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Preface

The book entitled "***Food Printing: 3D Printing in Food Industry***" aims to present various practical outbreaks of designing and preparing food using *Additive Manufacturing, also known as "3D printing."* This book presents multidisciplinary aspects of the evolutionary growth of this exception in food technology including social, industrial, administration, and scientific. Moreover, a variety of design ideas interacts to humans like printing of cakes, cookies and chocolates. Overall, it is believed that the combined efforts of the editorial team members and contributing authors this book massive attention across food industries, food technology, nutrition, dietician researchers, food manufacturing units, and academic platforms.

Mohali, Punjab, India — Kamalpreet Sandhu
Singapore, Singapore — Sunpreet Singh

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About the Editors

Kamalpreet Sandhu is an Educator and Researcher at Plaksha University, Mohali, Punjab, India. His area of research is Design Thinking, 3D printing, and Ergonomics for Podiatric Medicine. He has successfully established research collaborations in India and abroad to advance his research interest in Design Thinking and 3D Printing.

Sunpreet Singh is a researcher in NUS Nanoscience & Nanotechnology Initiative (NUSNNI). He has received a PhD in mechanical engineering from Guru Nanak Dev Engineering College, Ludhiana, India. His area of research is additive manufacturing and the application of 3D printing for the development of new biomaterials for clinical applications. He is working in collaboration with Prof. Seeram Ramakrishna, NUS Nanoscience & Nanotechnology Initiative, and Prof. Rupinder Singh, manufacturing research lab, GNDEC, Ludhiana.

Chapter 1
Materials for Food Printing

Jaspreet Kaur, Vishesh Bhadariya, Jyoti Singh, Prerna Gupta, Kartik Sharma, and Prasad Rasane

Abstract The materials required for food printing act as a restriction towards the uptake of additive manufacturing in industries. Therefore, the selection of material heavily depends on phase transition, various chemical reactions that are responsible for binding layers together, physical state and the process of the material. Usually 3D printing involves the use of plastics such as polylactic acid (PLA), acrylonitrile butadiene styrene, nylon, etc.; various other materials like hydrogels and cellulose along with its derivatives are also employed in additive manufacturing during manufacturing applications. Overall, 3D food printing materials possess different requirements for different phases, namely pre-extrusion phase and post-extrusion phase. During the initial phase, the food formulation should be in liquid form, which is ensured by smaller particle size of the food material, whereas in post-extrusion phase, the printed food should resist the structural deformation post deposition, which can be achieved by curing of printed food. Fibrous food materials undergo mechanical degradation with the help of shearing equipment such as mixer or kitchen blender. Various food materials are used in different printing methods, namely hydrocolloid systems (gelatine and xanthan gum), flavourings, modified turkey, scallop, wheat dough are used in cold extrusion method; milk chocolate in hot melt extrusion; mashed potato, cream cheese and chocolate in hot and cold melt extrusion; combination of icing, caster, silk sugars along with maltodextrins in binder jetting printing method; mint syrup, linseed oil, wax, carrageen shell, edible ink made of glycol, ethanol, glycerol or water in inkjet printing method; etc. The complete literature review reveals the various applications and challenges faced by researchers while conducting studies based upon food materials used for 3D food

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printing. This chapter aims to provide an updated analysis on the research into food printing technology.

Keywords 3D food printing · Properties of food materials · Materials · 2D and 3D printers · Utilization in food industry

1.1 Introduction

Three-dimensional or 3D food printing, also known as additive manufacturing, has been established since the 1980s. It is used to construct complex physical models based on 3D models without using any sort of cutting tools, fixtures, moulds, dyes and coolants as materials, and are added layer by layer from the computerized model. Owing to its wide range of applicability, this technology is widely used by several fields, including food industry, aerospace, fashion design, medical, automotive, architecture and automobile industry. Attractive printing or imaging or surfaces always appear to represent main idea behind the design and product. These days printing an image on food packets requires careful consideration of selecting inks which should be edible in nature and their production process should be environment friendly [1, 2]. In the new era of food packaging, food processing industries have considered the aspect of designing the packages to be very important. They realized that the attractive colour of foods, shape, size, ingredients and printing images on packets play a dynamic role in fetching the attraction of consumers. In current scenario, various patents (e.g. 3D printers with deposition and for rapid prototyping) are commercially available [3, 4]. Consumers are focused on specific traits of food products including food constituents and printing techniques [5]. Thus, food industries are now more focused on the consumer specific needs, which involve tasty food products that are remarkable in appearance and provide proper nutrition as well.

Food industries certainly face challenges with food packaging especially when plastic packaging materials react with food products which can result in migration of monomeric additives such as plasticizers, preservatives, antioxidants and stabilizers into the food materials [6]. It was reported in a research study conducted by Castle et al. [7] that food packages made from polypropylene material containing edible products that might chemically react with each other due to transferring of ink from the outer surface of package to the inner food constituents. Therefore, it was concluded from the experiment that food imaging or food print processing play an important role in food processing industry specifically when human health is taken into consideration. Recently, scientists are taking help of programming language such as visual basic and MATLAB as a part of their research in order to modify the food printing technology which helps in the determination of three-dimensional space distribution of colours [5].

This chapter aims to provide an emerging field available for researchers and industrialists in order to update the current innovations with respect to the technology for food imaging or printing onto food products. It will provide a deep insight to the readers about the consumer market, product development, product promotion, various properties and types of materials used in 3D food printing, comparison and technical advancements in the field of 2D and 3D food printers, applications as well as rationale of 3D technology in detail.

1.2 Methodology

The chief aim of the literature searching strategy was to explore the concept of 3D food printing, properties and types of materials most commonly used for 3D printing, comparison between 2D and 3D food printers, application of 3D printing in extrusion technology, inkjet printing, powder binding deposition, bioprinting and the rationale of 3D technology. A number of relevant publications were identified through searching over the electronic databases (ScienceDirect, PubMed, SciELO, Google scholar, SpringerLink and ResearchGate) based on keywords such as 3D food printing, properties, materials, 2D printers, 3D printers, applications of 3D food printing in food industry and rationale of technology. After searching suitable literature, 78 papers (including research and review articles) were reviewed which provided a detailed overview of all these aspects covered in this chapter.

1.3 Properties of Materials to be Used in 3D Food Printing

Various approaches exist in order to make the food purees printable in nature. Nevertheless, the fundamental mechanism for getting a productive 3D printout is quite indistinguishable and is independent of the type of additive used in the whole process. In the first phase of the process (i.e., pre-extrusion phase), it is highly desired that the food formulation must be fluid in nature and the particle size of the food material should be small. For instance, the high fibre food materials need to be degraded to reduce the particle size by using equipment of high shear quality. In the same line, food materials like powders (milk, sugar, starch, protein) and liquids including lemon juice can be utilized for 3D food printing. In the second phase of the process (i.e., post-extrusion phase), curing for the printed food is done in which the material undergoes deposition followed by the structural deformation. Therefore, the food material must bear the property of resistance against such sort of structural deformity. Curing is done either by employing heat treatment (for food materials) or by the use of UV radiations (for non-food applications). Taking the aforementioned properties of the food material into consideration, it is highly required to formulate food inks which are shear-thinning in nature. It allows the smooth flow of the food material through the printing nozzle by applying high shear at the nozzle end and once the material is printed onto the print bed, no further shear is experienced and the 3D shape of the food is also very well retained on the print bed. The two major factors which contribute to the shear-thinning behaviour of the food material include disentanglement of macromolecules (food fibres) in the solution and alignment of food emulsions in the layered form. The former factor affects the intermolecular forces of attraction between the molecules by reducing electrostatic attractions, Van der Waals forces as well as hydrogen bonding. While the latter factor *i.e.*, alignment of food emulsions in the layered form, leads to reduction of collision between food particles which further results in decreasing the viscosity of the emulsion and therefore, it exhibits shearthinning properties [8].

It has been revealed that while doing the practical procedures in 3D food printing, the optimization of hydrocolloid mixtures is done to obtain the desired degree of shear-thinning property of any particular food system. By ensuring that the particle size of the food material is small and the concentration is apt, shear-thinning property can be achieved as the cluster arrangement will be loose enough. Certain food additives are used in 3D food printing to enhance the printability of various food materials [8]. Yang et al. [9] conducted a research study in which potato starch in different concentrations was used as an additive to make lemon juice in printable form. The mixture of potato starch and lemon juice was subjected to heat treatment at 86 °C which resulted in swelling of starch granules followed by rupturing. It led to the release of starch constituents into the mixture and thereby increased the overall viscosity. A stable and desirable network of gel was formed on subsequent cooling of mixture. Therefore, the study proved that potato starch is a potent candidate for 3D food printing as it undergoes the desired process of gelatinization. The only drawback associated with the utilization of potato starch is that it should be used in high concentration in order to be comparable to the use of hydrocolloids.

Derossi et al. [10] attempted to formulate a printable food puree ink by mixing food puree (consisting of banana, dry milk powder, lemon juice, canned beans and dried mushrooms) with different concentrations of pectin solution. High-methoxyl pectin (HM pectin) and low-methoxyl pectin (LM pectin) can be used for this purpose as the former leads to the formation of strong gel networks followed by heating in the presence of acid and sugar, while the latter forms gel networks in the presence of Ca^{2+} ions. As pectin is a common gelling agent used in food industries, it contributes to the overall printability of food puree [8].

Liu et al. [11] used different concentrations of gelatine and mixed it with mechanically blended cooked meat and observed that the 3D printing process became smooth and consistent as compared to the sample of meat in which gelatine was not added. The result showed that phase separation was observed between liquid phase and solid meat, which ultimately results in nozzle blockage and therefore poor prints. However, upon the addition of gelatine there was improvement in overall process of printing and ultimately ends in consistent printing. Another study revealed that better printing quality was observed when 40 g of gelatine was added as compared to one in which only 20 g of gelatine was added. During hydration and rising the temperature to 40 °C, results in unravelling and denaturing of the amino acid chains of gelatine which later allows the hydrophilic R group to bind with water. Further cooling of the same till the temperature becomes same as that of room temperature, gelatine amino acid chains renatures themselves and forms fibrillar collagen. These helical structures crosslink with each other, thereby forming the gel network which is thermo reversible [12]. Studies revealed the potential role of gelatine in the formation of gel network throughout the cooked meat sample. Thus, gelatine (a hydrocolloid) is highly suitable for 3D food printing of the substances which contain high amount of protein content.

Lille et al. [13] used self-made cellulose nanofiber (consisting of 73% cellulose, 26% hemicellulose, 1% lignin) mixed with milk powder and starch to form food ink. The food ink so prepared consisted of digestible proteins derived from milk, carbohydrates from starch and non-digestible fibre owing to the presence of cellulose, hemicellulose as well as lignin.

Shoseyov et al. [14] attempted to utilize crystalline nanocellulose and nanofibrillated cellulose, which is monocrystalline and fibrillar, respectively. Owing to the good shear-thinning properties of these additives at low concentrations, they are capable of forming self-assembled gel networks and, moreover, these additives do not require any kind of heat treatment or cooling cycle for gel formation [8, 15].

Zhang and Zhang [16, 17] carried out research studies on various food materials (such as mushroom, tomato, blueberry, pumpkin, mulberry and fig) in order to formulate 3D printable rice vermicelli noodle. Alginate and carrageenan were used as an additive in this process. A mixture of sodium alginate, potassium alginate and carrageenan was prepared and mixed into the food ink followed by spraying of a mixture containing calcium gluconate, calcium lactate and calcium chloride after deposition of each successive layer. The purpose of spraying mixture of calcium salts over the alginate mixture was to promote the gelling process and a desirable gel network was formed [8].

1.4 Various Materials Used for 3D Printing Technology

3D printing requires good quality materials of consistent specifications to develop consistent high-quality devices for which there is need of establishment of procedures, agreements and requirements of material between purchasers, suppliers and end users of the material. Three-dimensional food printing has potential of producing fully functional parts by using polymers, metallic, ceramic and their combinations in form of hybrid or composites [18].

1.4.1 Metals

In automobile, medical application, aerospace and manufacturing industries, metal 3D printing technology is used as they possess good physical properties [19, 20]. Various materials used under this category are titanium alloys [21], aluminium alloys [22], cobalt-based alloys [23], stainless steels and nickel-based alloys [24, 25]. Due to the high specific stiffness, high recovery capacity, resilience, elongation and high treated conditions, cobalt-based alloys are recommended for dental application

[22]. Nickel-based alloys have high corrosion resistance and can resist temperature up to 1200 °C, which makes it more suitable for the production of aerospace parts [20]. Titanium alloys, because of their oxidation resistance, ductility, good corrosion and low density are used in 3D printing technology in aerospace and biomedical industry [21, 25].

1.4.2 Polymers

For the production of polymeric components, 3D printing technologies are used, and by using fused deposition modelling (FDM), they can form a 3D printed through deposition of extruded thermoplastic filament including acrylonitrile butadiene styrene (ABS), polyethylene (PE), polylactic acid (PLA) and polypropylene (PP) [26]. The low cost, low weight and processing flexibility of polymeric materials makes them suitable for 3D food printing [27]. These polymeric materials are used for the development of medical device products and provide mechanical support in orthopaedic implants [23].

1.4.3 Ceramics

The 3D technology also uses ceramics and concrete without any cracks or pores for the production of 3D objects and set up excellent mechanical properties. Ceramics possess good durability; properties like fire resistance; and due to their fluid state before setting, these can be moulded into any shape and geometry [28]. Ceramics are used in the dental aerospace industries and various materials used under this category are bioactive glasses, alumina and zirconia [29–32]. Among all, alumina powder is widely used in the areas of microelectronics, aerospace and high-technology industries [33]. Zirconia, especially hafnium-free zirconium, are used as construction materials in nuclear power sectors as they have low susceptibility to radiation and show low thermal neutron absorption [32].

1.4.4 Composites

Composites are used in high-performance industries because of their exceptional versatility, tailorable properties and low weight, and they include carbon and glass fibre–reinforced polymer composites [34, 35]. The difference in the properties of these two makes them suitable for different applications, like carbon fibre–reinforced polymers composite structures are used in aerospace industry as they have high strength, specific stiffness and good corrosion resistance, whereas glass fibre–reinforced polymers composite structures have various applications due to their cost-effectiveness and high performance [34]. Fibreglass, due to its high thermal conductivity and low coefficient of thermal expansion is suitable for 3D printing applicant [36].

1.4.5 Smart Materials

Smart materials are the those that can change the shape and geometry of the object and get influenced by external factors like water and heat [37]. These can be classified into shape memory alloys and shape memory polymers [38, 39]. Nickel titanium is one of the shape memory alloys that is used in electromechanical devices application but has some issues like density, transformation temperatures and reproducibility of microstructure. Shape memory polymer (SMP) responds to heat, electricity, light, etc. [38].

1.4.6 Special Materials

The examples of special materials include food, lumar dust and textile. Food materials like candy, meat, pizza, spaghetti, chocolate, sauce, etc., could be used in 3D printing technology to produced desired geometry and shape [40]. The advantage of 3D food printing allows the customer to alter the ingredients without reducing the taste and nutritive value [41]. From lumar dust, multilayered parts by using 3D printing could be developed which has potential applicability for future moon colonization [42]. In textile industries, 3D textile printing has important role to play as they reduces the cost of packaging material and also reduces the supply chain cost [43].

1.5 Other Available Printing Materials

Various efforts have been made to preprocess materials well suited for 3D printing and increase their thermal stability. The Netherlands Organisation for Applied Scientific Research (TNO) has proposed printing pureed food for old-age population because of their chewing and swallowing problems [44]. TNO has also developed printed customized meals for pregnant women, seniors, athletes by altering proteins and fat. They are further classified into natively printable materials and non-printable traditional food materials.

1.5.1 Natively Printable Materials

Natively printable materials include cheese, cake frosting, chocolates, hummus, hydrogel which can be easily extruded from syringe smoothly. Southerland et al. [45] has studied the application of mixture of starch, mashed potato and sugars as powder materials in Z corporation powder/binder 3D printer. Number of sugar teeth was developed for demonstration but none of them is the main course of meals. Fabaroni et al. [46] has tested pasta dough for printability and studied the viscosity, solidifying properties and consistency. These natively printable materials are highly stable to hold the shape after deposition and used in the field of medical and space industries. Food products made by natively printable materials can be easily controlled in taste, nutritional value and texture. For composite formulations like protein pastes and batters, post-deposition cooking process is required which make food product structure difficulty to retain their shapes [47].

1.5.2 Non-printable Traditional Food Materials

Foods like fruit, vegetables, rice and meat are not printable by nature but by adding hydrocolloids in these materials, their capability of extrusion can be enhanced. Complex geometrics and novel formulations were made by adding simple additives in traditional food recipes by Lipton et al. [47].

1.5.3 Post-Processing

The process of food printing does not require a high energy source to remove liquid ingredient completely from food composition. There is no need of solidification in fabricated layers as they have sufficient strength and rigidity to support its own weight without changing the shape [48].

1.6 Application of Hydrocolloids as 3D Food Material

Hydrocolloids are usually heterogeneous group of hydrophilic polymers that form gel-like or viscous dispersions when dispersed in water [49]. Various additives like pectin, starch, alginate, gelatine, nanocellulose, carrageenan, hydrocolloids, etc. are responsible for altering texture as well as rheological properties of pureed food to enhance the printability. Various hydrocolloids such as starch, guar gum, xanthan gum, locust bean gum, beta-glucan, alginate, pectin, inulin, konjac glucomannan are the ones which are most widely used now days. Number of approaches can be made

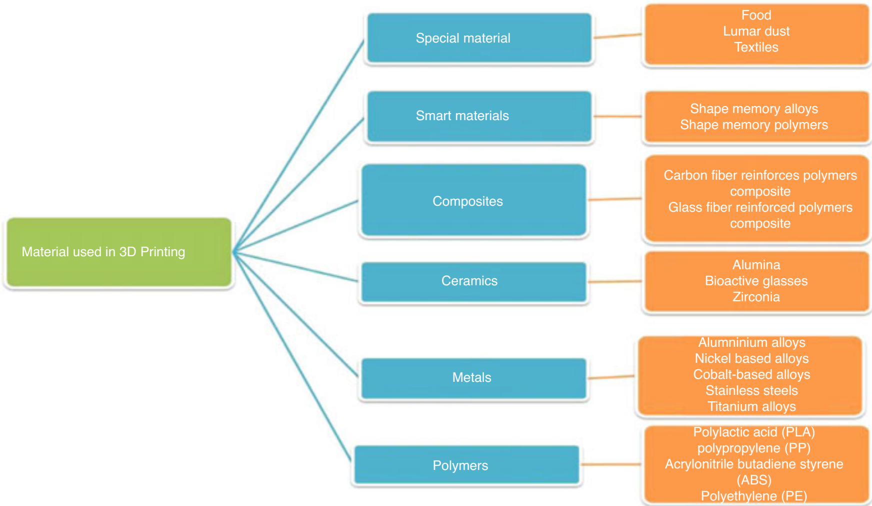

Fig. 1.1 Different materials used in 3D printing. (3D food printing is used as an advanced manufacturing technique by the industries. Various 3D printing materials like metals, polymers, ceramics and smart materials are used owing to their excellent physical and mechanical properties for the printing process)

to make purees printable and the mechanism for successful printing remains similar for almost all the additives [50].

Xanthum gum, which is obtained via aerobic fermentation of sucrose or glucose, is a commonly used as a thickener as it possesses better stability along with thickening ability at lower concentrations and remains stagnant at wide range of salt concentrations, pH and temperatures. The molecules of xanthan gum forms intermolecular clusters or aggregates either by polymer entanglements or hydrogen bonding. Hydrocolloids such as gelatine and xanthan gum are being used in combination with various food ingredients, where these act as alternative for making various printable food materials made up of protein, starch, etc. [4]. These two hydrocolloids, namely gelatine and xanthan, stimulate wide range of mouthfeels by providing different flavours and textures [49].

Thus, it can be concluded that the materials used for 3D food printing must meet certain specifications in order to give a fruitful result. There a several advantages as well as drawbacks associated with the use of this wide range of materials employed for 3D food printing technology, which should be considered while choosing the appropriate one. Some of the different materials used in 3D printing are shown in Fig. 1.1.

1.7 Comparison Between 2D and 3D Printers

Currently, most of the research focuses on the development of printable materials and control of printing parameters in order to improve the printing accuracy and product quality. However, the influence of material pre-treatment methods and post-processing techniques on 3D food printing have received less attention. This was due to the effect of pre-treatment technologies (crushing, gelation, recipe formulation, etc.) and post-treatment technologies (cooking, drying, frying, boiling, steaming, fast cooling technology, 4D printing, etc.) on the accuracy and shape fidelity of 3D printed food products [51]. For example, in 2012, EC passed a regulation permitting the use of food additive E445 (glycerol esters of wood resins) as an emulsifier in water-based inks used for inkjet printing on confectionary after a request from Mars Chocolate UK (William Reed Business Media 2012). A brief comparison between the 2D and 3D printing methods along with their technological advancements, principles, durability and other aspects has been presented chronologically in Table 1.1.

Table 1.1 Technological advancement of 2D and 3D printing in food

Company	2D printing		3D printing	References
Machine	EdiJET (Inkjet)	Laser marking	ChefJet, robotic and conveyor, moulding, extrusion, sintering, inkjet printing and bioprinting	[52]
Principle	Small ink drops generated and placed on substrate to form an image from digital file	Colour change or engraving, contactless, no additives, image from a digital file	Modified shape, size, designs, texture and shading	[53]
Technologies	Prints edible ink, ink tubings	Optical components, laser tube	Inkjet powder printing	[54]
Materials	Embedded letters/ logos in cookies, photo cakes, rice sheets and sweets	Meat products, eggs, cheese, medical products	Powdered sugars, starch, cornflour, liquid binders, military food, space food, elderly food, culture of cells	[16]
Platforms	As an emulsifier, customized and personalized marking	–	Motorized size, powder bed	[55]
Fabricated products	Full colour	Single colour	Sugar cube in full colour, meat, xanthan gum, sodium alginate	[47]
Marking distance	1–5 mm	Up to 1 m	Layers as thin as 16 μm	[4]
Durability	Low to high	Permanent	Permanent	[49]

1.8 Application of 3D Printing in Food Industry

Three-dimensional printing has emerged as one of the creative technologies in food. Its progression lies in providing better characteristic features, customized shape, design, colour, textural and flavour properties to food. Personalized nutrition design with simplified supply chain to meet consumers need and to facilitate new product development has also been observed [48]; for example, to improve the digestion of elderly people soft food was prepared by using 3D edible gel printer with a syringe pump and a dispenser by Serizawa et al. [56]. To provide an accurate and precise printing, three main aspects—material properties, process parameters and post-processing methods—are considered, respectively. Three-dimensional printing today finds applications in many industrial sectors like automobiles, medicine, textiles, civil engineering, military, agriculture and many food applications as food-layered manufacture (FLM) and can also be used with computer-aided design (CAD) tools [54]. Desired shape of the food can be processed and produced, and geometrical shapes can be obtained by using materials like chocolate, meat, candy, pizza, spaghetti, sauce, etc. [34, 57]. Without reducing the nutrient content, a desirable sensorial attribute can be maintained without compromising in quality, and thus a desirable healthy option can be produced. Today there is a growing demand for food with special dietary needs for people like pregnant and lactating mothers, growing and malnourished children, athletes, and patients with special care. Three-dimensional printing offers specific mixing of ingredients (carbohydrates, proteins and fats, respectively) with complicated but interesting food designs like pasta, crackers, chocolates, pizza, etc. [40, 41]. In 2018, propionic acid production by *Propionibacterium acidipropionici* immobilized on 3D-printed nylon beads was used for the first time to create a matrix for cell immobilization in the process of fermentation by Belgrano et al. It has been reported that these printed 3D beads can be used for other fermentation bioprocesses and are capable of promoting high-density cell attachment and propionic acid production.

An Italian bioengineer, Giuseppe Scionti in 2018 developed a technology using custom 3D bioprinter capable enough to generate fibrous plant–based meat analogues, mimicking meat texture and nutritional values and named it Novameat [58]. To minimize food waste NASA is looking into advanced technique to create 3D printed food that fit an astronaut's dietary needs [4, 59]. The various applications of 3D printing applications, namely extrusion process, inkjet printing, bioprinting and powder binding deposition, have been presented in Fig. 1.2 along with the detailed explanation of these approaches has been discussed in the sections below.

1.8.1 Extrusion Process

Extrusion process involves the deposition of powder-based or liquid-based material followed by heating (either by laser and or hot air) and then cooling leading to