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Advancing sustainable future food systems: The potential of edible 3D food printing

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Abstract

This review paper provides an in-depth analysis of 3D food printing technology, exploring its various applications and implications in the new normal era. The paper begins by introducing the concept of 3D printing technology and its associated devices, setting the foundation for understanding the subsequent sections. The categorization of 3D food printing techniques is presented, covering extrusion-based printing, inkjet printing (IJP), binder jetting, and hot air sintering. Each technique is described in detail, highlighting their unique characteristics and capabilities.

The principle and techniques of 3D food printing are explored, shedding light on the underlying mechanisms and methodologies employed in this emerging field. Emphasis is placed on the significance of ingredient selection for successful 3D food printing, as the choice of materials plays a crucial role in achieving desired outcomes such as taste, texture, and nutritional value.

Furthermore, the review paper delves into the applications of 3D food printing, examining its utilization in both small and large-scale food production settings. The potential of this technology to revolutionize the food industry by enabling customized, on-demand production is discussed, along with the associated benefits and challenges.

Lastly, the paper explores the role of 3D food printing technology in the new normal era, wherein adaptability and resilience have become paramount. It examines how this technology can cater to the changing needs and preferences of consumers, addressing factors such as personalized nutrition, dietary restrictions, and sustainable practices.

Overall, this review paper presents a comprehensive overview of 3D food printing technology, encompassing its various techniques, applications, and implications for the new normal era. It highlights the potential of this innovative technology to shape the future of food production and consumption, paving the way for a more efficient, customizable, and sustainable food industry.

Keywords: 3D food printing, additive manufacturing, ingredient selection, customization, sustainability

Introduction

In recent years, the field of 3D printing has experienced remarkable advancements, leading to transformative changes in various industries (Mahmood *et al*., 2022) [61]. One area that has particularly captured attention is 3D food printing, which has the potential to revolutionize how we produce and consume food (Granheim *et al*., 2022) [34]. This review paper aims to present a comprehensive overview of the evolution, categorization, principles, techniques, and applications of 3D food printing technology.

By examining the historical development and current state of 3D food printing, we will gain a deeper understanding of its progression and the different categories within this field. The underlying principles behind this innovative technology will be explored, providing insights into the fundamental concepts that enable the creation of edible structures and designs (Shahrubudin *et al*., 2019) [84].

Furthermore, this review paper will delve into the various techniques employed in 3D food printing, highlighting the diverse methods and materials used to fabricate food products (Jiang *et al*., 2019) [41]. By analyzing the applications of this technology across different sectors such as personalized nutrition, culinary arts, and food manufacturing, we can assess its potential impact on food production and consumption patterns (Espera *et al*., 2019) [29].

Moreover, an essential aspect of 3D food printing lies in the selection and utilization of ingredients. This review paper will emphasize the significance of ingredient selection in achieving desired texture, taste, and nutritional properties in 3D-printed foods. By exploring different ingredients and their compatibility with the printing process, we can uncover strategies to optimize the quality and sensory attributes of 3D-printed food products (Lin *et al*., 2020) [57].

Finally, this paper will also address the relevance of 3D food printing in the context of the "New Normal" era, where factors like sustainability, personalization, and convenience have gained significant importance (Baiano, 2022) [11]. By recognizing the potential of this technology to address these emerging needs, we can envision its pivotal role in shaping the culinary landscape of the future.

Overall, through a comprehensive examination of the evolution, categorization, principles, techniques, applications, and potential of 3D food printing technology, this review paper aims to provide valuable insights for researchers, professionals, and enthusiasts alike. The exploration of ingredient selection, coupled with an understanding of the technology's impact on various food production scenarios, will shed light on the transformative potential of 3D food printing in the culinary landscape of the future.

3D printing technology and 3D printing devices

3D printing (3DP) technology and devices have witnessed remarkable advancements and innovation, particularly in the field of food science. The foundation of 3DP, also known as additive manufacturing, lies in stereolithography (SLA/SL) technology (Tomašević *et al*., 2021) [96]. SLA/SL involves the photo polymerization of a liquid resin, achieved by exposing the resin to a light source. This process triggers a chemical reaction that converts the liquid resin into a solid layer, resulting in the formation of a highly crosslinked polymer (Venuvinod and Ma, 2004) [99]. Currently, there are four primary additive manufacturing techniques employed in 3DP of food products, both for commercial applications and research purposes. These techniques include extrusion printing, selective sintering, binder jetting, and inkjet printing (Ligon *et al*., 2017; Vithani *et al*., 2019) [56, 100]. In extrusion printing, soft materials are progressively extruded through a nozzle in layers to construct a three-dimensional object (Jin *et al*., 2016; Garland and Fadel, 2015) [42, 30]. Selective sintering involves the application of powdered materials in thin layers, which are selectively heated to enable the fusion of sugars or fats present in the powders, thereby forming three-dimensional layers within the objects (Godoi *et al*., 2016) [32]. Similarly, binder jetting employs liquid binders dispensed through thin nozzles to bind powdered materials together [Bae *et al*., 2023]. Lastly, inkjet printing employs low viscosity materials dispensed as a stream of droplets to fill the desired layout of an object (De Gans *et al*., 2004) [21].

Among the aforementioned techniques, extrusion printing is particularly well-suited for functional food production due to several reasons (Ramachandraiah, 2021) [75]. Firstly, it allows for the printing of various soft materials with diverse rheological properties. Secondly, it is a well-established technology widely used in other fields, such as food engineering, making it easier to adapt different technical solutions or entire machines for food production, especially in research settings (Paxton *et al*., 2017) [71]. Moreover, the printing parameters of most extrusion-based devices can be readily adjusted, often using open-source software (Bonatti *et al*., 2021) [14]. This flexibility is crucial since previous studies have demonstrated the impact of different printing techniques and setups on the nutritional properties of printed food products (Weller *et al*., 2015) [103]. For instance, a study revealed the influence of nozzle diameter and printing temperature on the viability of probiotics in mashed potatoes (Singh *et al*., 2022) [85]. Similarly, another study investigated the influence of the surface-to-volume ratio of the printed structure on the viability of probiotics, concluding that combining 3D printing and baking could enhance probiotic survival in final products (Yoha *et al*., 2021) [110]. Additionally, extrusion-based printers are the most prevalent types of food printers available commercially, encompassing both professional and consumer markets. It is worth noting that the literature also encompasses homemade 3D printers (Malik *et al*., 2022) [62].

While most 3D printers can handle a range of pastes, specialized food-specific devices for substances like chocolate and pancake batter have also been developed (Attarin and Attaran, 2020) [6]. Additionally, a majority of printers feature syringe mechanisms with limited raw material capacity, often requiring refilling (e.g., capsules with a total capacity of 100 mL). Roughly half of the printers are equipped to heat their raw materials to temperatures ranging from 60-100 °C, either in the tanks or on a build plate (Smith *et al*., 2018) [86]. However, multi-material printing within a single build remains limited, especially when it comes to using different types of food or colors, with only a handful of printers possessing such capability. An intriguing design example is the FoodiniTM, which incorporates five interchangeable supply tanks for multi-material printing (Bandyopadhyay and Heer, 2018) [12]. Furthermore, most 3D printers have relatively compact dimensions (around 200 mm for the X/Y-axis and 100 mm for the Z-axis). Some printers employ various nozzle diameters to accommodate a broader range of raw materials while ensuring improved speed and precision. Commercial 3D printers typically fall within the price range of 300–5000 Euros (Joshi *et al*., 2020) [43].

Market research has identified key characteristics that would ideally be present in 3D printers for functional food production. (Weller *et al*., 2015) [103]. These characteristics include: (1) ease of cleaning and refilling, facilitating the use of different raw materials; (2) the ability to utilize self-produced ingredients and fine-tune printing parameters; (3) minimized printing time in terms of duration; (4) interchangeable nozzles with different diameters for versatile material usage and optimization; (5) thermally controlled tanks with high capacity and a build plate allowing simultaneous cooking and printing; and lastly, although not critical, (6) the ability for multi-material printing, enabling superior food design with consideration for nutritional value, taste, and aesthetics (Azam *et al*., 2018) [9].

In a study on applied extrusion at room temperature to print lemon juice gel using the extruder conveying screw, study explored the use of extrusion as a method for 3D printing lemon juice gel (Yang *et al*., 2018) [109]. After that, another study also conducted the experiment via the similar system to print fish surimi gel. The results shown that the nozzle diameter, the nozzle movement speed and the extrusion rate affect the quality of 3D food printing, excluding the nozzle height. To print solid stating material (Dick *et al*., 2021) [22]. In a study investigated on melting extrusion for printing complex chocolate model based on machine design, including mechanism design. The results shown that there are two important areas of design in which designing the extruder assembly to be as rigid as possible, thereby reducing flexion and enabling more accurate deposition of chocolate and improving the design of active cooling system to quench the chocolate at lower temperatures (Lanaro *et al*., 2017) [51].

Categorization of 3D Food Printing Technique

The 3D food printing technique can be categorized into three main categories: extrusion-based printing, inkjet printing (IJP), and binder jetting.

Extrusion-Based Printing

Extrusion-based printing involves the construction of food models by extruding food material through a nozzle under constant pressure (Sun *et al*., 2018) [88]. This technique is similar to conventional Fused Deposition Modeling (FDM), but the starting material for extrusion-based printing can be either solid or soft paste with low viscosity, whereas FDM typically uses wire as the starting material (Krueger *et al*., 2022) [50]. In this process, the material is loaded into an extruder cylinder and then extruded through a nozzle using ram pressure to create the desired food shape layer-by-layer. Examples of foods fabricated using this technique include dough, meat paste, and cheese (Godoi *et al*., 2016) [32]. In a study, experiments with sugar cookies found that variations in ingredient concentration, such as the ratio of butter, yolk, and sugar, influenced the fabrication of the food model. To simplify the model fabrication process, transglutaminase and bacon fat were added (Kelly, 2019) [49].

Inkjet Printing (IJP)

Inkjet printing involves the dispensing of a stream of droplets from a thermal head onto specific regions of food surfaces for surface filling or decoration, such as on cookies, cakes, and pizzas (Manaf and Yusof, 2021) [63]. This process generally uses either thermal or piezoelectric heads. In a thermal inkjet printer, the print head is electrically heated to generate pulses of pressure that push droplets out of the nozzle (Wijshoff, 2010) [104]. There are two types of inkjet printing methods: continuous jet printing and drop-on-demand printing. In continuous jet printing, ink is continuously ejected through a piezoelectric crystal by vibrating it at a constant frequency. Some conductive agents may be added to achieve the desired flow properties of the ink (Zettl *et al*., 2023) [112]. In drop-on-demand printing, a valve controls the ink to be ejected from the heads under specific pressure. Drop-on-demand systems generally have slower printing rates compared to continuous jet systems, but they offer higher resolution and precision in the produced images (Tam *et al*., 2021) [91]. Inkjet printers are typically used with low viscosity materials and are not suitable for constructing complex food structures. Commonly deposited materials include chocolate, liquid dough, sugar icing, meat paste, cheese, jams, gels, and others (Gunjal *et al*., 2022; Kaur *et al*., 2022) [35, 46].

Binder Jetting

Binder jetting is an additive manufacturing technology that constructs models by selectively bonding layers of powders using a binder (Bourell and Wohlers, 2020) [15]. In this process, small droplets of binder, with diameters less than 100 μm, are sequentially deposited onto the surface of the powder bed using a drop-on-demand print head with a raster scanning pattern (Oropeza *et al*., 2022) [69]. After the liquid binder is deposited, the entire surface of the powder bed is exposed to a controlled amount of heat, often using a heat lamp, to partially cure the binder and establish sufficient mechanical strength within the generated layer (Mostafaei *et al*., 2021) [68]. This strength allows the layer to withstand shear and gravitational compressive forces during the spreading and printing of subsequent layers. These steps are repeated for each layer until the complete feature is achieved (Romberg *et al*., 2022). The successful fabrication of parts using binder jetting relies on the properties of the powdered material and binder. The binder should have suitable low viscosity, surface tension, and ink density to prevent spreading from the nozzles (Charoo et a., 2023) [17]. A study demonstrated the use of food-grade inks with suitable properties for successful inkjet printing in a Fujifilm Dimatix printer. The researchers aimed to develop inks that met the specific requirements of the inkjet printing process while ensuring their safety for food applications (Jiang *et al*., 2019) [41].

Hot Air Sintering

Selective laser sintering (SLS) and hot air sintering (HAS) are rapid 3D printing processes that primarily utilize powdered materials (Kafle *et al*., 2021) [44]. In SLS and HAS, a 3D model is created using 3D software, and an infrared laser or hot air beam is directed to a scanner. The laser or hot air beam is then reflected onto a bed containing the powdered material, selectively fusing the particles and constructing a solid structure layer by layer (Barszcz *et al*., 2021) [13]. The scanning motion of the laser or hot air beam is determined by the 3D digital description provided by the software. After each layer is scanned, the powder bed is lowered by one layer thickness, and a new layer of powder is applied on top. This process is repeated until the entire 3D object is completed (Zheng *et al*., 2023) [115].

SLS allows for the construction of multiple layers, each containing different food substrates. In some cases, single-component powder SLS machines are used, where the laser only melts the outer surface of the particles, resulting in surface melting (Awad *et al*., 2021) [8]. The non-melted cores of the particles fuse together and with the previous layer to create a 3D object. HAS, on the other hand, uses a low-velocity stream of hot air to selectively fuse the powdered layers. The hot air beam moves in an alternating motion along the X and Y axes on top of the powder bed. Unsintered powder can be reused in the process (Mantihal, 2019) [65].

SLS has been successfully used to fabricate complex 3D structures using sugar or sugar-rich powders. However, these methods are limited to powder-based materials. The main advantages of SLS and HAS are their ability to sinterize various powdered materials and their faster printing speed compared to other methods. These methods also require minimal post-processing and support structures. However, they are not suitable for printing fresh food ingredients, and additional steps such as removing excess powder are necessary after the sintering process (Liu and Zhang, 2019) [59].

Principle & Techniques of 3D Food Printing

The technical term used for a process of '3D printing' or 'rapid prototyping' is 'Additive Manufacturing' (AM). It is defined as the process of "binding materials to create objects using 3D model data, layer by layer" (Haleem and Javaid, 2020) [36]. The principle of 3D food printing is solid free-form (SFF) method. On the basis of 2 dimensional shapes, the SFF method formed a three-dimensional print with controllable silhouette by assembling Computer Assisted Manufacturing (CAM) and Computer Aided Design (CAD) (Lee *et al*., 2010) [116]. This method consists of Stereo lithography Lasing (SL), Fused Deposition Modelling (FDM) and Selective Laser

Sintering (SLR) (Xie, 2023) [106]. The main method used in 3D food printing is Fused Deposition Modelling (FDM). This is used for printing a variety of foods, including molten state in liquid form such as chocolate, sugars etc. (Kaur *et al*., 2022) [46]. In preparation of purees, doughs and gels no structuring agent is required. They are directly deposited on the surface. To support the structures of the purees, doughs and gels, structuring hydrocolloids are used as the deposited material (Agunbiade *et al*., 2022) [3]. To build 3D structures, various kinds of layer deposition are used, including Stereolithography Apparatus (SLA), Selecting Laser Sintering (SLS), Powder Binder Printing (PBP), Fused Deposition Modeling (FDM) and Three-Dimensional Printing and Gluing (Sathies *et al*., 2020) [79]. Arduino IDE and Repetier-Host are the computer software which are used to control the system that prints the articles as per the 3D drawings because of the printer's great accuracy and resolution, printed models are of fine quality (Sandoval-Rodriguez *et al*., 2021) [78]. According to the specificity of the product, the 3D food printing technology requires suitable materials or ingredients as ink and printers (Escalante-Aburto *et al*., 2021) [28]. 3D food printers are not the same as regular printers. They use a variety of things as ink, including architectural materials and food items (Attarin and Attaran, 2020) [6]. The most basic component of a food printer is a syringe (syringe's one end is connected to an electric engine and another end is connected to one or two nozzles), plastic clips (that fix the nozzle in place). To mix and keep all of the materials, several barrels or reservoirs are required (Dávila *et al*., 2022) [20]. To deliver the ingredients, syringes or nozzles are used. The electric motor is used to push or extrude the ingredients from the syringe, and the system is acknowledged as an extruder (Seoane-Viaño *et al*., 2021) [83]. The printer can be outfitted with multiple extruders. Dual-feed extruder can also be used which pushes two seperate ingredients of different colours from the syringe to create a variant colour by altering the ingredients mixing ratio. 'Builder' (a Holland manufacturer) developed this food printer with colour mixing and dual-feed extrusion (Song and Paulos, 2021) [87]. The components are deposited one layer over another on the planar heating platform, which also cooks the raw material. On the basis of the fabrication, the 3D printers are categorized into four categories, including triangle-structure printers, triangle-clawstructure printers, rectangle-cassette-structure printers and rectangle pole-structure printers (Wang *et al*., 2021) [102]. Triangle and rectangle–cassette structure printers are the utmost popular among all in the market due to their best performance. Triangle shape printers are simple in structure, convenient in maintenance and have low cost. They have poor design and low accuracy whereas rectangle – cassette shape printers have higher accuracy and good designs. But they have complicated installations and are expensive (Agunbiade *et al*., 2022) [3]. The general components of 3D printers are the frame, control circuit, mechanical seals and the motor. The control circuit is the very important component of the 3D printer. Basically, it controls the printer's operation and serves as a bridge between the machine and the computer (Audibert *et al*., 2022) [7].

Importance of ingredient selection for 3D Food Printing

The careful selection of edible ingredients for 3D food printing involves considering their properties and suitability for the printing process. The raw materials utilized in 3D food printing should be in a state that allows them to be easily printed, whether it is a liquid or solid powder form, and should possess flowing properties (Tejada-Ortigoza and Cuan-Urquizo, 2022) [93]. Additionally, these materials should have the capability to undergo heat-induced plasticization or melting. This is necessary to ensure that the ingredients maintain their desired flowing properties throughout the printing process (Tambe *et al*., 2021) [92]. Basic ingredients suitable for 3D food printers should exhibit plasticity, adhesion, and the ability to maintain their shape. These properties enable easy extrusion and stacking without collapsing. Examples of such basic ingredients include wheat, rice, corn powder, as well as sugars such as chocolate and sugar. These ingredients are commonly used in various food preparations and can be heated to achieve a desired viscosity while retaining their shape over an extended period of time (Maniglia *et al*., 2020) [64].

The food materials utilized as "food ink" in 3D food printers must possess the ability to flow through the printer nozzle and solidify or set after being deposited onto the printing surface. To achieve the desired printing outcomes, the viscosity and taste of these food materials can be carefully controlled (Gholamipour-Shirazi *et al*., 2019) [31].

In addition, a range of additives can be introduced to the basic ingredients to enhance their physical properties and enrich their nutritional value. These additives can be categorized into carbohydrates, proteins, fats, and food viscosity agents, each serving a specific purpose. The carbohydrates category includes substances such as starches (e.g., agar, gelatin, flour, potato starch, rice starch), sugar substitutes (e.g., maltitol, xylitol, isomaltose), and others. Proteins, such as petty, surimi, edible insects, bean protein, pectin, pea protein, whey protein, and egg protein, offer functional and nutritional benefits (Singh *et al*., 2022) [85]. Fats, such as butter, margarine, and cooking oil, can be utilized to enhance taste and improve the texture of the printed food. Food viscosity agents, including gums (e.g., gum arabic, carboxymethyl cellulose), carnauba wax, and shellac, are employed to improve stability and viscosity (Scheele *et al*., 2023) [81]. By carefully selecting and incorporating these additives, the properties and characteristics of the food materials used in 3D food printers can be modified, resulting in enhanced printing performance and customized food products (Jagadiswaran *et al*., 2021) [39]. Carbohydrates serve as additives in 3D food printing and include agar, gelatin, flour, potato starch, rice starch, maltitol/xylitol, and isomaltose. These carbohydrates offer specific functionalities and characteristics in the printing process. Agar, when subjected to high temperatures, easily melts and forms a gel-like structure, providing stability to the printed food (Zhang *et al*., 2022) [113]. Gelatin, on the other hand, has the ability to form a gel when combined with water and heated during the cooking process. Rice starch, distinct from potato or wheat flour, exhibits a less viscous nature but contributes to a crispy texture when cooked. It imparts unique sensory attributes to the printed food. Maltitol and xylitol are utilized as alternatives to sucrose, particularly in high-calorie chocolate products, aiming to reduce the overall calorie content. These sugar substitutes offer similar sweetening properties while addressing concerns related to obesity and calorie intake. Isomaltose, another carbohydrate additive, plays a role in preventing the formation of a rigid network structure. By reducing contraction, it helps maintain the desired shape and structure of the printed food, contributing to overall quality and appearance. Proteins, including patty, surimi, edible insects, bean protein, pectin, pea protein, whey protein, and egg protein, can serve as valuable additives in 3D food printing, offering a range of functional and nutritional properties (Zhou, 2023) [47]. Patty, when incorporated into the printing mixture, enhances adhesion, particularly when combined with mashed meat and starch-like substances. This improved adhesion contributes to the structural integrity of the printed food (Tibrewal *et al*., 2022) [95]. Surimi, known for its texture and versatility, easily blends with starch, enabling smooth and consistent mixing within the printing process (Dong *et al*., 2019) [24]. Edible insects are gaining attention as an alternative protein source with notable environmental benefits. Their inclusion in 3D food printing formulations expands the range of sustainable options available (Liceaga, 2022) [55]. Bean protein, derived from beans, offers significant nutritional value, particularly in vegan diets. It provides a plant-based protein source that can be incorporated into printed food products (Vatansever *et al*., 2020) [98]. Pectin, a polysaccharide found in various fruits, exhibits gelling properties and can be used to produce gel-like food simulants within the printing process, expanding the range of textures achievable (Zhang *et al*., 2022) [113]. Pea protein and whey protein have been specifically studied for their effects on 3D printing performance. These proteins contribute to the functional properties of the printed food and have implications for texture, structure, and overall printing outcomes (Liu *et al*., 2022) [60]. Egg protein, derived from eggs, offers unique properties in terms of structure, binding, and nutritional content. Its incorporation can provide desirable attributes in 3D printed foods (Wilson *et al*., 2020) [105]. By leveraging the diverse properties of these protein additives, 3D food printing can create products with enhanced functionality and nutritional profiles, catering to various dietary preferences and requirements (Xie *et al*., 2023) [106]. Fats, including butter, margarine, and cooking oil, can be employed as additives in 3D food printing to enhance taste and texture. Butter, known for its rich flavor, not only contributes to the taste but also contains vitamins that can enrich the nutritional profile of the printed food. It is often considered a healthier option compared to margarine, which can potentially contain trans fats that are less desirable for health (Yu *et al*., 2023) [111]. Margarine, while used as a substitute for butter in some cases, may have higher levels of trans fats, which can have negative health implications when consumed in excess. Care should be taken to select margarines that are trans fat-free or have lower levels of trans fats (Pipoyan *et al*., 2021) [71]. Cooking oil, another fat additive, serves to smooth the dough and facilitate the lamination process during 3D food printing. Its inclusion can improve the workability and pliability of the printing material (Masbernat *et al*., 2021) [67]. By incorporating these fats as additives, 3D printed food products can attain enhanced taste, texture, and overall sensory appeal. However, it is important to consider the specific properties and health implications associated with different fat sources, making informed choices in their selection and usage (Scheele *et al*., 2023) [81]. Food viscosity agents play a crucial role in 3D food printing by enhancing the stability and viscosity of the basic ingredients. Several commonly used viscosity agents include gum arabic, xanthan gum, kappa carrageenan, carnauba wax, shellac, and carboxymethyl cellulose (CMC).Gum arabic and xanthan gum are widely utilized as food stabilizers, contributing to improved stability and viscosity in the printing process (Cheng *et al*., 2022) [19]. They help maintain the desired texture and structure of the printed food. Kappa carrageenan, another common food stabilizer, assists in achieving the desired viscosity and gelation properties in the printed food (Thakur *et al*., 2023) [94]. Carnauba wax, known for its natural properties, is employed as a coating agent, enhancing the appearance and texture of the printed food. It provides a glossy finish and helps protect the printed surface (Amin *et al*., 2021) [5]. Shellac, typically associated with furniture finishing, is also used as a food-grade product. In 3D food printing, it aids in enhancing stability and viscosity, contributing to the overall quality of the printed food (Cerqueira *et al*., 2022) [16]. CMC, or carboxymethyl cellulose, is an edible substance that serves as an effective viscosity agent. It enhances the emulsifying properties and stickiness of the ingredients, allowing for better control of the flow and consistency during the printing process (Keller, 2020) [48]. By incorporating these food viscosity agents, the stability, viscosity, and overall printing performance of the basic ingredients can be improved, leading to high-quality and well-structured 3D printed food products (Leontiou *et al*., 2023) [53]. In addition to the previously mentioned ingredients, vegetables and fruits can serve as valuable basic ingredients in 3D food printing, offering essential minerals and vitamins. These ingredients can be processed and homogenized to be used in both solid and liquid forms, providing flexibility in terms of form and taste based on the desired mixing ratio and injection process (Xie *et al*., 2023) [106]. Vegetables, such as leafy greens, root vegetables, and cruciferous vegetables, are excellent sources of various vitamins, including vitamin C, vitamin K, and folate. They also provide essential minerals like potassium and magnesium, contributing to the nutritional content of the printed food (Pant *et al*., 2021) [70]. Fruits, with their vibrant colors and natural sweetness, offer a wide range of vitamins, including vitamin C, vitamin A, and several B vitamins (Prakash *et al*., 2019) [74]. They are also rich in minerals like potassium and fiber, adding both nutritional value and flavor diversity to the printed food. By incorporating vegetables and fruits as basic ingredients, 3D printed food products can benefit from their nutritional properties, offering a balanced and wholesome eating experience. The versatility of these ingredients allows for customization and experimentation, enabling the creation of unique and nutritious food items using 3D food printing technology (Waghmare *et al*., 2022) [101].

In conclusion, the selection of ingredients plays a crucial role in the success of 3D food printing. Careful consideration of their properties, suitability for the printing process, and ability to maintain desired flowing properties is essential. Basic ingredients such as wheat, rice, corn powder, chocolate, and sugar provide plasticity, adhesion, and shape retention, enabling easy extrusion and stacking. "Food ink" materials should flow through the printer nozzle and solidify or set after deposition, with viscosity and taste carefully controlled. Additives, including carbohydrates, proteins, fats, and food viscosity agents, can enhance physical properties and nutritional value. Carbohydrates like agar, gelatin, flour, potato starch, rice starch, maltitol, and isomaltose offer specific functionalities and characteristics. Proteins, such as patty, surimi, edible insects, bean protein, pectin, pea protein, whey protein, and egg protein, contribute functional and nutritional benefits. Fats like butter, margarine, and cooking oil enhance taste and texture. Food viscosity agents, such as gum arabic, xanthan gum, kappa carrageenan, carnauba wax, shellac, and carboxymethyl cellulose, improve stability and viscosity. Incorporating vegetables and fruits provides essential minerals, vitamins, and flavor diversity. By carefully selecting and incorporating these ingredients and additives, 3D food printing can create customized, nutritious, and visually appealing food products. The versatility and potential for innovation in ingredient selection contribute to the continuous development of this technology, opening up new possibilities in the realm of food creation.

Application of 3D food printing

In small scale food production

The application of 3D printing (3DP) in small-scale food production, such as restaurants, cafés, and bakeries, offers several advantages (Leontiou *et al*., 2023) [53]. One significant benefit is the ability to customize unique products and enhance the artistic presentation of food. The studies have showed, 3D printing, it becomes possible to create precise and intricate designs, enabling the development of gourmet-style food presentations (Mantihal, 2019) [65]. This technology empowers operators in the food industry to design edible foods with distinct patterns that cater to individual tastes and preferences (Kauppi *et al*., 2019) [45]. The customization options are vast, allowing for personalized and visually appealing food creations. In addition to aesthetics, 3D food printing allows for the exploration of texture and flavor combinations through layered manufacturing techniques. This opens up opportunities to produce unique food products that offer a delightful sensory experience (Escalante-Aburto *et al*., 2021) [28].

Small cafés and bakeries can leverage 3D printing to decorate food items like biscuits and cakes, adding a touch of creativity and reducing labor costs (Talens *et al*., 2021) [90]. By automating certain aspects of food decoration, businesses can streamline their processes and achieve consistent and intricate designs (Satwekar *et al*., 2023) [80]. To make the utilization of 3D printing technology in small-scale food production profitable, larger quantities of food and a food printer with a larger reservoir become essential (Addanki *et al*., 2022) [1]. Efforts are underway to develop larger reservoirs that are easy to refill, allowing for more efficient production and greater output. For example, Porimy's Chocolate Product 3D printer operates automatically, requiring users only to load the food material and customize the food design through 3D software. Such advancements simplify the process and make it more accessible to small-scale food producers (Mantihal *et al*., 2020) [66].

In summary, 3D printing offers tremendous potential for small cafés, restaurants, and bakeries in terms of customization, artistic presentation, and cost reduction. As technology continues to advance, it is expected that 3D printing will play an increasingly significant role in enhancing the culinary experience and expanding the possibilities for food production in the small-scale food industry.

In large scale food production

Adoption of 3D printing (3DP) at an industrial scale presents certain challenges. To achieve mass production and economies of scale, a 3D food printer must be capable of handling larger capacities and producing food items within a shorter timeframe (Hossain *et al*., 2020) [38].

Further research and development are necessary to address these challenges. One area of focus is the development of industrial-scale 3D food printers that can accommodate the higher production volumes required in an industrial setting (Jayaprakash *et al*., 2020) [40]. These printers would need to be designed with larger capacities, faster printing speeds, and enhanced durability to withstand continuous operation (Economidou *et al*., 2020) [26]. In addition to the hardware aspects, it is crucial to study and optimize the quality of food products manufactured through large-scale 3D printing. This involves understanding the properties of food materials suitable for such printing processes (Mostafaei *et al*., 2021) [68]. Factors such as viscosity, flow behavior, and texture need to be carefully considered to ensure consistent and high-quality food output (Zhang *et al*., 2022) [113]. Research efforts should also explore the scalability of recipes and formulations to meet the demands of mass production. This includes investigating how ingredients and their ratios might need to be adjusted to maintain the desired taste, texture, and nutritional properties when producing food in larger quantities (Liu and Ciftci, 2021) [58]. Furthermore, the development of efficient post-processing techniques, such as cooling, curing, or finishing methods, may be required to ensure the timely and consistent production of high-quality food items at an industrial scale (Dizon *et al*., 2021) [23].

In summary, the successful adoption of 3D printing technology at an industrial scale requires not only the development of suitable large-scale 3D food printers but also a comprehensive understanding of food material properties and their impact on product quality. Further research and development are essential to address these challenges and unlock the full potential of 3D printing in large-scale food production.

3D Food Printing Technology for New Normal Era

During the COVID-19 pandemic, the importance of self-service has grown due to the need for physical distancing between customers and clerks. This has led to an increased demand for personalized 3D food printing services that cater to individual food designs, while non-contact production services have gained more attention (Varvara *et al*., 2021) [97]. One example is Blue Rhapsody, a spinoff that offers customized pasta made according to customers' preferences as an online product, allowing for electronic transaction services (Ramundo *et al*., 2020) [76]. The online market, which has become more active during the pandemic, is expanding the market share of innovative 3D printed foods. Similarly, Nourished, a British company, sells customized foods focusing on health, nutrition, and well-being through pre-packaged products and an online sales system (Ameta *et al*., 2022) [4].

In addition to the 3D food printing industry, the global market for fermented foods and health food ingredients is expected to grow significantly, reaching $875.21 billion by 2027, a 15.5-fold increase from $56.59 billion in 2019 (Hassoun *et al*., 2022) [37]. The preference for fermented foods is also increasing as personal healthcare gains recognition. It is crucial to develop fermented foods as processed foods to facilitate customer acceptance of new traditional foods (Tagliazucchi *et al*., 2019) [89]. Therefore, 3D food printing can be utilized to create a customized diet based on personal health by incorporating the value of fermented and malt foods. As a result, 3D printed foods with personalized health functional ingredients are also being applied to functional foods (Escalante-Aburto *et al*., 2021) [28].

NASA's space food development project aims to utilize 3D printing technology to develop pizza products with an extended shelf life of 30 years (Enfield *et al*., 2022) [27]. Various materials used in 3D printing technology, such as sugars, complex carbohydrates, and proteins, can be stored in powder form for extended periods, preserving their organic molecule units for more than 30 years (Portanguen *et al*., 2019) [73]. The Food Synthesizer, developed by Anjan Contractor, offers personalized nutrition tailored to individual situations, considering factors such as gender, age, race, vital signs, and specific medical conditions (Agrawal *et al*., 2022) [2]. Furthermore, it is anticipated that governments will be able to address the challenges of food waste reduction and hunger, which are becoming significant social issues (Chen *et al*., 2023) [18]. The food industry as a whole, including agriculture and fisheries, is expected to undergo a turning point in response to the global challenges posed by population growth (Gomez-Zavaglia *et al*., 2020) [33].

Overall, 3D food printing technology, combined with the market demand for personalized and healthy food options, holds great potential for addressing various societal and consumer needs, from self-service during pandemics to personalized nutrition and sustainable food production.

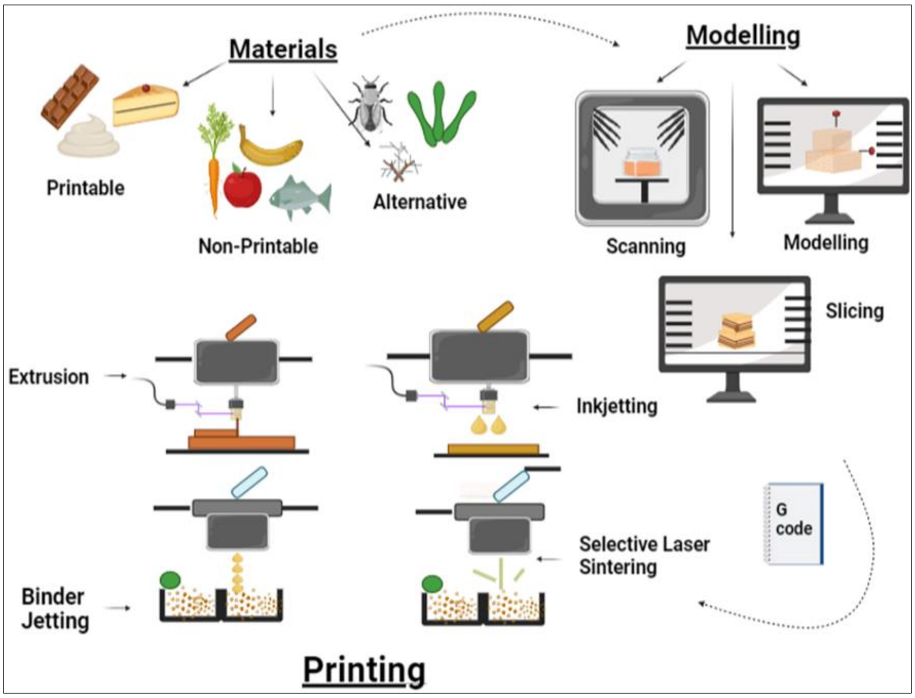

Fig 1: The process of material selection to 3D food printing

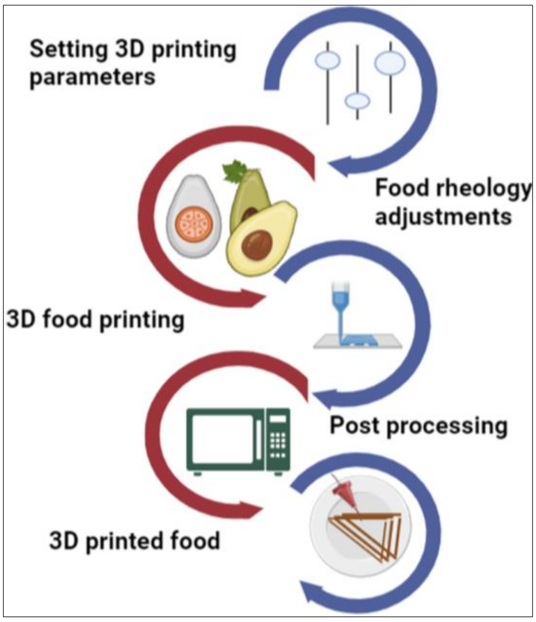

Fig 2: Schematic flow diagram of 3D food printing

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Conflict of interest

The authors declare that there are no conflicts of interest

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