Journal of International Technology and Information Management

Volume 29 | Issue 1 Article 2

2020

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Sharmin Attarin
Bryant University, sattaran@bryant.edu

Mohsen Attaran
CSU-Bakersfield, mattaran@csub.edu

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Attarin, Sharmin and Attaran, Mohsen (2020) "Food Printing: Evolving Technologies, Challenges, Opportunities, and Best adoption Strategies," *Journal of International Technology and Information Management*: Vol. 29 : Iss. 1 , Article 2.
Available at: https://scholarworks.lib.csusb.edu/jitim/vol29/iss1/2

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Food Printing: Evolving Technologies, Challenges, Opportunities, and Best adoption Strategies

Sharmin Attarin
(Bryant University)

Mohsen Attaran
(CSU-Bakersfield)

ABSTRACT

3D printing is a process of making three-dimensional objects using additive processes where layers are laid down in succession to create a complete object. Companies across the globe are actively piloting and leveraging the inherent benefits of 3D printing technology. Today, 3D printing can revolutionize food innovation and production through better creativity, customizability, and sustainability. In this paper, we conducted a literature review to explore 3D printing's current technologies and applications in the food industry, including its advantages, its potential implications, and its obstacles to rapid growth. Finally, the article investigates the future of 3D printing in the food industry. Our discussions bring new insight into the transformative potentials of 3D food printing and provide practitioners a way to discover more effective strategies to adopt technology.

Keywords: 3D Food Printing; Printing precision; Culinary Printing; Personalized Nutrition; Customized Food Design; Confectionery Market

Disclosure of Interest

The authors report no conflicts of interest.

Design/methodology/approach

We conducted a literature review and searched for papers that contained the word "3D Printing," "3D Food Printing," "Culinary Printing," "Customized Food Design," and "Personalized Nutrition" in their titles, keywords, or abstracts. These articles were selected for conducting our reviews. Our review of past work focused on identifying areas where 3D printing is being applied in the food industry. Papers were selected form the EBSCO Applied Science & Technology Source, the Web of

Science, and a variety of Internet sites, including ResearchGate, and Google Scholar, through February 2020. The outcome of the review is a summary of 3D printing capabilities and their impact on the food industry performance.

INTRODUCTION

Three-dimensional printing, more formally known as additive manufacturing (AM) or rapid prototyping, has been around for decades. The first working 3D printer, "Stereolithography Apparatus," was created in 1984 by Chuck W. Hull of 3D Systems Corp (Bogue, 2013). The 3D printer works in a very similar way to the standard inkjet printer. However, instead of printing layers of ink on paper, a 3D printer uses materials to build a three-dimensional object (Berman, 2012). Many in the industry use the terms 3D printing and additive manufacturing interchangeably. Additive manufacturing (AM) is the broader and more all-inclusive term. Additive manufacturing refers to the technology of producing a final three-dimensional product by depositing thin layers of material upon each other (Wohlers and Gomet, 2014). A variety of materials can be utilized, including metals, plastics, resins, rubbers, ceramics, glass, and concretes (Bogue, 2013). Most commercial 3D printers use a computer-aided (CAD) design to translate the design into a three-dimensional object. The design is then used by the 3D printer to deposit the layers of material (Chua et al. 2010).

3D printing technology is maturing and has worked its way into several markets. Maturing technology is helping the next generation of users adopt 3D printing. In the early days, technology was costly and not feasible for the general market. In recent years, however, costs drastically decreased, allowing 3D printers to find their way into many industries, including distributed manufacturing (Chua & Leong, 2014), prototyping, and product designs (Pei, 2014), and healthcare products (Murphy & Atala, 2014). Today, 3D printing is reemerging, and it is now one of the hottest and exciting advancements in the design and marketing world. COVID-19 highlighted the importance of 3D printers and drastically increased their applications in making personal protective equipment for healthcare workers by universities, tech firms, and 3D print enthusiasts. As the now Coronavirus pandemic takes hold over the globe, 3D printers have helped to fill the critical gaps in the supply chain and have ensured that same level of face shields, nasal swabs, adaptors, valves, ventilators, and other complex medical supplies continue to reach hospitals (Petch, 2020).

In the past few years, 3D food printing emerged as a technology that has the potential to revolutionize the food industry through precision, customization, and innovation in the structure and texture of various foods. (Feng et al., 2018; Le Tohic et al., 2018). 3D printed food is a way of preparing a meal in an automated additive manner. 3D food printers work in virtually the same way as traditional 3D printers. Most 3D food printers use extrusion printing technology and use paste-type ingredients instead of using plastic material. A syringe or cartridge holds food ingredients and printer 3D print food, layer after layer, generally through a syringe-like extruder, and create a wide range of food – from pizzas to cakes (Sun et al., 2015b; 2018). The raw material used in a 3D food printer must have a certain degree of viscosity and must, therefore, be inserted into a syringe-like container for later extrusion. The most common ingredients used by food printers are chocolate, pancake batter, cream, and paste-type food. Advanced printers allow you to use other food ingredients, including vegetables, dairy products, grains, confections, and other food materials (Kakuk, 2019).

3D food printers are finding their applications in professional, industrial, and personal use-cases**.** Moreover, as 3D printed food can be customized according to users' needs, it can be helpful in many fields, such as medicine and may also represent a hope for the world hunger crisis in the future. It can also deliver transformative solutions for sustainability, food waste reduction, and fully personalized nutrition (Kakuk, 2019).
Section II explores 3D printers' current technologies, trends, and applications in different industries. Section III highlights critical roles 3D food printing play in the food industry, reviews different food printing processes and trending technologies, discusses advantages and transforming potentials of the technology, evaluates the market size, and summarizes major food printers' players. Section IV discusses challenges in applying food printing in a way that would allow for its significant and rapid growth. Section V reviews the application of 3D food printing and highlights its transformative potentials across specific food areas. Section VI provides a summary and conclusions.

3D PRINTING TECHNOLOGIES, TRENDS, AND REAL-LIFE APPLICATIONS

According to a recent study by International Data Corporation (IDC), worldwide spending on 3D printing (including hardware, materials, software, and services) was $11.4 billion in 2018. The spending is expected to exceed $14.0 billion in 2019 and will exceed $23 billion by 2022, with a five-year compound annual growth rate of more than 18.0 percent (Daquila and Shirer, 2018). These figures highlight a 3D market that is thriving.

Status of Technology

Each 3D printing technology has its strengths and equipment and is suitable for different applications. Some 3D printers are using melting or softening materials to produce the layers. The two popular technologies using this way of 3D printing are Selective Laser Sintering (SLS) and Fused Deposition Modeling (FDM). SLS was developed and patented by a few professors at the University of Texas at Austin in the mid-1980s. The technology utilizes a high-powered laser (such as carbon dioxide laser) to fuse small particles of plastic, ceramic, metal, or glass powders into a mass that has the desired 3-dimensional shape. The most common material for SLS is nylon. The technology is a popular choice among engineers for functional prototyping. It is also a cost-effective alternative to injection molding for limited-run or bridge manufacturing.

SLS can produce strong structured parts from a relatively wide range of commercially available powder materials. This technology is accessible and in extensive use due to its ability to make low cost and reliable structured parts directly from digital CAD data. It is a popular process for creating prototypes and even final products. SLS desktop printers start at $10,000.00. Industrial printers are available from $100,000.00.

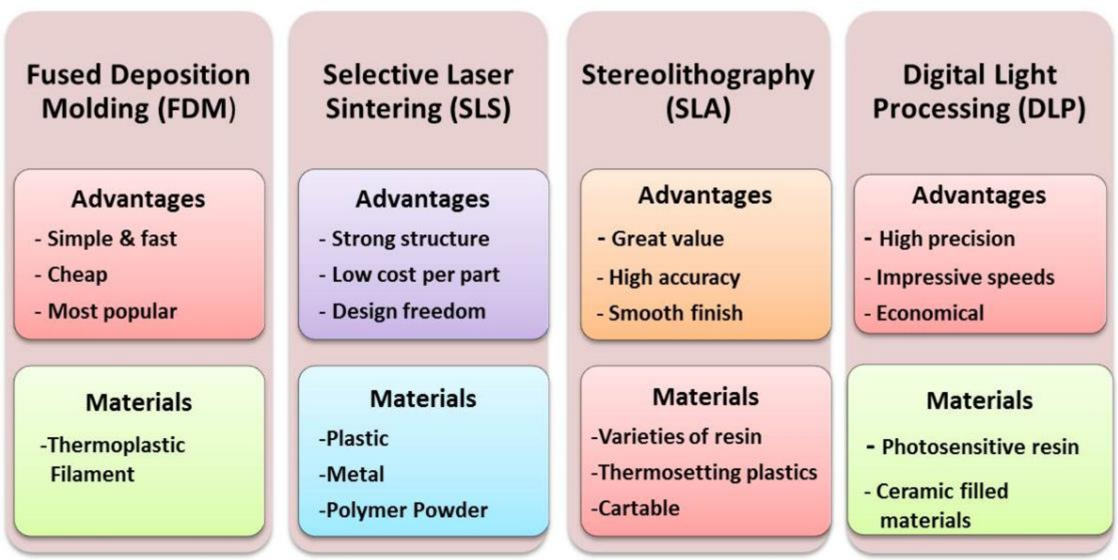
FDM, also called Fused Filament Fabrication (FFF), utilizes thermoplastic materials injected through indexing heated nozzles onto a platform. FDM is the most popular of all the 3D printing technologies and has been around since the early 1990s. It is easy to implement and can create very high-quality products. FDM is not the best option for printing complex designs or parts with intricate features. The technique is well suited for quick and low-cost prototyping of simple parts and basic proof-of-concept models (Dudek, 2013). Today, many printers are using this technology that ranges in price from only a few hundred dollars on up. FDM mid-range desktop printers are available at $2,000.00. Industrial systems start at $15,000.00.

Another 3D printing method is called SLA or Stereolithography utilizes laser technology to cure layer-upon-layer of photopolymer resin. First, the laser hardens the resin for a layer. Then the model is lifted, and another layer is created beneath the previous. This builds a 3D object with the highest resolution and accuracy by adding successive layers (Ma, 2013; 3DPrinting.com, 2016). The significant advantages of SLA are the ability to create very high-quality parts with high precision and smooth finish surface detail of all plastic 3D printing technology. It is an excellent option for highly detailed prototyping, and it is widely used in a range of industries, including manufacturing, dentistry, jewelry, and education. This makes SLA ideal for creating finely detailed objects (Ma, 2013). SLA professional desktop printers start at $3,500.00. The large-scale industrial printers are available from $80,000.00.

Finally, Digital Light Projection or Digital Light Processing (DLP) uses similar technology as SLA. The only significant difference is the light source used to cure the resin. DLP printers use a specially developed digital light projector screen where the projector screen flashes an image of a layer all at once. On the other hand, with the SLA 3D printer, the laser has to individually cure the resin in a "point-to-point" technique making DLP printers faster than SLA printers. DLP printers are economical and can achieve highly specific parts (Greguric, 2018).

Figure 1 summarizes some key characteristics of the four most popular 3D printers' technologies, highlights the materials they use with a summary of their advantages. Over the coming years, we expect to see dozens of new technologies related to 3D printing to appear.

Figure 1. 3D Printing Technology and Materials



Evolving Trends

In the past, 3D printing technology was not capable or cost-effective enough for most applications, and the speed of its adoption was not at the rate that the market expected. However, 3D printing has gone through several changes over the years. 3D printers are more affordable, more reliable, and easier to use. Several trends are fueling the evolution of 3D printing and are enhancing its abilities and offerings. These trends are summarized below.

1. **Functionalities -** Typically, 3D printers can be narrowed down to either having higher capabilities at a higher price or having more primitive capabilities for a lower price. However, during the past few years, the gap between these two classifications of printers is closing. These two types of printers often have more of the high-end capabilities but come at a lower cost than they have in the past (Earls and Baya, 2014). As the 3D printing industry continues to grow and progress, the continued availability and affordability of more capable printers are expected to continue.

2. **Printing Speed -** Speed is an important performance factor and a key challenge in 3D printing. It prevents the technology from being a practical means of manufacturing in some instances. For example, in the production of prosthetics, it still takes hours and even days to produce a product. Speed could be improved by using higher-quality components and by optimizing the designs and movement of the lasers (Earls and Baya, 2014). The technology for increasing printing speed for large objects is currently in the making. Features like larger nozzles for faster polymer deposition, high-speed laser cutters with larger work areas, and high-speed motors to accelerate printer heads are considered. With these technological innovations, print speed will no longer be a barrier to the further growth of the 3D printing industry (Earls and Baya, 2014).

3. **Capabilities -** Many 3D printers still require upkeep and supervision to ensure the printing process is accurate. Having fully autonomous printers would reduce the need for the technology to be monitored by a human, thus considerably making 3D printing more practical and appealing to the masses. Some "hobbyist" 3D printers are already seeing a shift towards autonomous capabilities. For instance, many printers sold to consumers include a feature called auto-leveling, which makes the process of leveling the printer's platform completely autonomous, as the printer can calibrate itself. As designs and R&D efforts come to fruition, 3D printers could eventually be entirely autonomous and be able to monitor the printing process on their own, ensuring accurate designs.

4. **Disrupting Traditional Manufacturing -** A key benefit of the first 3D printing machines was the reduction of time in product development of prototypes. Now 3D printers are poised to help many industries reduce production time, increase efficiency, and reduce costs. The ability to make prototypes faster and at a lower cost enables companies to quickly test multiple configurations, reducing product-launch time to market (Cohen et al. 2014).

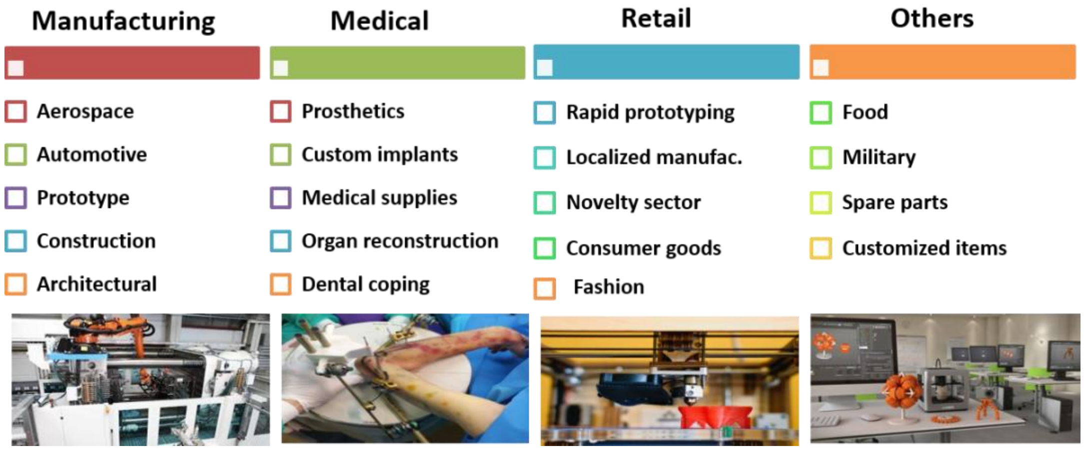
Real-World Applications

A key benefit of the first 3D printing machines was the reduction of time in product development of prototypes. The technology has come a long way from its roots in the production of simple plastic prototypes (Cohen et al. 2014). Today, 3D printers produce fully functional components, including complex replacement parts, batteries, transistors, and LEDs. Now 3D printers are poised to help many industries reduce production time, increase efficiency, and reduce costs (Attaran, 2017).
According to an estimate by McKinsey, various 3D applications will generate an economic impact of $230 billion to $550 billion per year by 2025. International Data Corporation (IDC) reported that the leading applications for 3D printing are prototypes, parts for new products, and aftermarket parts. These three applications will account for 45 percent of worldwide spending in 2019. Additionally, dental and medical support objects and tissue/organ/bone printing will see a five-year compound annual growth spending rate of more than 21.0 percent (Daquila and Shirer, 2018).

Finally, 3D printers have been playing a critical role in filling the critical gaps in the supply chain of the medical industry during the coronavirus pandemic. 3D printers have been used in the design and production of personal protection equipment for healthcare workers. From protective masks to parts for ventilators, individuals, and private sectors are busy printing parts to ease the shortages of medical supplies caused by sudden demand during COVED-19 pandemic.

Industries benefiting from 3D printing are summarized in Figure 2.

Figure 2. Industries Benefiting from 3D Printing Technology



3D PRINTING AND THE FOOD INDUSTRY

3D printing of food is being developed by squeezing out food materials, layer by layer, into three-dimensional objects. A large variety of food items are appropriate candidates, such as chocolate and candy, and flat foods such as crackers, pasta, and pizza (Wong, 2014; Chew, 2017). 3D food printing or culinary printing manufactures food products with customization in shape, color, flavors, textures, and nutrition. 3D food printing is being considered in the food sector due to its multiple advantages such as personalized nutrition, customized food designs, simplifying the supply chain, and broadening of the available food material. 3D food printing has excellent advantages in low volume food fabrication of customized items in food services. 3D technology printers help in the formation of the 3D shape and deliver the food with a visual aesthetic and, most importantly, good taste (Liu et al., 2017).

3D printing is changing the U.S. food industry as Millennials (ages 23 to 38 in 2019) have focused so much on food as a critical part of their social, political, and economic consciousness. According to market research conducted by Packaged Facts, Millennials focus on fresh, creative, and personalized foods that have been a changing development in the fast-casual foodservice segment. There is an increasing demand for customized food products. Even grocery chains are working the do-it-yourself trend in fresh foods. The mix-and-match and built-it-for-me trend have diversified to all sectors of the restaurant industry as well (Refrigerated & Frozen Foods, 2018). Millennials also have inspired restaurants to expand into more

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diverse food areas such as salads, fusion, and sushi due to growing global palates. The costs of producing those food products are relatively high. 3D printing is a tremendous breakthrough in today's food industry by reducing the time the food industry must give to creative, personalized, and broader offerings.

Food Printing Processes

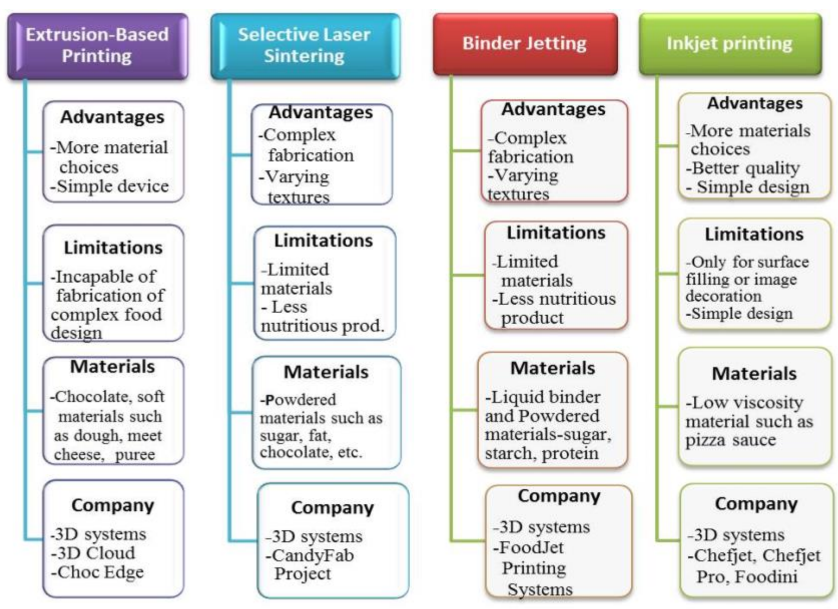
3D food printing consists of the different processes: 3D model building, objects printing, and post-treatment. In the first step, the 3D model is designed by Computer Aided-Design (CAD); the model is conversed into the STL file and is sliced by layer to get the outline of each section. Then, the printer makes the 3D objects by the deposition of materials layer-by-layer. The printed objects can be trimmed, cooked, or baked as required by the user (Yang et al., 2017) Recently, several researchers discussed significant development in 3D food printing and investigated the relationship between process parameters and resulting printed food properties. The study was focused on the printing parameters to optimize the printing process (Yang et al., 2017).

The printing precision of 3D food printed object is influenced by several factors. The shape of the 3D model, slicing parameters, the flow performance of ingredients, and the post-treatment effect structure accuracy and shape stability of printed food. Other critical factors for the structure accuracy of printed food objects are the properties of food ingredients, such as rheological properties, thermal properties, and chemical properties (Liu et al., 2017). Printer's characteristics, such as height, nozzle diameter, printing rate, nozzle movement rate, layer thickness, are also critical for the quality of resulting printed food (Hao et al., 2010). Finally, the printing precision can be affected by the deformation caused by the post-treatment, such as drying and baking (Liu et al., 2017). The design of the 3D model is an important factor that can determine or influence the stability and precision of final printed objects. A good model should meet the needs of consumers and should be suitable for the parameters used in printing processes, such as printers, food inks, and post-printing processing treatments (Guo et al., 2019).

Food Printing Emerging Technologies

3D printers manufacture and create food utilizing lasers, powdery materials, and nozzles. Currently, there are four techniques available in food printing, as shown in Figure 3. The applied technologies are related to the properties of the edible materials that are printed (Godoi et al. 2016). Some printers use thermal energy from the laser, hot air, and heating elements to sinter or melt the powder. Others use ink-jet type printing head to spray solvent or binder. For liquids, chocolate, or paste technologies such as hot-melt extrusion, also called Fused Deposition Modeling (FDM) is used. The material is heated above its melting point, and it solidifies quickly after extrusion and welds to the previous layers. This technology is used to create personalized 3D chocolate products (Hao et al. 2010; Causer, 2009). This technology can also be used at room temperature for soft materials extrusion using materials such as dough, meat, paste, processed cheese, and puree (Godoi et al. 2016). The technology provides an engineering solution for digitalized food design and nutrition control. Lille et al. (2018) investigated the applicability of extrusion-based 3D food printing technology for food pastes made of protein, starch, and fiber-rich materials. The advantages of food printers using this technology are compact size, low maintenance cost, and easily interchangeable print heads. Sun et al. (2018) provide a comprehensive analysis of how to apply this technology to innovate food texture and taste. Severini et al. (2016) evaluated variables affecting the printability of cereal-based products and identified additive layer deposition technology as the one that obtained the proper structures. Finally, Dankar et al. (2018) focus in-depth on optimizing extrusion-based food printing, which supports the widest array of food and maintains numerous shapes and textures. PancakeBot is an example of a printer that uses this technology to create pancakes by automatically dispensing batter directly onto a griddle. Users can make their pancake designs or select from layouts included in the software or browse through an online community that is updated with new designs every week (PankaceBot.com, 2019).

Figure 3. Food Printing Emerging Materials and Technologies



For powders like sugar with low melting points, Selective Laser Sintering (SLS) technology is used, which can generate food containing multiple layers with each layer having different food components (Godoi et al. 2016). A related technology in this category is Selective Hot Air. Sintering and Melting (SHASAM). This food printing technology uses a beam of hot air to fuse sugar powders and print 3D food items (Godoi et al. 2016). Food printers in this category can build complex food items in a short time without post-curing. CandyFab built several printers capable of sintering and melting a bed of sugar and sugar-based product. TNO's Food Jetting printer applies the laser to sinter sugars and sugar-based powders.

For liquid-based and powder-based materials, Binder Jetting printers can create complex 3D food fabrication with varying textures (Pitayachava et al., 2018). In this technology, each powder layer is distributed evenly across the fabrication platform. The liquid binder sprays and binds consecutive powder layers (Sachs et al. 1990). Post-processing may be required to remove moisture or improve strength. The food printer designed based on Binder Jetting technology offers advantages such as faster fabrication and low maintenance costs. The disadvantages are rough surface finish, high machine cost, and limited materials. Sugar Lab is an example of a printer that uses sugar and different binders to fabricate cakes for special events (Yang et al. 2001).

Another technology used for 3D food printing is inkjet printing (Kruth et al. 2007). This technology uses liquid-based and low viscosity materials such as paste or puree. Other materials that are commonly used are chocolate, liquid dough, cheese, jams, and gels. The food printer designed based on inkjet printing dispense a stream of droplets from the syringe-type print head in a drop-on-demand way to create edible food products such as cookies, cakes, or pastries. The technology is used only for surface filling or image decoration. The advantages of food printers using this technology are fast fabrication, high resolution, and accuracy, and multiple material choices and colors. ChefJet manufactured by the 3D Systems is an example of a printer that uses this technology to crystallize the thin layers of fine-grain sugar into a variety of geometric configurations (web site). Choc-Edge is another printer from Natural Foods, dispenses chocolate from syringes into a beautifully melty pattern (website). In 2015, Natural Machines (a Barcelona-based company) developed one of the first 3D food printers called Foodini. The cutting-edge printer uses fresh ingredients loaded into stainless steel capsules to make foods like pizza, brownie, and stuffed pasta. The printer has different types of nozzles and allows printing with almost any food material from mashed potatoes to chocolate. The printer creates fascinating food designs and customizes and balances dishes to amaze customers. The machine is also an Internet of Things (IoT) appliance. It can be connected to the internet, and recipes and designs can be uploaded from anywhere (Foodini Website, 2019).

Advantages of Food Printing

The potential benefits of 3D printing technology applied to the food sector are numerous. Technology fundamentally changes food preparation and manufacturing. Significant benefits are summarized below:

- **Saving Time and Effort** – Food printing can save time and effort when it comes to experimenting with intricate food design.
- **Innovation in Healthy Food** – Food printer provides an opportunity for food manufacturers to produce better and healthier food. This may lead to the creation of a unique food formulation for dietary needs or customized nutritional supplements (Wegrzyn et al., 2012).
- **Innovation and Culinary Creativity** – Chefs and cooks around the world are leveraging food printing to create food in a variety of designs, colors, and shapes.
- **Food Sustainability** – To help solve the food scarcity problem in the world, food printers can reduce the amount of chemical additive and also minimize waste and overconsumption (Phillips, 2013). A new study provided the parameters that impacted the sustainability of the technology and proposed the improvements to be applied for 3D food printing to achieve the full potential (Guo et al., 2019).
- **Reducing Health Risks –** 3D printing of food skips the process of cooking and/or microwaving, which reduces potential health risks associated with human exposure to carcinogens and toxic radio waves.
- **Management of Food Production –** 3D food printing has the potential to change food production practices reducing food product waste and ensuring better control of inventory. The technology also improves direct-to-consumer relationships.

Transformative Potentials of Food Printing

3D food printing is now becoming more of a reality. The technology is changing how the food industry operates. The technology is transforming the consumer experience, the way that foods are created with more complex and original shapes and innovative recopies. It offers more customization to better adapt to a diversity of diets. In addition to endless possibilities, 3D printed foods may bring about many positive implications, including eliminating malnutrition, improving food scarcity,

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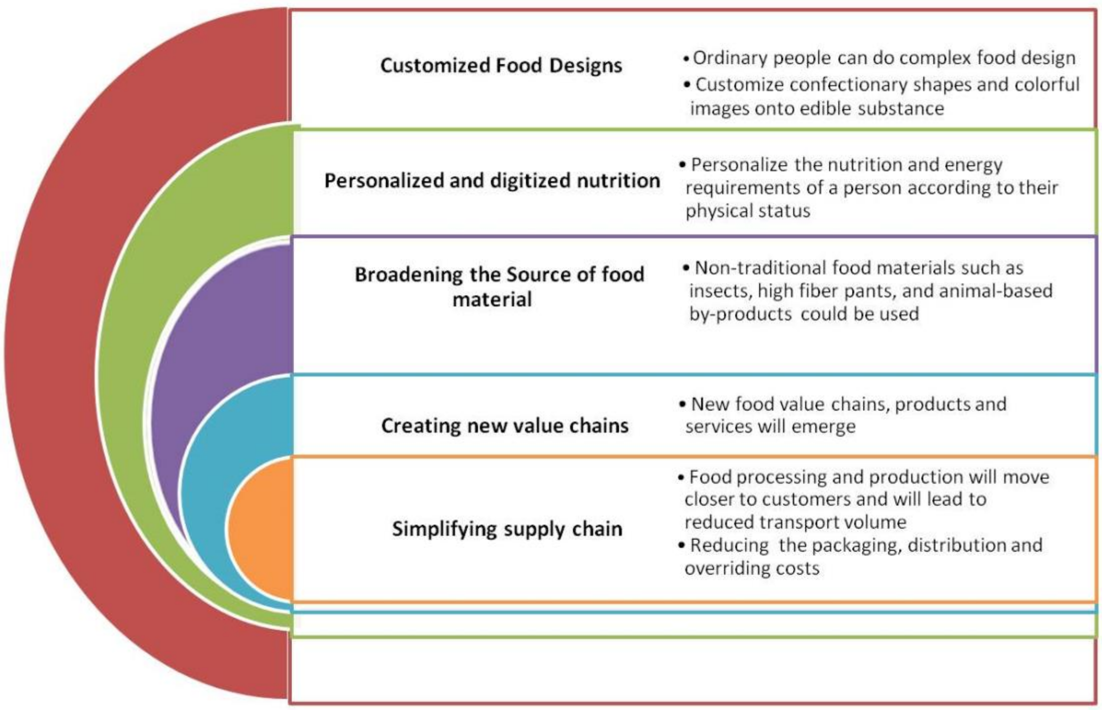
ISSN: 1941-6679-On-line Copy

creating new value chains, etc. The critical motivators for 3D food printing are on-demand production, customization, and geometric complexity (Lipton et al., 2015). Figure 4 summarizes the positive implications and transformative potentials of this technology. More in-depth details and ramifications are discussed below.

Figure 4. 3D Food Printing Transformative Potentials



1. **Customized Food Design –** Food customization processes involve hand-made skills with low production rates and high cost. Food printers provide a platform for those experimenting with food forms and flavors to achieve intricate and fantastic food designs that cannot be produced by ordinary people (Sun et al. 2015a). Food printers can also be used to customize colorful confectionary images and shape onto a surface of solid edible substances (Young, 2000; Zoran and Coelho, 2011). Finally, food printers empower people to create the most amazing new recipes and dishes, making cooking more creative, faster, tastier, and healthier. When it comes to cocktail garnishes or 3D chocolate structures,

candies, and sugar sculptures, a trained pastry chef cannot achieve the perfection that food printers can.

2. **Personalized and Digitized Nutrition –** Recently, the interest in the customization of food in terms of shape, dimension, internal structure, nutritional values, taste, has been exponentially increasing. 3D food printing produces food structures with desired dimensional, sensorial, and nutritional properties (Severini et al., 2016). 3D food printing can enable precise control of people's diets by digitizing and personalizing the nutrition and energy requirements of a person according to one's physical and nutrition status (Severini & Derossi, 2016; Yang et al., 2017). Personalized food printing holds the promise of fixing malnutrition problems and can significantly improve wellbeing. One example is Foodini - an intelligent 3D food printing kitchen appliance that enables one to print their own real, natural ingredients into precise portions and shapes. Foodini helps create unique new recipes and dishes, making cooking more creative, faster, tastier, and healthier (Foodini website, 2019).
3. **Broadening the Source of Food Material –** 3D food printing can expand the source of available food material. Non-traditional food materials such as high fiber plant-based materials, animal-based by-products, and insects can be used by these printers to create a variety of foods (Severini & Derossi, 2016; Payne et al., 2016). Food printing can be used to print a variety of alternative protein sources such as vegetable sources, algae, and insects to reduce our reliance on animal proteins and to achieve healthier diets. These alternative proteins are low in cholesterol, consume very little space and water relative to livestock. They greatly reduce environmental footprint and impact the sustainability of our planet (Kakuk, 2019).
4. **Creating New Value Chains –** 3D food printing can alter or broaden existing food value chains. It can also help to develop new products and services into the marketplace. The technology could change the manufacturing and preparation of food fundamentally. It could eliminate the entire process, remove the need for grocery stores, chefs, or associated jobs (Koenig, 2016).
5. **Simplifying the Supply Chain –** 3D food printing facilitates smooth on-demand production and implementation of a build-to-order strategy of food production. The technology makes it possible to locate production facilities near the end customer. Therefore, the delivery of food is no longer a restriction. This results in a shortening of the customized food supply chain and savings in

packaging, distribution, and overhead costs (Chen, 2016; Jia et al., 2016). The need for large bulk inventories will be a thing of the past. Another benefit of food printing is its potential to simplify and facilitate food distribution into hard-to-reach locations (Benton, 2015).

Food Printing Market Size and Forecast

3D food printing is evolving quickly, and its market is expected to expand at a compound annual growth rate of 50 percent during the period 2017-2024 and is expected to reach $400 million by 2024 (Kenneth Research, 2019). Prominent factors driving the market include growing demand for customized food and increasing demand from healthcare applications. Figure 5 depicts the market share of 3D food printing worldwide in 2018, broken down by world region. North America (United States, Canada) accounted for about 36 percent of the global 3D food printing market, followed by Europe 31 percent and the Asia Pacific at 22 percent. It is estimated that the market in the Asia Pacific will continue to grow due to factors such as a high rate of aging and poverty, and lack of adequate amount of food to feed the (Statista, 2019; Kenneth Research, 2019). Another recent study analyzed the 3D food printers' market in terms of technology, food product, ingredient, vertical, and region (Marketsandmarkets, 2019). Table 1 summarizes the findings of this report. Column 2 of this table rank-order each category based on its usage and popularity.

Figure 5. 3D Food Printing Worldwide market - 2018

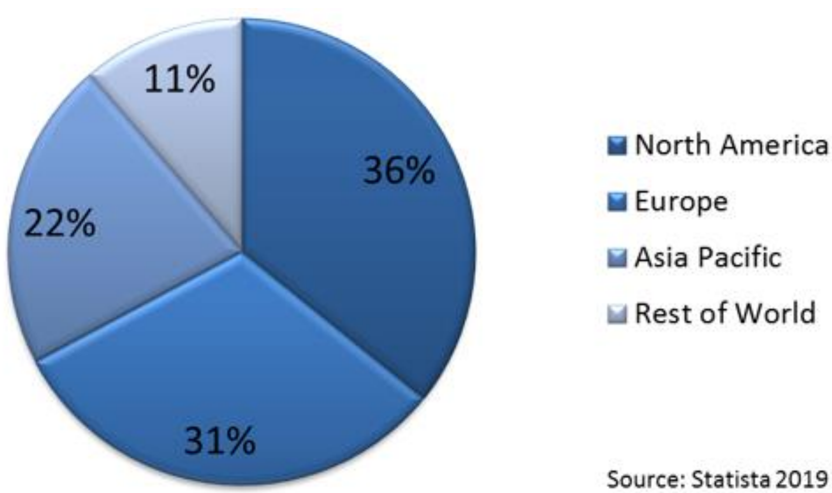


Table 1. Global 3D Food Printers Market Segmentation

Source: Marketsandmarkets, 2019; Kenneth Research, 2019

Categories	Segmentation
Technology	• Fused Deposition Modelling (FDM) • Hot Air Sintering • Binder Jetting • Open Source
Market Segments	• Confectionary • Bakery • Meat & Seafood • Dairy (Under Research) • Others (If Any)
Ingredient	• Dough • Fruits • Proteins • Sauces • Carbohydrates • Others (If Any)
End-User	• Government • Commercial • Residential
Region	• North America • Europe • Asia Pacific • South America, the Middle East & Africa
Printers/Manufacturer	• ChefJet/3D Systems • Choc-Edge/Natural Foods • The Foodini/Natural Machines

Food Printing Major Players

3D printers use hardware and software to print food. Most food printers come equipped with user-friendly interfaces and pre-loaded recipes. Designs are either onboard the printer, accessible with the computer, or can be self-designed and uploaded by the user. Users can also access the recipe or deign with a mobile device. Printer's instructions are easy to follow, and interfaces are engineered to be easy to use with plug and play onboard recipes and design (Kakuk, 2019). The choice of right printer is important since the quality of resulting printed food is affected by processing factors such as printing height, nozzle diameter, printing rate, nozzle movement rate, layer thickness, and temperature (Hao et al., 2010). Table 2 summarizes 3D food printers available on the market for the manufacturer suggested retail price under $6,000. We realize these prices may vary over time or change from one country to another.

Table 2. Food Printers Major Suppliers and Their Products

Sources: 3dsourced, 2020; Lansard, 2020

Food Printer	Material	Company Country/	Applications	Description
The Focus	Paste-type food	byFlow /Dutch €3,300	Catering	It works with refillable cartridges containing any kind of paste-type food. Users have the possibility to access downloadable recipes.
Choc Creator V2 Plus	Chocolate	The Choc Edge/ UK £2,380	Catering	A desktop printer that takes tempered chocolate and extrudes it through a food-grade stainless steel nozzle.
The Mycusini	Chocolate	Print2Taste/ Germany $440	Home	A compact printer that fit on a kitchen countertop. It uses a stainless-steel cartridge that is refilled with chocolate provided by the manufacturer.
Mmuse - Chocolate 3D Printer	Chocolate	Mmuse/China $4,499	Catering	It is a closed-framed 3D printer that uses chocolate beans as consumables that melt in the extruder, just as with regular 3D printing.
Foodini	Paste-type food	Natural Machines/ Spain $4,000	Catering	It has a generous array of wide nozzle sizes and wide cartridges and can print all kinds of paste-type food.
Createbot 3D Food printer	Paste-type food	Createbot/ China $2,349	Home and Catering	It is a multi-ingredient support food printer that can print any kid of paste-type foodstuffs.

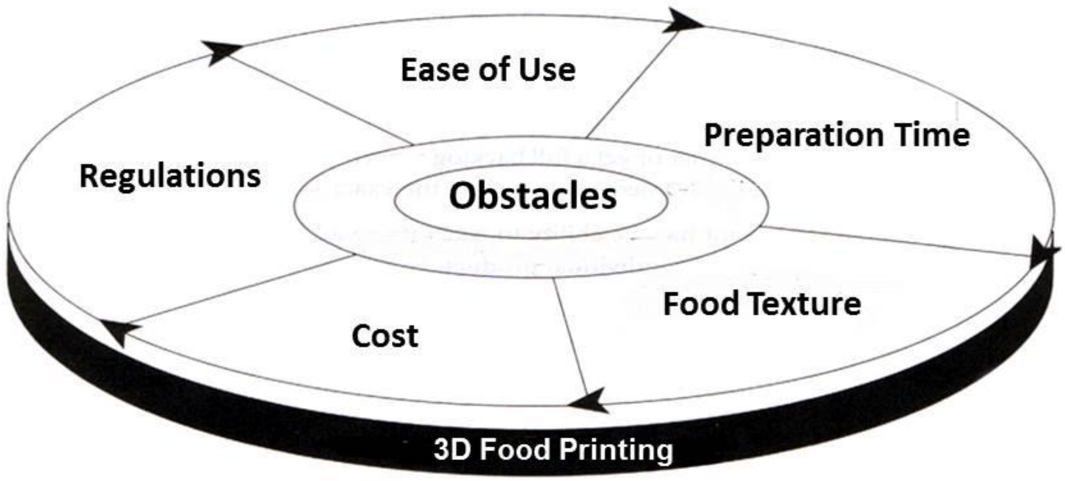
WiiboxSweetin	Paste-type food	Wiiboox/China $1,999	Home and Catering	It allows for the extrusion of a variety of edibles from its thick paste extruder. It offers an auto-leveling mechanism, freeing the user of tedious bed-leveling operations.
Print2Taste Procusini 4.0	Pasta, Chocolate, Marzipan, Cassis, Fondant	Procusini/ Germany €2,382	Catering	A plug-and-play printer featuring an effortless cartridge system for its feedstock. Five specially formulated food cartridges are available for the printer.
ORD Solutions RoVaPaste	Paste-type food	ORD Solutions/ Canada $1,999	Home and Catering	It is a multi-material printer able to 3D print with other materials than food, such as clay or silicone.

OBSTACLES TO THE RAPID GROWTH

While 3D food printing is a breakout technology poised to change customized food fabrication, implementation of the technology is only in its infancy. There are numerous challenges in applying the technology in a way that would allow for its significant and rapid growth. Liu et al. (2017) identified three challenges on 3D food printing, including printing precision, process productivity, and production of multi-flavor, multi-structure products. They also argued that in order to realize a precise printing, factors such as material properties, process parameters, and post-processing methods should be investigated. Nachal et al. (2019) identified key challenges in 3D food printing, emphasizing the need for future research in this field. Severini et al. (2016) discussed variables affecting printability of foods and the quality of 3D food structure and suggested these factors to be considered for applying 3D food printing for catering services or a large industrial scale. Godoi et al. (2017) investigated the behavior of food material properties during the application of 3D printing techniques. They suggested that to realize precise printing, factors such as printability, applicability, and post-processing needs to be considered. They also evaluated how the advantages and limitations of 3D printing techniques affect the end-use properties of the printed food constructs. Finally, Danker et al., (2018) researched the benefits and limitations of 3D food printing. The study identified four obstacles ordinance, and guidelines, food shelf life, ingredients restrictions and post-processing hampering the quality of the printed process.

The major obstacles of implementing 3D food printing are summarized below and range from the internal structure and materials to government and cost restrictions (Figure 6).

Figure 6. Five key Obstacles of 3D Food Printing



1. **Cost –** The cost of the printing equipment is currently considered a barrier to entry. Food printing equipment and materials costs make the technology expensive. Widespread consumer adoption will depend on food printers dropping in price. However, this will not be a reality for much longer. The commitment to advancing 3D food printing technology is substantial. The price of 3D food printers will decrease as technical developments increase, and more manufacturers enter the industry.
2. **Ease of Use –** Food printers use specialized equipment and parts, which makes them difficult to use and manage. Setting up a printer takes quite a bit of patience and time. This might be one of the reasons experts and enthusiasts have primarily used food printers. Engineers need to craft a system that is hygienic, food-safe, and very easy to set up, operate, and maintain. Complex design software programs are easy to download, but they are not moderated and may

not work on different types and brands of food printer. Working knowledge of CAD design is also needed to custom design a layout model.

3. **Production/Preparation Time –** 3D food printing is relatively slow in comparison to traditional mass food production. Although the change time between production runs in food printers do not exist, the production outputs trail in comparison to conventional mass production run times. Traditional food processing will be the preferred mechanism of production unless the production times of the printers can be improved when large quantities are demanded. Food printers are more likely to be used in mass food customization, as it offers the ability to create highly customized food in limited inventory to better adapt to a diversity of diets.
4. **Food Texture –** One of the problems with food printing is the nature of the texture of food. Not every type of food can be food-printed. For example, food that is not strong enough to be filed is not appropriate for 3D printing. Food printers should go beyond the printing of shapes to the printing of food textures, both existing and new (Nachal et al., 2019).
5. **Hygiene and Safety –** Few health concerns should be noted when working with food printers. The important one is bacteria buildup in the design where food can get stuck in mechanical parts or small cracks and spaces, and bacteria grows. 3D Food Printers are specifically made for food. As such, manufacturers of 3D food printers are keen on food safety concerns. Every aspect of a 3D food printing process, including machines, must be clean and food safe. As with any kitchen, space must be kept clean and hygienic standards must be maintained. Another consideration has to do with temperature fluctuations during the extrusion process. Heating and cooling process may represent a health concern for food and may make food susceptible to microbial growth, bacteria, or fungus.
6. **Regulations –** In recent years, controversies regarding 3D printing regulation and intellectual property have been on the rise (Tran, 2015). The growth and adoption of 3D printing of food could have enormous social and commercial implications if not regulated effectively. 3D food printing brings along many unique legal challenges, including safety and labeling (Lemley, 2014). Regulation of 3D food printing has already been brought into question. The FDA has not proactively regulated the 3D printed food industry until it knows what the industry wants to be (Halterman, 2015). A lot of players in this industry may not understand how they are going to be regulated. As the limits of 3D

food printing continue to be tested and new issues become known, regulations and government intervention could restrict who can perform printed foods and what can be printed.

APPLICATIONS OF 3D FOOD PRINTING

3D food printing has the potential to revolutionize food innovation and protection through better creativity, personalized and digitized nutrition, and broadened sources of food materials. They are opening the new doors for the customization of the food products with the delivery of a potent mix of the right nutrients. The application of 3D food printing across specific food areas are summarized in Table 3 and are discussed below:

Table 3. Industries Benefiting from Food Printing

Industry	Applications	Benefits Gained
Military and Space	• Production of meals on demand • Production of meals in remote locations • Producing food during long space missions	• Enables the Army to deliver food tailored for each soldier • Extends the shelf life of food material • Printing food in zero gravity • Reducing delivery and production cost of food in space
Confectionery & Bakery Markets	• Printing chocolate structures, candies and sugar sculptures	• Dispense chocolate into beautiful and high-throughput confectionary
Elderly Market	• Production of proper food at Nursing Homes • Customized medical and nutritional supplements	• Design meals with the right taste and proper ingredients for elders • Create unique food formulation for dietary needs
Restaurants	• Production of Meals on demand • Customized food products in shape, color, flavors, textures, and nutrition	• Moves cooking technologies into the digital age • Improves creativity • Reduces cost and increases efficiencies

1. **Military and Space –** The US Army has been testing the production of meals on-demand on the battlefield. Each soldier has different caloric requirements. Food printers enable the Army to personalize and customize meals for

individual soldier's nutrition and energy requirements. Meals designed by 3D food printers could help each soldier perform at their best. The technology could also extend the shelf life of food material by keeping them in raw material form rather than in cooked form (Kite-Powell, 2014). In the next 10 to 15 years, the US Army will be delivering food tailored for each soldier, possibly on the battlefield (Szoldra, 2016; Benson, 2014). Food printers make it possible to have meals printed in remote locations, as the delivery of material is no longer a restriction. This benefit of technology makes it possible for 3D food printing in space. The current space food system does not meet the personalized energy and nutritional requirements of astronauts. Besides, the refrigeration equipment needed for individually packaged food takes up many spacecraft resources. NASA has been testing food printing in zero gravity in hopes of producing food during long space missions (NASA, 2014; Lin, 2015). The objectives are to meet the requirements of food safety, taste, and personalized nutritional and energy requirements of astronauts for long space missions (Lin, 2015; Lipton et al. 2015). This would decrease the need for the shuttle to make trips to the international space station to deliver food materials, thus significantly reducing the lead-time on replacement materials. A reduction in lead-time would result in a decrease in inventory and a reduction in costs. To quantify the cost reduction, transporting one pound of material into space amounts to approximately $10,000 (King, 2012). Not only could this technology be used for food printing on the international space station, but it could also allow deep-space crewed missions, as meals could simply be printed on the shuttle.

2. **Confectionery and Bakery Market –** Sweets are widely consumed in the world, and significant food printing companies such as CandyFab, 3D Systems, Choc Edge, and Fouche Chocolates are focusing on sweets. Scientists at the University of Exeter created the first 3D commercial chocolate printer called ChocCreator (Davide & Xavier, 2015). Since then, several leading food printer companies and researchers are focusing on the development of machines capable of printing both tasty and visually appealing sweets using sugar, chocolate, and cheese. The standard technology used by 3D printers for printing of sweets is extrusion-based printing. For example, 3D Systems developed a machine based on this technology called Cocojet, ideal for the baker or chocolatier, which can print various shapes in chocolate (Zhuo, 2015). The device was developed in collaboration with Hershey, a global leader in chocolate and confections, and named "the most advanced 3D chocolate printer

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in operation" (Halterman, 2015). 3D Systems also developed two other printers called Chefjet and Chefjet Pro that use Binder Jetting technology and crystalized fine-grain sugar to create 3D chocolate structures, candies, and sugar sculptures (Ngo, 2015). Other companies prefer using syringes to dispense chocolate into beautiful chocolate and high-throughput confectionary.

3. **Elderly Market –** Most older adults at nursing homes are suffering from chewing and swallowing difficulties and are often provided with unappealing food, which causes the loss of appetite and leads to under eating and nutritional deficiencies (Sun et al. 2015a). The nursing home or consumer with a food printer at home could log into an online database of recipes and design tasty meals with proper ingredients. A German nursing home uses a 3D food printer, mixing mashed peas, carrot, and broccoli, and creates a product called Smoothfoods. They serve this to elderly residents who face difficulties in chewing. Over 1,000 such facilities in Germany adopted the technology (Gamboa, 2017). An Italian 3D printing company called WASP is testing a printer that can produce gluten-free versions of popular foods (Kenneth Research, 2019).
4. **Restaurants –** 3D food printing offers restaurants the potential to improve food innovation, create personalized and digitized nutrition at reduced time and cost (Refrigerated & Frozen Foods, 2018). CEO Antony Dovbrzensky manufactures the entire dining experience at Food ink, including the tables, the cutlery, and the food. La Enoteca in Barcelona features a dish called, Sea Coral. The Foodini printer uses a seafood puree to sculpt a flower-like design, and the chefs embellish it with an assortment of seafood- a time-consuming and challenging design to create by hand (3Dprinting.com, 2017).

SUMMARY AND CONCLUSIONS

Traditional food manufacturing machines use decentralized methods for producing food products. They create a food item by integrating different machines, performing different actions on the raw ingredient. On the other hand, the 3D food printers work on the centralized methodology and as a stand-alone unit that performs multiple actions on the raw ingredients to cook a programmed food. The 3D printing process is simpler and eliminates many steps used in traditional manufacturing. The technology enables faster product design, customization, cost reduction, faster product testing, and more. For instance, medical, dental, aerospace, and retailers are using 3D printing technology successfully in the areas of product and tool development. Furthermore, its advances are increasingly becoming relevant in the food industry. Food printing technology is truly innovative; it opens new opportunities and lends itself to many possibilities for businesses looking to improve food efficiency and design. Food printing significantly streamlines traditional methods and has the potential to become the norm over the decade to come. Today, food printing is no longer an idea but a reality. It can revolutionize food innovation and production through customizability, better creativity, and sustainability. It could eliminate the entire process, from grocery shopping to preparing the ingredients and cooking.

Currently, 3D food printing is being applied in food areas such as military food, space food, elderly food, and sweets food. Several factors are enhancing the popularity of the food printing industry. The influential Millennial demographic has focused so much on food as a critical part of their social, political, and economic consciousness. Their focus on fresh, personalized, and made-to-order foods has been a game-changing development for the food industry. Food printers are also becoming more affordable. Additionally, manufacturers are improving the capability of the printers to boost culinary creativity and customizability of nutrition and ingredients. It is not far in the future where we might be eating pizzas, pasta, quiche, or brownies all printed by a food printer.

Food printers, though advantageous, are still an emerging technology that must overcome several challenges, including cost, speed, and ease-of-use. However, 3D printers are getting better every year, and the price is falling owing to the increasing adoption and technological developments. The future of 3D food printing is bright, as there is no limit to the scope and the future of the 3D culinary printing industry. The technology will have a massive impact on the global economy, giving customers a significant degree of freedom in choosing the type of food they want to eat. However, some experts argue that 3D food printers are still missing the ability to actually cook or bake. That is why cooking robots could be more and more popular in the future.

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