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Research Article

BRIEF INSIGHT INTO 3D FOOD PRINTING, FUNCTIONAL INGREDIENTS REQUIRED, TYPES OF DIFFERENT 3D FOOD PRINTING TECHNOLOGIES

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A R T I C L E   I N F O

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A B S T R A C T

Three dimensional (3D) food printing is a novel and unique technology which combines both food technology and manufacturing processes to design distinctive food constructs with enhanced flavor, color, texture, taste and shape. This review aims to highlight the unique features of 3D food printing, its role in the food manufacturing, processing and packaging industries, application of this in outer space particularly in NASA, along with the recent advances undergone in this field which includes application of different printers and inks, printing techniques according to the requirements and needs. The essential ingredients of the edible food materials used as printable materials along with their pre-treatment and post treatment is discussed. A brief insight is provided into the 4D food printing technology which is derived from 3D printing, its applications and robustness. The future scope and prospects of 3D food printing in the medical, pharmaceutical and food industry has been discussed focusing mainly on elderly people, pregnant women and patients.

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INTRODUCTION

Three dimensional (3D) printing technology is considered as a part of additive manufacturing process that involves layer by layer construction of complicated, solid and grid-like structures and geometrical figures. Phase transitions and chemical stimuli act as adhesives in order to provide contact between the layers and thereby bind them together. The year of 1980's showed the emergence and development of 3D printing.3D food printing method is a combination of 3D printing technology and food manufacturing process in which fruit and vegetable juices, powders, starch, meat, algae, insects and chocolates are used as edible materials. Customized and tailored edible food products can be produced which cater to the requirements of the customers based on their age, gender, lifestyle and occupation by the addition of desired nutrients, functional components or by reducing/eliminating the undesired ingredients which help to maintain and promote good health, free from diseases[1].3D food printing helps in the mass production of food materials which results in economic and environmental benefits[2].Other synonyms of 3D printing technology include Additive Manufacturing Technology (AM), rapid Prototyping (RP)/ Solid Free Form Fabrication (SFF). 3D food printing has emerged as an efficient technology over the years because of its ability to produce customized food along with the desired size and shape, due to the reduction in the production costs, minimum duration of time required for the manufacturing process etc. 3D food printing helps to customize food materials based on the requirements like nutritional factors which include the functional components such as proteins, carbohydrates, lipids ,vitamins, minerals and dietary fibres in proper proportions[3]. It caters to the calorie intake of the individuals as well[2]. 3D printed foods were produced initially mainly focusing the interests of elderly people, patients facing swallowing difficulties, athletes, astronauts, pregnant women and the army. Extrusion based printing was the first technique used for 3D food printing[3]. Different techniques are employed for 3D food printing which include extrusion based printing, selective laser sintering, binder jetting and inkjet printing. The applications and advantages of these printing techniques are discussed in detail in the later sections. Some of the currently used commercial 3D extrusion based printers include BeeHex Robot pizza printer which can print chocolate and pizza respectively. Foodini, ByFlow and Procisini 3.0 are the other 3D extrusion based printers which have the ability to print savory and sweet food[2]. 3D food benefits the soldiers by enhancing the shelf life and thereby catering to their food requirements. Space food can be prepared by dehydrating the food materials to ensure longer shelf life without spoilage for later consumption[1].

Role of the functional ingredients in the edible food materials used for 3D food printing:

The functional ingredients can be classified into functional carbohydrates, functional proteins, functional lipids, vitamins and minerals, probiotics and algae.

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Table 1 Functional ingredients used in 3D food printing

Sl.No	Functional ingredient	Action	Reference
1	Functional Carbohydrates		[1]
1.1	Maltitol and Xylitol	Addition of maltitol and xylitol in chocolates can reduce the problem of obesity	[1]
1.2	Isomaltose	Isomaltose is an ideal substitute for sucrose. It can also act as a lubricant which helps to moisten the ink formulations	[1]
1.3	Xanthan gum	Xanthan gum is a hydrocolloid which functions as a gelling or a thickening agent to improve the mechanical stability of food constructs after processing.	[1]
1.4	Dietary fibre	Dietary fibres play a vital role in gastrointestinal peristalsis, speed up the passage of food through the GI tract, and modulate the absorption of nutrients.	[1]
2	Functional Proteins		[1]
2.1	Pea protein	Pea proteins are rich sources of essential amino acids except methionine. They enhance the texture properties, improve the structure stability and balance the nutritive contents of the printed food structures.	[1]
2.2	Whey protein isolate	This helps to promote good health by reducing diseases. This provides resistance to virus and oxidation.	[1]
2.3	Insect protein	Insect proteins are good sources of proteins and minerals.	[1]
3	Functional Lipids		[1]
3.1	Lecithin	Lecithin is an important constituent of biofilms. It possesses antioxidant properties.	[1]
4	Vitamins and minerals	Required for the growth and development of the body. Vitamin D and Vitamin E are considered.	[1]
5	Probiotics and algae	Probiotics produce antimicrobial substances and perform immunomodulatory roles. This is useful for people suffering from metabolic diseases, periodontal diseases and inflammatory bowel diseases. An algae Nostoc sphaeroides has the ability to cure variety of medical conditions such as inflammation, indigestion, night blindness, burns and anxiety.	[1]

Some of the properties of the edible materials used to predict the efficiency of printability.

Some of the techniques followed for post treatment include cooling, cooking, drying and 4D food printing.

Table 2 Properties of the edible materials

Sl.no.	Properties of Edible Materials	Applications	Reference
1	Shear modulus of the material	Used to predict the shape deformation of 3D printed foods.	[2]
2	Flow behavior index n	Food materials should possess low viscosity for easy outflow through the nozzle.	[2]
3	Elasticity	Food materials possess complete elastic properties below the yield stress.	[2]
4	Hardness	The shape of the materials and extrusion characteristics depend on the hardness of the food material.	[2]

Pretreatment of the materials used for 3D food printing: It is very important to select materials with suitable physical and chemical properties like particle size, fluidity, rheology along with the mechanical properties for 3D food printing. Some of the commonly used materials for 3D food printing include cells, tissues, ceramics, synthetic polymers and metals. Some of the properties to be possessed by the food materials include appropriate viscosity, fluidity, rapid recovery performance and proper mechanical strength, for easy outflow through the nozzle tip and being able to self-support and maintain the shape after printing. Therefore, pretreating of food ingredients so as to meet all these properties such as rapid recovery behaviour, proper fluidity and appropriate mechanical strength are very vital and essential to achieve successful printing. Comminution and microencapsulation are some of the methods used to obtain powdered 3D food materials. Comminution helps to obtain the powder with appropriate flow ability and particle size by incorporating falling abrasive bodies in order to crush, grind and mix the materials. Microencapsulation is a process wherein solid particles are formed by embedding solid, liquid and gases in a microcapsule. This technology helps to embed the functional components such as vitamins, minerals, enzymes, probiotics etc. so as to protect against the environmental cues[3].

Post treatment of the materials used for 3D food printing: Some defects are seen on the surface of the food materials after the completion of 3D food printing process. Therefore post treatment processing operations are performed to ensure and improve the precision of the product along with the stability of the shape.

Some of the drying methods used include oven drying, vacuum microwave drying and freeze drying. Based on the type of drying method selected and the material of the printed food, appropriate range of temperatures are incorporated for drying purposes. Rapid cooling method tries to effectively maintain the stability of the 3D printed food structures. Some of the cooking methods include steaming, frying, baking etc. Information Technology and Mechatronics are currently used as advanced technologies as a part of modern cooking techniques to procure varied tastes and flavours[3].

Mechanism of action

3D printing technology is an automated manufacturing method which is based on layer by layer deposition or distribution. The food structure is created in CAD programming and other complex forms can be created thereafter. The created food structure is made in Standard Tessellation Language (.STL) file format. The model is made as a limit model with triangular facets in. STL document file[4].

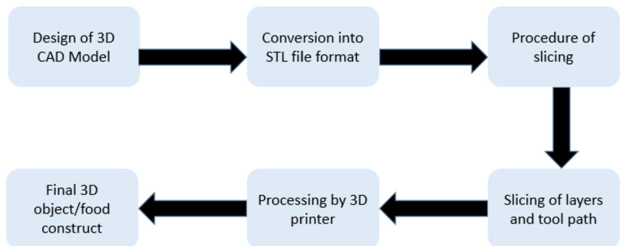


Figure 1 Basic workflow of 3D printing technology[4]

A well formatted and well defined sequential procedure is followed for 3D food printing technology. The procedure begins with the designing of a 3D CAD model which is of the desired geometry. Information about the surface features is obtained by scanning the created models. Next different slicing softwares are used based on the requirement and they are sliced into different individual layers. Machine codes get generated for each of the layers during the above process. Eventually G codes and M codes get generated which are transferred to printers for printing preferred recipes. Numerical control language is referred by G codes which are produced by the CAD software which helps to guide the motors with respect to printing speed, printing region and printing axis. Auxillary commands are referred to by M codes which assist in machine functioning. A slicing software is essential for printing complex 3D structures and geometries. Based on the requirements such as model development, scanning and printing applications, different types of softwares are available and in use. Since the G codes consume high memory space, the data is converted into. STL file format for easy processing[5].

Types of 3D printing techniques

The following points are the prerequisites considered while implementing 3D printing technology on the food materials used 1) material of the food 2)The technique of 3D printing 3)Design of 3D structure and the path followed for the designing 4) Assessment of the quality of the printed objects and the printing parameters used.

Material: Choice of proper material along with the deep analysis of physical, rheological and chemical properties[6].

Technique of 3D printing: The properties of the materials, its applicability and post processing requirements play a vital role in the choice of the right 3D printing technique[6].

Design of 3D structure and the path followed for the designing: This is performed using different softwares. The mechanism of action is already discussed in the above sections.

Assessment of the quality of the printed objects and the printing parameters used: Based on the mechanical properties and the shape fidelity, the quality of printed objects and printing parameters is assessed[6].

Based on the driving mechanisms of printing, the different classifications include extrusion, heat source and inkjet printing.

Extrusion based printing: This is also known as Fused Deposition Modelling (FDM)[8]. This is the easiest and the simplest method of 3D food printing. The mechanism is that a robotic arm having a cylinder/syringe moves along the surface thereby extruding material through a nozzle. The deposition of layers one after the other is done by directing the cylinder/syringe at specific, predetermined locations using a 3D model. Food pastes having high viscosity are used in syringe based extrusion printers. The food ink used for this purpose is extruded with the help of a die or printing head which is expected to have mechanical properties or viscosity that permits vertical assembly[7].Usually three types of extrusion mechanisms are performed using extrusion based 3D food printing which are air pressure based, syringe based and screw based extrusion[8]. Extrusion temperature is also one of the important parameters for quality printing in extrusion based printers.

Inkjet printing: An array of pneumatic membrane nozzle jets are used which can lay down tiny drops of food inks on the moving objects placed below. A digital image in the form of a graphical, cavity deposition or surface filling is created by collection of drops. Low viscosity materials are usually handled in inkjet printers. This method is mainly used to print on flat food materials rather than on complex food constructs and structures. The surface energy of the inks and the rheological properties are modified by temperature and hence is an important parameter in inkjet printing[7].There are two types of inkjet printing known as continuous and drop on demand printing respectively. Inkjet printing is used for confectionaries and decoration purposes. This technique works best for low viscosity materials such as jams, gels, liquid dough and chocolates[8].

Binder Jetting: In this technique, the powdered material is evenly distributed over the fabrication platform and the two consecutive powder layers are bound together using a liquid binder spray. A counter rotating roller is used to uniformly spread the layer of powder on different layers. After this step, an inkjet print-head is used which jets out a liquid binding agent onto the powder layer to create a 2D pattern for the layer. This technique is known for its low material cost and fast fabrication. However the materials obtained from this technique possess rough surface finishes and also the cost of equipment is comparatively high[7]. To increase the mechanical strength and to allow the deposition of successive layers, the surface is usually irradiated after the deposition of the binder.

This technique can be used to print powdered materials such as protein, sugar, starch and chocolates[8].

Table 3 Materials and the types of printers used in 3D food printing

Sl. No.	Type of Material Used For Printing	Type of Printer Used	Reference
1	Liquid based materials	Both extrusion and inkjet printers are used	[6]
2	Powder based materials and structures	Heating mode type of printers are used wherein hot air and laser is used as a mode of heat. Binder jetting or inkjet printers are also used	[6]

Table 4 Types of extrusion temperatures and their mechanism of action

Sl. No	Extrusion Temperature	Materials Under Consideration	Mechanism of Action	Reference
1	Room Temperature Extrusion (RTE)	Dough, chocolate paste, hummus, cookies, pizza	RTE helps to fabricate complex confectioneries along with high repeatability	[7]
2	Hot-Melt Extrusion (HME)	3D chocolates	The molten or the semi solid ink used is extruded at relatively high temperatures from the printing nozzle which needs to solidify immediately after extrusion and weld to the previous layers.	[7]
3	Hydrogel-forming Extrusion (HFE)	Fruits, food for elderly people with swallowing difficulties	Dispersions or hydrocolloid solutions are printed into polymers, gel settings or hardening baths with the help of syringe pipette, vibrating nozzle, jet cutter and others.	[7]

Selective sintering: Based on the type of sintering method used, this technique can be classified into two types namely selective laser sintering (SLS) and selective hot air sintering and melting (SHASAM). The principle on which both these techniques are based is the same where a sintering source is used to fuse and combine the powdered particles and thereby form a solid layer. After the first layer gets completed, a new layer of powder is distributed on top of the previous layer using a roller. Most beneficial aspect of selective sintering is that the complex food structures can be constructed within a short duration of time without post curing. Nevertheless as many variables are involved in this procedure, the fabrication operation is complex[7].Some of the properties possessed by the materials include melting temperature, flowability, glass transition temperature, particle size, processing factors. Starch, fat granules and sugars are considered as some of the starting materials for selective sintering technique[8].

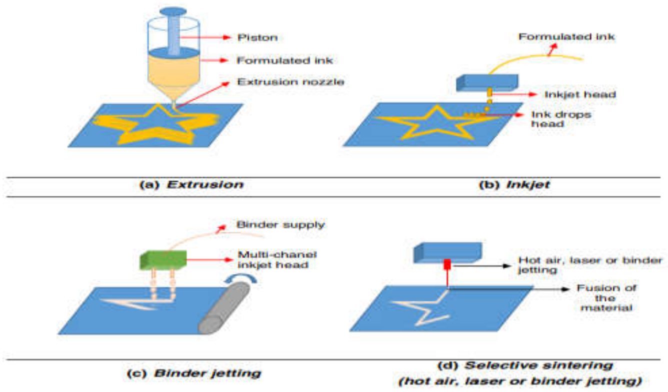


Figure 2 Different types of 3D food printing techniques[7]

3D printers

Table 5 Different types of 3D printers in use

Sl.No	Printer	Company Of The Printer	Food Materials Printed	Reference
1	RoVaPaste	ORD Solutions, Canada	Marshmallow, jam, honey peanut butter, ketchup	[8]
2	VX	ZMorph, Poland	Cream, cheese, dough	[8]
3	Foodini	Natural Machines, Spain	Crushed nuts, food pastes	[8]
4	Fab@Home Model 3	Creative Machines Lab, USA	Cheese, cookie dough	[8]
5	3D Food Printer	Create Bot, China	Chocolate, mashed potatoes	[8]
6	Food 3D printer	Micromake, China	Salad sauce, tomato sauce	[8]

Types of inks used: Food inks can be referred to as the final printable forms of any edible substance which is prepared from one or more raw materials. They are generally in the form of pastes or gels which can be extruded easily from the printer nozzle. Food inks can be broadly classified into two types namely natively extrudable and non natively extrudable. Natively extrudable inks are the type of inks which have favourable viscoelastic properties that allows direct extrusion without the addition of any matrix materials such as binders and gums. Materials used under natively extrudable inks are dairy, hydrogels and confectionery. More number of steps are required for the production of printable food inks under the non natively extrudable inks as these inks cannot be extruded through nozzles in their raw form. Materials used under non natively extrudable inks include plants where fruits, algae and vegetables are included along with meat[9].

Future of 3D food printing

Novel food textures are obtained from the food constructs by varying the microstructures

The internal structure of 3D printed objects is changed by the efficacy of layer by layer 3D printing technology wherein the infill patterns and infill percentages are varied which helps to control the density of raw materials in order to fabricate freeform geometries with different textural properties[10].

Food modified with improved texture for people facing chewing and swallowing difficulties

A medical condition known as Dysphagia/ swallowing disorder is experienced by patients facing discomfort and difficulty with chewing and swallowing the food. Different texture modified foods are currently available in the market such as smooth pureed fruits, thickened drinks, smooth pureed vegetables, soft, moist and easy to swallow foods. Improving the visual appeal, creating novel soft structure, supplementing essential nutrients in between the layers, maintaining the food consistency, critical for patients and elderly is achieved through a software where materials are extruded digitally in a layering pattern using 3D printing technology[10].

Increase the intake and consumption of fruits and vegetables among children

As we know that children and kids are often fussy and choosy about consuming fruits and vegetables, 3D food printing provides an alternative solution to this problem. Consumption of fruits and vegetables is vital for the growth and development of children as they are sources of energy, antioxidants, dietary fibres, vitamins, minerals etc. Novel designs are constructed with enhanced nutrition, change in colour, shape and size which attracts kids towards these food constructs[10].

Production of healthy foods with the reduction of sugar, salts and fats

3D food printing technology has the potency to localise the required ingredients and nutrients between the layers without mixing with the whole raw material and thereby contribute towards the production of healthy food. Consumption of fats, sugar and salts in high amounts is not recommended and is not safe for maintaining good health[10].

Sustainability is enhanced by preventing the wastage of perishable materials

3D food printing technology has the potency to reduce the wastage of food by utilising distorted fruits and vegetables, meat cut-offs, seafood, fish etc. which are low value foods and can otherwise be discarded. These perishables can be used at a later stage by processing and converting into required forms using the technology of 3D food printing[10].

Comparison between 3D and 4D Printing Technology

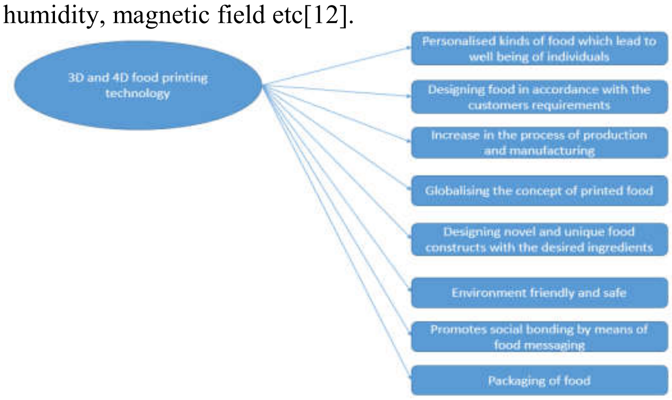
4D printing offers greater advantages compared to 3D printing in recent times because of the fast growth of smart materials and multi-material structures which form the basis for 4D printing. Some of the changes incorporated and updated in 4D printing include change in the printed configuration over time, which depends on the environmental stimuli in comparison to 3D printing. Time-dependent deformations of products are used to pre program 4D printed structures. Smart material acts as the core element of 4D printing technology which provides more deformable, expandable and flexible characteristics of printed products in response to a specific stimuli[11].

Table 6 Comparative analysis between 3D and 4D Printing Technology[11]

Categories of Classification	3D Printing Technology	4D Printing Technology
Methodology of printing	Printing is performed by laying down 2D structures one above the other from bottom to top.	This is an extension of 3D printing technology.
Types of printer used	3D printer is used	Smart, multi material 4D printer is used
Materials used for printing	Metals,thermoplastics,ceramics, are some of the materials used for 3D printing	Multi-materials,smart materials, materials that are self-assembled, self actuating and self-sensing are some of the materials used for 4D printing
The concept of the design to be produced	Drawing or scanning of the 3D digital object is done	Digital 3D object with deformation features is made
Related equipment to the printers used	selective laser sintering,material extrusion and apparatus	selective laser,binder and modified nozzle
Flexibility of the product	No flexibility is seen	Flexibility is seen after printing with respect to color, shape, various functions and other conditions
State of the product	Structure is static	Structure is smart and dynamic
Cost of the equipment	Equipment is comparatively low in cost	Equipment is comparatively high in cost
Outlook of the product in the market	Medium	Medium to high
Applications of 3D and 4D printing technologies	This is used in engineering and design, education, medical, aerospace, consumer products, military and defence, robotics etc.	This is used in construction, aviation, biomedical devices, medical, transportation, soft robotics, aerospace etc.

4D Food Printing

4D printing is an advanced innovation and development of 3D structures and geometries which is changeable in terms of property, shape and its functions over time.4D printing has the ability to self-assemble, multifunctional purpose, self repair and also provide predictable, reprogrammable and time dependent properties. 4D printing technology is mainly based on five important factors namely the 3D printers or the equipment used, the stimulus responsive material, the mechanism of interaction, the stimulus and finally mathematical modelling. The materials used in 4D printing are smart materials such as polymers, nanocomposites and shape memory alloys. Whenever a specific external stimuli is induced on smart materials, they have the ability to transform a preprogrammed method to respond to a particular stimuli[11]. Important factors considered in 4D food printing include mechanical properties and structural design. The different stimuli used for 4D food printing include temperature, humidity, magnetic field etc[12].



CONCLUSIONS

3D printing has emerged as an innovative and promising technology in the agriculture and food industry. 3D food printing has opened large avenues and provided people with different alternatives compared to the conventional foods. 3D food printing is effecient, comparatively less in cost, and requires a short duration of time for the printing process. This technology can be used to reduce and eliminate malnutrition and hunger problems all over the world. NASA and military camps also consider this technology to produce food constructs with longer shelf life and better storage ability.

This caters to the specific food requirements of patients, elderly people and pregnant women. High nutritional foods can be obtained which can be customised by adding the functional components. This will help in increasing the production and manufacturing of food products. Both 3D and 4D food printing help in globalising the concept of printed foods. This technology is environment friendly and safe. It causes no harm or pollution to the environment. Food packaging and processing is improved using 3D food printing technology due to the availability of different types of 3D printers. Finally the consumer acceptance and feedback is essential in order to gain their confidence in terms of the nature of the food materials, taste, appearance and safety concerns through more explanatory labelling systems.

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