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REVIEW OPEN ACCESS

The Future of Food Manufacturing: A Review on 3D Printing for Sustainable and Smart Food Systems

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Abstract

This review paper provides an in-depth analysis of the application of 3D printing in the food processing industry. Also referred to as additive manufacturing, this technology has revolutionized traditional production methods by enabling precise, layer-by-layer fabrication of complex structures using computer-aided design (CAD) models. In the food industry, 3D printing commonly known as food printing integrates digital gastronomy with additive manufacturing to produce customized food products that differ in shape, texture, taste, color, and nutritional profile. Unlike mass production techniques that emphasize uniformity, 3D food printing empowers personalization, on-demand food production, and sustainability. This review consolidates findings from multiple studies to highlight the principles of 3D food printing, materials suitable as food inks, industrial and domestic applications, benefits, limitations, and future prospects. Special emphasis is placed on the role of 3D printing in addressing global challenges such as malnutrition, food waste, and the growing demand for plant-based and alternative protein sources. Finally, this review also examines economic feasibility and consumer acceptance, concluding that 3D food printing is poised to transform food design, processing, and consumption in the coming decades.

Keywords: Food Manufacturing; 3D Printing; Sustainability; Food Systems; Food processing

Introduction

Three-dimensional (3D) printing, often referred to as additive manufacturing, has rapidly transitioned from its origins in industrial prototyping to become a transformative technology across diverse fields such as medicine, aerospace, and construction. In recent years, its integration into the food industry has attracted significant attention, giving rise to the term 3D food printing. Unlike conventional food processing methods that emphasize mass production and uniformity, 3D food printing allows for customization, personalization, and digital integration in food preparation. This capability represents a paradigm shift in how food can be designed, produced, and consumed. (Sun et al., 2015).

The growing consumer demand for individualized nutrition, convenience, and creative culinary experiences has accelerated interest in this technology. For example, elderly individuals who struggle with swallowing may benefit from softer, customized food textures, while athletes may require high-protein formulations designed to meet specific energy demands. Hospitals can potentially use 3D food printers to provide nutrient-enriched meals tailored to patients' recovery requirements. Similarly, food service industries, from restaurants to catering companies, are exploring the use of this technology to create visually appealing, innovative dishes that set them apart in competitive markets.

Technically, 3D food printing combines food science with engineering. The process begins with a digital blueprint designed using Computer-Aided Design (CAD) software. The model is then sliced into layers, and the printer deposits edible materials known as food inks in sequential patterns. Depending on the materials used, additional steps such as baking, frying, or drying may be necessary to complete the food product. The versatility of this process makes it possible to print foods with unique geometries, colors, textures, and even nutrient compositions. (Dankar et al., 2018).

Beyond its novelty, 3D food printing carries social and economic implications. On a small scale, it empowers chefs and home users to create artistic dishes with minimal waste. On an industrial scale, it has the potential to streamline supply chains, reduce food loss, and provide sustainable alternatives by incorporating underutilized ingredients such as insect proteins and algae. Furthermore, 3D printing is being investigated for space exploration, where traditional cooking is impossible. NASA has supported projects that examine how astronauts on long-duration missions can receive nutritious and appealing meals produced with 3D printers.

History of 3D Printing

The evolution of 3D printing in food processing is a fascinating journey that closely mirrors the broader advancements in additive manufacturing. The story begins in the 1980s, with Chuck Hull's invention of stereolithography, which laid the technical foundation for digital fabrication of complex shapes but was initially limited to industrial materials like plastics and resins. By the early 2000s, innovators began to adapt these technologies for edible materials, culminating in the Cornell University Fab@Home project in 2006, which enabled the printing of foods such as chocolate, cheese, and dough using multi-material extruders. This marked a pivotal shift, moving 3D printing from prototyping and manufacturing into the culinary realm.

Throughout the next decade, diverse companies and research teams refined methods for printing edible substances. Candy Fab pioneered large-scale sugar sculptures, while Choc Edge brought the first commercially available chocolate printer to market in 2012. Specialized applications emerged, including the PERFORMANCE project by biozoon GmbH, which produced easily chewable foods for seniors, and Modern Meadow's printing of in vitro meat with bioprinters, showcasing new possibilities for protein sources. Major food companies such as Hershey's partnered with 3D Systems to introduce chocolate printers for personalized, intricate candy pieces, and other manufacturers, like Barilla, experimented with pasta designs using 3D printing technology. As technical capabilities matured, 3D food printing branched into printing purees, pastes, and even plant-based meat analogs, reflecting societal trends toward personalization, sustainability, and health. Contemporary innovations such as FELIXprinters' dedicated food printer range, Revo Foods' supermarket debut of 3D printed salmon alternatives, and Cocoa Press's advanced chocolate printer have made 3D printed foods commercially accessible. The market now includes machines for professionals and consumers alike, allowing personalized nutrition, new textures, and reduced food waste. Ongoing scientific research explores more complex ingredients, printing processes, and applications, but challenges remain around scaling, cost, safety, and consumer acceptance. Thus, the history of 3D food printing demonstrates a dynamic interplay between technological innovation, culinary creativity, and evolving consumer needs, shaping a new frontier in food production.

Principles of 3D printing

3D printing, also known as additive manufacturing, is a revolutionary technology that enables the creation of three-dimensional objects from digital models by successively adding material layer by layer.

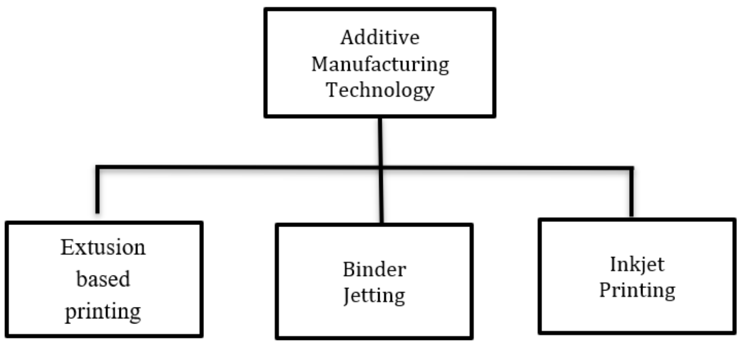

Fig. 1. Classification of 3D printing techniques

The foundation of 3D printing lies in its additive nature: instead of subtracting material (as in milling or drilling), material is precisely placed layer by layer until the desired form is realized. The process begins with a computer-aided design (CAD) file or a 3D scan, which defines the object's geometry. This digital model is exported as a printable file format such as STL or OBJ and then sliced into hundreds or thousands of cross-sectional layers using slicing software. The sliced file is sent to the printer, which interprets instructions to deposit, cure, or sinter material in sequential layers. After printing, parts often undergo post-processing rinsing, curing, and mechanical finishing to achieve the required properties and surface quality. (Dankar et al., 2018).

Major 3D Printing Technologies

Several distinct technologies fall under the umbrella of 3D printing. The following are the principal approaches: (Lee et al., 2021).

- **Fused Deposition Modelling (FDM):** The most widely known desktop method, FDM heats and extrudes thermoplastic filament in successive layers. Popular for prototyping and low-cost applications.
- **Stereolithography (SLA)**: This process uses a UV laser to cure liquid photopolymer resin. SLA is known for producing smooth finishes and high accuracy, commonly used in medical and dental fields.
- **Selective Laser Sintering (SLS):** SLS employs a laser to fuse powdered polymer, metal, or ceramic materials, making it suitable for industrial applications and strong, complex designs
- **Digital Light Processing (DLP):** Similar to SLA, but uses a digital projector to cure resin quickly, enabling faster production cycles.
- Binder Jetting: This technique fuses layers of powder with a liquid binding agent, allowing for full-color printing and large-scale items.
- **Material Jetting and Powder Bed Fusion:** Specialized methods for precision parts, including jetting droplets of material or fusing powder with directed energy

Details of Extrusion, Selective sintering printing, inject printing and Binding printing (Marga et al., 2012).

Extrusion based printing - Fused deposition modelling/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 multi coloured 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).

Food printer configuration (Dalbhagat et al., 2019)

The Cartesian configuration, Delta configuration, Polar configuration, and Scara configurations are the multi-axis stages used in food printing.

Cartesian Configuration

The Cartesian arrangement, as seen in plate , contains X axis for left-to-right, Y axis for front-to-back and Z axes up-and-down motion. It includes with a printer moving along X-Z axis and a square stage positioned on Y-axis, or vice versa, with a printhead moving along Z-axis and a square stage positioned on X-Y axis. Pizza printers made by BeeHex Robot, Foodini, and Choc Creator are a few examples of Cartesian configuration. This configuration makes it difficult to use as a consumer end device since it needs a lot of space to operate as a printer. The moving printhead is also quite heavy when filled with food, which slows down printing and causes a jerking action every time the printing direction changes. Large-height 3D-printed food portions could collapse as a result of it. Last but not least, the Cartesian configuration's comparatively sluggish printing speed is a bottleneck that prevents it from being used in commercial machine designs.

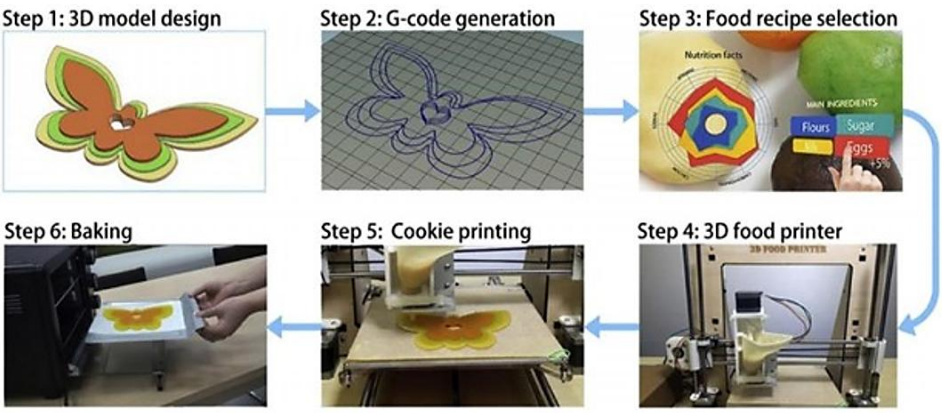

Fig. 2. Pictorial representation of Extrusion-based 3D Food Printing

Delta Configuration: A triangle print head is carried above a fixed circular print stage by three arms in a delta arrangement. This configuration has fewer parts, which lowers machine and maintenance costs. Delta-configured machines, including the Pinya3 printer is now being developed for the market. This printers are less expensive, quicker, and can produce higher volume food pieces in less time than the Cartesian configuration. However, when the print head is moving at a quicker rate and is filled with liquid produce (such as melted chocolate), the quick acceleration and deceleration may result in liquid vibration during the printing process. As a result, the extrusion procedure could become unstable. For applications comprising the extrusion of liquid materials, a modified Delta configuration a fixed print head with a moving print stage is recommended.

Polar Configuration: Polar configuration, as compared to Cartesian configuration, employs polar coordinates to explain points on a circular grid as opposed to a square. This type of printers typically features a rotating stage as well as a print head that can lift up and down to cover the Z axis and left and right to cover the tangential axes of X and Y, as illustrated in plate 4(c). With just slight mechanical imperfections and minimal calibration, this configuration can provide a perfect circle and equal performance for all direction movements. Examples include the TNO food printer and the XOCO 3D printer, both of which have a rotating build plate and a single pillar.

SCARA Configuration: Selective Compliant Assembly Robot Arm (SCARA) has seen a significant increase in attention from the food production industries. This set up is simple to construct and was modified for 3D printing. It comprises of an X-Ymoving robot arm and an extra actuator for Z-moving motion. This configuration has been used in the conceptual design "Sanna: the food printer of 2020" from Columbia University to transform unprocessed raw, frozen food purees into delectable, cooked, and texturized plates (Lee et al.,2021).

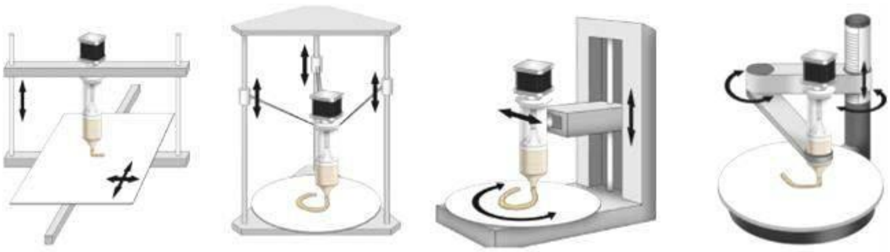

Fig. 3. Food printer configuration: A. Cartesian configuration , B. Delta configuration, C. Polar configuration D. SCARA configuration

Printing variables and process parameters

Tip diameter of Nozzle, rate of deposition, nozzle height, suck back and push back times, hot air temperature, and air gap between layers are important design and process characteristics in 3D printing. Researchers have developed nozzle tips with a reduced diameter that produce smooth, fine-resolution food prints. Larger tip sizes and faster printing rates both diminish the printer's accuracy and resolution. Lower nozzle heights lead to insufficient printing accuracy and weak mechanical properties in chocolate products, whereas excessively maximum nozzle heights make it challenging for the material supply to reach the printing platform. The importance of nozzle height as a printing parameter was validated by investigations using lemon juice (as a semi soild). They also created a function that connects the extrusion rate, movement speed, and nozzle diameter. Lower speeds can produce continuous filaments; too high speeds (over 35 mm/s) cause the filaments to drag. The stage speed, extrusion rate, and nozzle diameter all influence layer thickness. Better food surface and thinner layer thickness may result from smaller nozzles, and vice versa.

For the same extrusion rate, a higher stage moving speed might break the deposited stream or result in deformation, while a slower stage moving speed could cause the extruded stream to accumulate, resulting in an increase in layer thickness and a reduction in surface quality. While printing food, the extrusion rate shouldn't be constant or only proportionate to the immediate stage movement speed, but should be almost adjusted to account for the stage speed variation. A low extrusion rate is advised, for instance, if the stage movement speed is almost zero and the printing path is changing direction. The printed food portions may expand in some places and become hollow in others while the extrusion rate is constant. The extrusion rate throughout the printing route should be adjusted using an intelligent control technique.

Advantages

Customization & Personalization
- Tailored nutrition (low-fat, high-protein, allergen-free)
- Unique shapes, textures, and designs

Precision & Consistency
- Exact portion control
- Uniform appearance and texture

Reduction of Food Waste
- Uses only required ingredients
- Converts by-products into printable food

Innovation & Creativity
- Complex shapes, multi-layered designs
- Novel textures, colors, and flavors

Health & Therapeutic Applications
- Patient-specific diets
- Soft or modified textures for elderly and children

On-Demand Production
- Fresh food anytime, reducing storage needs
- Useful in remote areas and space missions

Enhanced Efficiency
- Automated, labor-saving production
- Rapid prototyping of new products

Sustainability
- Reduced energy use
- Localized production minimizing transport and packaging

Challenges and Limitations

Ingredient Compatibility and Printability

One of the primary challenges in 3D food printing is that not all food ingredients are suitable for printing. Successful printing depends on the rheological properties of food materials, such as viscosity, elasticity, gelation, and shear-thinning behavior. For example, doughs, chocolates, and cheese extrude smoothly and solidify quickly, but fresh fruits, vegetables, and meat often lack the necessary flow properties. To make them printable, stabilizers like hydrocolloids, starches, or gums must be added, which can alter taste, texture, and nutritional value. This reliance on additives may reduce the "naturalness" of foods, which some consumers may reject (Miyanaji et al 2018).

Printing Speed and Productivity

Current 3D food printers are slow compared to traditional food processing equipment. While conventional baking or extrusion systems can produce hundreds of units in minutes, a 3D food printer may take several minutes to print a single portion. This limitation makes it unsuitable for mass production or fast-paced food service environments such as restaurants or catering. Scaling up printing speed without compromising accuracy and structural integrity remains a key technical challenge (Kamble et al., 2022).

Cost of Equipment and Maintenance

High costs of 3D food printers, specialized cartridges, and maintenance hinder their commercial adoption. Even though smaller consumer-grade food printers are entering the market, industrial-grade machines with reliable performance remain expensive. Additionally, the cost of training personnel, replacing nozzles, and maintaining hygienic standards further increases the financial burden. For small businesses or developing countries, affordability is a major barrier.

Hygiene and Food Safety Concerns

Food safety is a critical issue in 3D food printing. Residual food material inside printer nozzles or cartridges can act as a breeding ground for microbial contamination if not cleaned properly. Maintaining hygienic conditions requires strict cleaning protocols, which are time-consuming and labour-intensive. Moreover, because 3D printing often involves partially processed or semi-solid materials, the risk of bacterial growth during printing and post-processing is higher than with conventional cooking methods. Ensuring consistent food safety standards is therefore a major concern.

Limited Ingredient Diversity and Nutrient Stability

Although research has demonstrated printing with chocolates, doughs, or pastes, the range of printable food inks is still narrow. Many foods lose their nutritional value or desirable sensory properties during the printing process. For example, high heat used in Selective Laser Sintering (SLS) may degrade vitamins, while extrusion pressure may damage delicate bioactive compounds. Preserving both the nutritional quality and sensory attributes of food remains a significant challenge (Praveena et al., 2022).

Consumer Acceptance and Perception

Food is not just about nutrition; it is deeply connected to culture, tradition, and psychology. Many consumers perceive 3D printed food as artificial, synthetic, or "unnatural." While novelty may attract early adopters, skepticism about safety, taste, and nutritional integrity may hinder large-scale acceptance. Building consumer trust will require awareness campaigns, demonstrations, and regulatory approval.

Regulatory and Standardization Issues

Currently, there are no well-defined regulatory frameworks specific to 3D printed foods. Issues such as labeling requirements, safety standards, and approval of novel food ingredients remain unclear. Without proper guidelines, scaling up production for commercial sale is risky. Standardization of equipment, materials, and post-processing protocols is also lacking, which hinders the establishment of consistent quality benchmarks.

Technical Challenges in Texture and Shelf-Life

Replicating the texture and mouthfeel of traditionally prepared foods is difficult with 3D printing. For example, achieving the crispiness of baked goods or the juiciness of meat products requires complex multi-material printing and precise post-processing. Additionally, many printed foods have poor shelf stability, as they may collapse, dry out, or become contaminated more quickly than conventional foods.

Environmental and Energy Concerns

While 3D printing is often promoted as a sustainable technology, it also raises environmental concerns. The process requires electricity for prolonged periods, and food waste may still occur due to failed prints or clogged nozzles. Packaging and storage of food inks in cartridges may add to plastic waste unless biodegradable solutions are adopted.

Future Prospects

Sustainable and Efficient Production

3D food printing offers a sustainable approach to food production by minimizing waste and optimizing ingredient usage. This technology allows for precise control over portion sizes and ingredient combinations, leading to reduced food waste and more efficient use of resources. Additionally, the ability to utilize alternative protein sources, such as plant-based ingredients and algae, aligns with global efforts to promote environmental sustainability in food systems.

Personalized Nutrition and Health

Advancements in 3D food printing enable the creation of customized meals tailored to individual dietary needs and health requirements. For instance, researchers have developed 3D-printed foods specifically designed for individuals with dysphagia (swallowing difficulties), ensuring that these meals are not only safe to consume but also nutritionally rich and palatable. This capability extends to personalized nutrition, where meals can be crafted to meet specific health goals, such as weight management or enhanced athletic performance.

Culinary Innovation and Consumer Experience

The integration of 3D printing in culinary arts is revolutionizing food presentation and creativity. Chefs can now design intricate and customized food structures, offering unique dining experiences that blend technology with gastronomy. This innovation is not limited to high-end restaurants; bakeries are also adopting 3D printing to streamline production processes and introduce novel designs. For example, Maison Bécam, a French bakery chain, has implemented a 3D cake printer that allows for the creation of elaborate cake bases with a single click, reducing manual labor and expanding creative possibilities.

Specialized Dietary Solutions

3D food printing is making significant strides in addressing specialized dietary needs. The European Union has invested in projects like PERFORMANCE to develop 3D-printed "smoothfood" for individuals in care homes who have difficulties with chewing and swallowing. These meals are designed to be both safe and appealing, helping to prevent appetite loss and malnutrition among vulnerable populations.

Market Growth and Economic Impact

The global 3D food printing market is experiencing rapid growth, with projections estimating a compound annual growth rate of 34.2% from 2024 to 2030, reaching USD 2.26 billion by 2030 This expansion is fueled by increased consumer demand for personalized and sustainable food options, as well as advancements in printing technology that enhance the feasibility and scalability of 3D food production.

Technological Advancements

Ongoing research and development in 3D food printing are leading to significant technological advancements. Innovations such as adaptive and context-aware volumetric printing (GRACE) are enabling the creation of complex, customized food structures with minimal user intervention. Additionally, novel printing techniques like liquid rope coiling are allowing for the production of food items with tunable porosity and texture, enhancing both the sensory experience and nutritional profile of printed foods.

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