant change in dimensional and microstructural.	Derossi et al., 2018
Mashed potatoes	Moisture content, rheological properties, NMR analysis.	Impact on shape retention, extrusion behavior and viscosity.	Liu et al., 2018a
Egg yolk and egg white blended with rice flour	Flow behavior, texture, viscosity, water activity, color and printability of material supply.	The egg yolk and egg white were not printable. However, the addition of rice flour blend improved the printability. Also, this significantly improved stability and strength of printed egg yolk and egg white.	Anukiruthika et al., 2020

Food based on milk protein (enriched with whey protein isolate)	Rheological properties, texture analysis, water distribution, existing form of protein particles in pastes.	Significant impact on hardness and adhesiveness of foods.	Liu et al., 2018b
Cookies	Water distribution, texture, rheological properties, size parameters, fat and protein distribution.	Impaction on retention of shape, consistency in shape and textural properties of cookies	Yang et al., 2018
Processed cheese	Texture, melting properties, cheese microstructure and color analysis.	Showed higher melting behavior and less hardness.	Le Tohic et al., 2018
Plant-based meat analogues	Texture, microstructure, printing performance, rheological properties, and moisture distribution.	The choice of raw materials (i.e., rice protein, soy protein isolates and wheat gluten) had a crucial effect on viscoelastic properties, textural properties and printability of meat analogues.	Qiu et al., 2023

Although quality assessment is crucial for 3D food printing, examining the effects of individual ingredients or raw materials enhances our understanding of the process. For instance, specific rheological properties of these ingredients are essential for 3D printing and play a key role in achieving the desired texture of the printed foods (Thangalakshmi et al., 2021; Qiu et al., 2023). Liu et al. (2019) identifies three key stages where 3D printing of food is linked to the rheological properties: (i) extruding of raw materials/food through nozzles: (ii) the recovery phase involving temperature and shear recovery; and (iii) self-supporting phase related to yielding stress at room temperature. Thus, it is important to determine how different ingredients impact the physiochemical, textural and sensory characteristics of 3D printed foods.

8. Conclusion

As 3D printing has evolved a lot in the past decade, it has contributed to innovative methods of developing food with a minimum human contact as well as aiding people receiving specialized foods. This review has explored the evolution of 3D printers, the mechanism that

3D printers follow, market analysis of 3D food printers for guiding the readers to choose the best available printers for their specific aim. The review intensively examines the constituents employed in various 3D printed edible foods. In this process, a wide range of food ingredients was selected and tested for achieving targeted texture, taste, and nutritional compositions of 3D printed foods. Though the future looks bright, several obstacles still need to be overcome, including governmental barriers, customer acceptance, and technology constraints. 3D food printing is leading food science research and can transform multiple industries. It is expected that advancing technology can be essential in addressing global food issues, enhancing food security and sparking innovative cooking techniques.

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