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3D Bioprinting : A Review on Technology and its Application in Food and Agriculture

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Abstract

Three-dimensional (3D) printing is an innovative technology adopted to develop customized products. 3D bioprinting is the utilization of 3D printing - like techniques to combine cells, growth factors and biomaterials to fabricate products that maximally imitate natural tissue characteristics. The technology has its major advancements in medical, drug and cosmetics field and is in its infancy stage in food and agricultural fields. 3D bioprinting applications in plant science field including investigation of cell dynamics, cultivation of cells and fabrication of customized plant culture systems is a matter of study present days. The major research in 3D bioprinting in food industry is done in meat applications. Attempts are being made to culture meat cells in suitable medium and to convert it into printable form that can be further processed. Researches are progressing to develop real textured food using plant tissue regeneration. Further, development of 3D printable food packaging systems from bio materials is also a matter of research. The review throws light on the current developments and methods of 3D bioprinting process in food and agriculture sector.

Keywords : 3D bioprinting, Bio ink, Extrusion bioprinting, Inkjet bioprinting, Laser assisted bioprinting

Agriculture and food processing fields need to adopt the recent developments in science, technology and engineering sectors in order to feed the rising population and to ensure food safety and security. Food products are rapidly evolving, owing to the recent developments in the preservation techniques as well as with the wide variety of value addition that can be performed with a product. Hence, there is a need for researchers to follow up the latest trends, better practices and tools in order to work efficiently. Personalization is considered as the key way to disrupt traditional methods of food processing and 3D printing can be considered as an effective way to achieve personalization thereby enchanting a wide variety of customers. 3D food printing (3DFP) is the process of manufacturing food products using a variety of additive manufacturing techniques. But so far, the diversity of textural properties of food that can be designed using 3DFP are rarely taken into account and the real personalization and innovation through 3DFP is barely considered. In this context, the concept of 3D printing of cells to produce food with cellular like structure is an innovative one. Bio printing is an innovative process of arranging cellular and acellular components that precisely position and allocate biomaterials with cells to construct complex 3D functional living tissues (Handral *et al.,* 2020).

The development of a 3D bioprinting process involves the contribution from various disciplines such as biology, biomaterials and engineering. The 3D bioprinting technology is mainly focused on biomedical applications in tissue engineering with respect to the drug discovery and human tissues (Derby, 2012). The bioprinting is applied in pediatrics in surgical planning, tissue constructs and drug printing (Vijayavenkataraman *et al*., 2017). The technology is used for surgical planning, developing heart models and in brain surgeries (Cantinotti *et al*., 2016 and Weinstock *et al*., 2015). Prosthesis, a device used to replace missing parts of human body or to enhance the functionality of any part of the body is developed using 3D bioprinting (Vijayavenkataraman *et al*., 2017). Tailor-made drugs that are compatible with independent patient needs can also be synthesized using 3D bioprinting (Melocchi *et al*., 2016).

3D printing is already effectively utilized in agricultural field to develop hand tools, shovels and irrigation equipment (Crisostomo and Dizon, 2021). 3D printed plant-inspired constructs are revolutionizing the biomedical field. The 3D printed constructs of plant cells and tissues helps in getting better information on cell behavior and dynamics. Customized 3D printed tissue culture systems and hydroponics system can indeed revolutionize agricultural field.

In the field of food processing, the only developed technology in bio-printing is developing meat and meat alternatives. Researches are going on to develop plant cell based foods and variety of food having textural properties similar to the native product as well as various packaging materials. 3D bioprinting of meat can avoid environmental and health issues and could decrease slaughtering of animals thereby replacing conventional meat production (Rorheim *et al*., 2016). The technology is in its infancy stage in food applications and it needs to overcome difficulties such as economics, nutritional and organoleptic properties, industrial scale-up, nutrient inputs needed for cell culture, food safety and ethical issues to prosper (Portanguen *et al*., 2019).

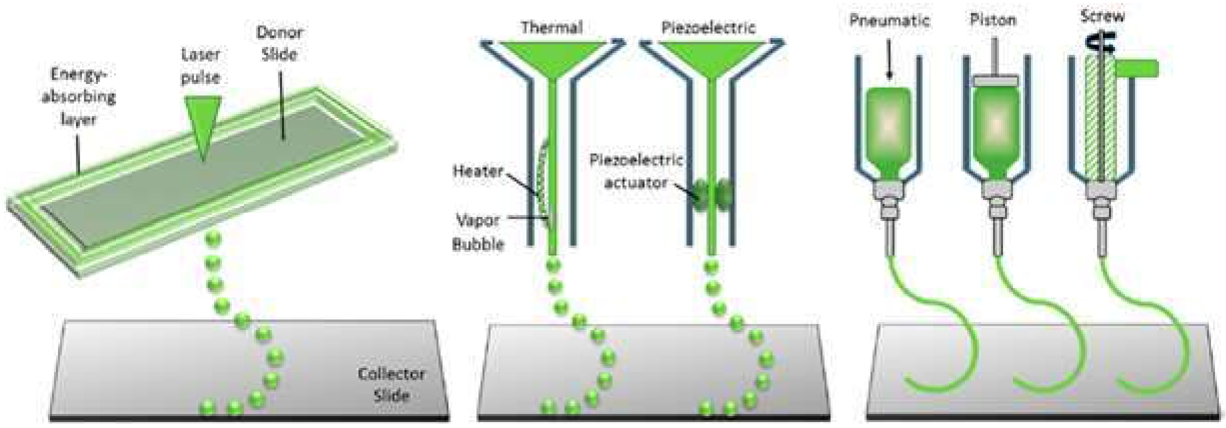
Considering the importance of 3D bioprinting in food industry, this review aims to discuss the various technologies under 3D bioprinting, the steps involved, the currently developed potential applications along with the limitations and challenges faced in global market.

3D Bioprinting Technologies

The main technologies used for deposition and patterning of biological materials are inkjet, extrusion and laser assisted printing (Murphy and Atala, 2014) (Fig. 1).

Laser Assisted Bioprinting

Laser assisted bioprinting (LAB) works on the principle of laser induced forward transfer. The device consists of a pulsed laser beam, a focusing beam, ribbon that has a donor support made from glass and covered with a laser energy absorbing layer such as gold or titanium and a layer of biological material prepared in a liquid solution and a receiving substrate facing the ribbon (Fig. 1a). The laser pulses get absorbed by the ribbon to generate a high pressure bubble that propels cell containing material towards the collector substrate (Murphy and Atala, 2014). Laser fluence (energy absorbed per unit area), surface tension, wettability of the substrate, air gap between ribbon and substrate and thickness and viscosity of biological layer affect the resolution of LAB (Guillemot *et al*., 2010). Since LAB is nozzle free, clogging of nozzle is avoided and is compatible with a wide range of viscosities. Preparation of each individual ribbon is time consuming and costly and metallic residues are found in the final bioprint owing to the vaporization of the metallic laser absorbing layer during printing.



(Vijayavenkataraman *et al*., 2017)

Fig. 1 : Three main bio printing technologies : (a) Laser assisted bio printing, (b) inkjet bio printing, (c) Extrusion bio printing

Inkjet Bioprinting

Inkjet bioprinters, known as droplet-based bioprinters, use thermal or acoustic force to eject liquid drops onto a substrate and build constructs layer-by-layer (Fig. 1b). Bioinks made of cells, scaffold materials and growth factors can be deposited accurately by controlling the droplet size and deposition rate (Vijayavenkataraman *et al*., 2017).

In thermal inkjet printing, pulses or pressure caused due to heating of print head, forces the droplets from the nozzle. The temperature can reach around 300 °C without affecting the stability or post processing feasibility of bio molecules (Cui *et al*., 2012). High print speed, low cost and wide availability stand as some advantages of thermal inkjet bio printing, while, low droplet directionality, non-uniform droplet size, frequent clogging of nozzle, risk of exposing cells to high thermal and mechanical stress and unreliable cell encapsulation poses considerable disadvantage to the use of thermal inkjet bio printing (Murphy and Atala, 2014). Piezoelectric inkjet printers eject droplets from the nozzle due to pressure induced as a result of voltage applied across piezoelectric crystal (Cui *et al*., 2012). These printers working in a frequency range of 15-25 kHz can induce damage to the cell membrane and high force is required to eject droplets of high viscosity (Kim *et al*., 2010).

The major limitations of inkjet bio printing lies in the need to have a biological material in liquid form and the difficulty in achieving biologically relevant cell densities (Cui *et al*., 2012). Along with these drawbacks, inkjet bio printers have the potential to introduce concentration gradient throughout the 3D structure by altering the drop densities (Iwanaga *et al*., 2015).

Extrusion Bioprinting

Extrusion bioprinting is the most affordable and common bioprinting method. In this method, cells suspended in prepolymer solutions are loaded within disposable grade syringes or reservoirs and subsequently printed on to a platform driven by pressurized air or by mechanical forces generated either by a piston or a rotating screw (Murphy and Atala, 2014) (Fig. 1c). Pneumatic extrusion bioprinters have simple drive mechanism where force is only limited by the air pressure capabilities and is compatible with high viscous hydrogels. In case of mechanical dispensing systems, more control material flow is possible owing to the delay of compressed gas volumes in pneumatic systems. Screw based systems offer high spatial control and is suitable for hydrogels with higher viscosities (Chang *et al*., 2011). The method yields continuous bead of material rather than liquid droplets. Materials with

TABLE 1

Features of 3D bio printing technologies

Properties	Bio printer type			References
	Inkjet	Extrusion	Laser assisted	
Material	Liquids, hydrogels	Hydrogels, cell aggregates	Cells in media	Vijayavenkataraman *et al.,* 2017
Material viscosities	3.5-12 mPa/s	30 mPa/s to 6×10^7 mPa/s	1-300 mPa/s	
Gelation methods	Chemical, photo	Chemical, photo cross cross linking temperature	Chemical, photo linking, Shear thinning, cross linking	
Preparation time	Low	Low to medium	Medium to high	Murphy and Atala, 2014
Print speed	Fast (1-10,000	Slow (10 - 50 mm/s) droplets per second)	Medium to fast (200 - 1,600 mm/s)	
Cell densities	Low, <10^6 cells/mL	High, cell spheroids	Medium, 10^8 cells/ mL	
Printer cost	Low	Medium	High	

shear thinning properties are suitable for extrusion bioprinting (Guvendiren *et al.*, 2012).

One of the main advantages of extrusion bio printing is the ability to deposit very high cell densities (Murphy and Atala, 2014). The major limitation lies in the decrease of cell viability due to an increase in extrusion pressure. Different features of the three technologies are shown in Table 1.

3D Bio Printing Process

The overall process of 3D bio printing can be achieved *via* three distinct steps, *viz.,* pre bioprinting, bioprinting and post bioprinting.

Pre-Bioprinting

The first step is to formulate a model that can be used by the printer and the selection of right materials for printing. Cells needed for printing are selected and multiplied. The cell mass thus formed is mixed with oxygen and other nutrients to keep them viable.

Selection of Starter Cells

Self-renewing cells that develop cells required to constitute required product are the best suitable starter materials (Kadim *et al*., 2015). Stem cells of either embryonic or adult origin are suitable for cultured meat production where embryonic stem cells are considered as best source since they have potential to proliferate and differentiate to all cell types required for cultured meat production (Roberts *et al*., 2015). However, adult cells such as satellite stem cells and adipose derived stem cells are also considerable cell sources (Wankhade *et al*., 2016).

Selection and Optimization of Growth Media

A growth media is a nutrient liquid designed and formulated to satisfy the physiochemical and physiological cues for nourishing cells to grow on substrates such as scaffolds or matrices (Handral *et al*., 2020). Growth factor and serum are considered as important factors to achieve cell maturation. Fetal bovine serum isolated from an adult, newborn or fetus animal source is widely used for the culture of myosatellite cells in meat production but is against the ethical concept of bioprinting (Dessels *et al*., 2016). The use of antibiotics in growth media is still a standard practice but controversial. The carrot calli obtained from surface sterilized carrot discs were cultured in murashige & skoog medium in order to prepare a callus based food ink for innovative food production (Park *et al*., 2020).

TABLE 2

Biomaterials used in 3D bio printing

Bioink material	Overview	Advantage	Dis advantage
Agarose	Polysaccharide extracted from seaweed	Non-toxic cross linking high stability	Non degradable poor cell adhesion
Alginate	Naturally derived bio polymer from brown algae	Mild cross linking conditions (Ca^{2+}) Rapid gelation high bio compatibility	Slow degradation kinetics poor cell adhesion
Chitosan	Polysaccharide obtained from the outer skeleton of shellfish. Non animal derived one from fungal fermentation	High biocompatibility Anti-bacterial properties	Slow gelation rate
Gelatin	Protein substance derived from partial hydrolysis of collagen	High biocompatibility High water solubility Thermally reversible gelation	Poor shape fidelity limited rigidity
PCL/PLA/PLGA	Bio degradable, thermoplastic polymer and copolymers	High strength and rigidity	Low cell adhesion and proliferation
Pluronic F127	Poly (ethylene oxide) and poly (propylene oxide) block copolymer	Printable at room temperatures hear thinning material	Not suitable for long term cell culture

Media optimization includes alteration of various chemical and physical parameters in the growth media. The chemical parameters include alteration of major and minor salts, nitrogen ratios, carbohydrate type and amount and phytohormone composition (Davies and Deroles, 2014). In the view of efficiency and cost of production, physical conditions such as aeration, temperature, pH, light and agitation rate appear to be important parameters (Davies and Deroles, 2014).

Scaffolding

Scaffolds are the framework for cells to adhere, grow and attain tissue maturity by mimicking the native three dimensional tissue (Handral *et al*., 2020). Scaffolds for cultured meat production must have biologically active, large surface area, flexibility and porosity to support tissue maturation and should be edible without any allergic responses when digested (Datar and Betti, 2010). The fibrous nature of the scaffold is important to enhance the organoleptic properties of printed meat products. Soy protein and gelatin is considered suitable for fibrous meat products (Mac Queen *et al*., 2019). Decellularized apple hypanthium tissue (cells from which nucleic acids, lipids and proteins are removed) having an internal structure composed of cell walls that encompass pores and air pockets are found to be suitable to fabricate 3D matrices that support mammalian cells (Modulevsky *et al*., 2014).

Design and Development

Design software can determine the nutritional and sensory profiles of the product. The computer modelling can accelerate processes and product optimization and help the industry to maturate in years (Handral *et al*., 2020). To achieve the required designs and final products, the design needs to be developed in any CAD software including AutoDesk, AutoCad, Solid works or Solidedge and converted into a.stl file using slicing software. The slicing software creates a G-code, thus creating files that are readable by the 3D printers (Noorani, 2017).

Bioprinting

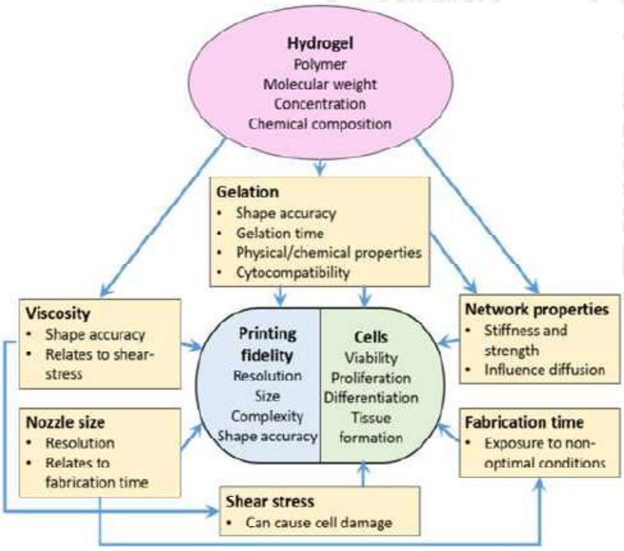
The bioprinting step includes formulation of bio-inks, determining the viscoelastic properties of the ink and setting up the printing parameters in a 3D bioprinter.

Bio-Ink Formulation

Bio-inks are materials used to produce engineered/ artificial live tissue using 3D printing. The combination of cells with biopolymer gel yields a bio ink. The major requirements of a bio ink to be used for 3D bioprinting purpose are bio printability, shear thinning behavior, *in-situ* gelation, viscoelasti city, biocompatibility with live cells, permeability of O_2, nutrients and metabolic wastes, tissue regeneration and bio degradation. The most commonly used biomaterials in 3D bioprinting are given in Table 2.

Hydrogel based bio-inks appear to be appealing to fabricate extra cellular matrix bio-inspired analogues considering the elastic hydrated intrinsic network (Cernencu *et al*., 2019). Inks based on proteins such as gelatin, collagen, fibroin and polysaccharides such as alginate, chitosan and agarose are currently under development (Moroni *et al*., 2018). Pectin, a heterogenous polysaccharide extracted from biomass, allows hydrogel formation by ionic cross-linking and UV photopolymerization to design new bio-inks (Pereira *et al*., 2018). The ink prepared by mixing carboxylated-cellulose nanofibrils (CNF) mixed with low-methoxylated pectin preserved the shear thinning property of CNF while increasing the yield stress and printability of the ink (Cernencu *et al*., 2019). Besides, high amount of live plant cells and air bubbles can be successfully encapsulated into pectin-based bio-inks and can be 3D printed with good accuracy and reproducibility (Vancauwenberghe *et al*., 2019). Callus based bio-inks derived from carrot calli and alginate solution showed adequate printability and structural conformity at lower cell densities (Park *et al*., 2020). Schutyser *et al*. 2018, developed sodium caseinate dispersion with sucrose, pectin and potato starch. Wang *et al.,* 2018, developed bio ink by mixing fish surimi gel with sodium chloride. Vitamin D-enriched orange concentrate with wheat starch and k-carrageenan gum was developed by Azam *et al.* 2018. Egg white protein mixtures with gelatin, corn starch and starch was a developed hydrogel by Liu *et al*. 2019.

The composition of various components in hydrogel affect the rheology and printability. The suspensions of different starches at varying concentrations were printed in hot extrusion and was found that rice starch suspensions at 80°C and concentration 15 per cent to 25 per cent (w/w) showed good shape stability and smooth surface (Chen *et al*., 2019). The multi-component gel of carrageenan-xanthan gum-potato starch developed by Liu *et al*., 2019, showed best printing performance at 1 per cent, 0.25 - 0.5 per cent and 2 per cent (w/w) of k-carrageenan, xanthan and starch, respectively. The selection of suitable biocompatible matrix for printing is based on flowability (easy manipulation and extrusion), cell viability (limitation of shear stress) and final rigidity (stability of 3D structure) and is schematically shown in Fig. 2.



(Malda *et al*., 2013)

Fig. 2 : Conceptual relation between variables critical in bio fabrication

Visco Elastic Characteristics

The visco-elastic characteristics that are often calculated for the bio inks include the storage modulus (elastic modulus) (G'), loss modulus (viscous modulus) (G''), loss factor (tan δ) and complex viscosity (Anila *et al*., 2020). The G' reflects the mechanical strength of the material and indicates its ability to have an elastic solid-like behavior/accumulated energy (Theagarajan *et al*., 2020). G" is the measure of the viscous response of the material supply that represents the amount of dissipated energy during each deformation cycle. Thus, G" refers to the ratio of stress to strain under vibratory conditions (Yang *et al*., 2018). The loss tangent ($\tan \delta = G''/G'$) is a parameter used to determine the nature of viscoelastic property exhibited by the material supply. A tan δ value < 1 indicates that the material has predominant elastic behavior and a tan δ value > 1 is indicative of the viscous behavior of the material supply (Liu *et al*., 2018).

Bio Printer

Bioprinters or 3D bioprinters are automated devices for the additive fabrication of 3D functional tissues and organs based on the digital models that are created *via* various scans using biomaterials. The size of the printer and number of nozzles depend upon the functional requirement of printer. Laser sources and temperature controls are different in different systems but the characteristics such as robotic positioning in the X-Y-Z axis, nozzle or disperser or extrusion machine, operational system and receiver substrate are similar. The Rokit *in vivo* 3D bio-printer manufactured in South Korea is shown in Fig. 3.

The 3D bioprinting process starts with the design of the product in a suitable software. Besides the information given by the slicing software, information of choice of material and other printing parameters is given to the printer. The printer can thus read the design and deposit the bio material onto the receiver in a layer-by-layer fashion. The required depth and thickness are obtained by the appropriate movement of print head. Once a layer reaches the platform, it solidifies either by cooling or chemical reaction and a new layer is deposited to form a stable structure. The list of various bio-printers commercially available is shown in Table 3.

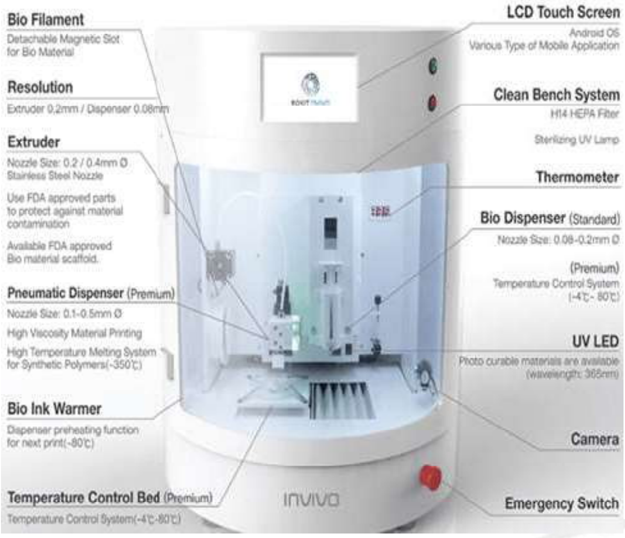


Fig. 3 : Rokit Invivo 3D bioprinter

Various parameters for 3D printing affect the structure, strength and stability of a 3D printed construct. The important parameters to consider in order to obtain a sustainable product is shown in Fig. 4. The various parameters include:

Infill : It is a value usually represented in percentage that shows how much a solid model should be filled in with material when printed.

Number of Shells : It is a value that sets the number of outlines printed on each layer of object, the more shells the stronger the printed object is.

Layer Height : It is the main parameter that affects print quality as it sets the thickness of each layer that is being printed.

Temperature : The temperature at which the printer needs to be.

Printing Speed : The speed at which the printing head moves while extruding the filament to create the physical representation of the 3D model.

Movement speed : The speed that the printing head moves when it is not printing a material. Here the speed can be faster than while travelling and normally up to twice the speed while printing.

Warner *et al*., 2019, studied the effect of printing temperature on uniformity and dimensional accuracy of printed structures for a gelatin-carrageenan gel. Liu *et al*., 2018, optimized extruder offset and retraction value in dual-extrusion printing of mashed potato and strawberry juice gel to reduce deviation from designed model and avoid oozing of inks during switching and pausing of individual extruders.

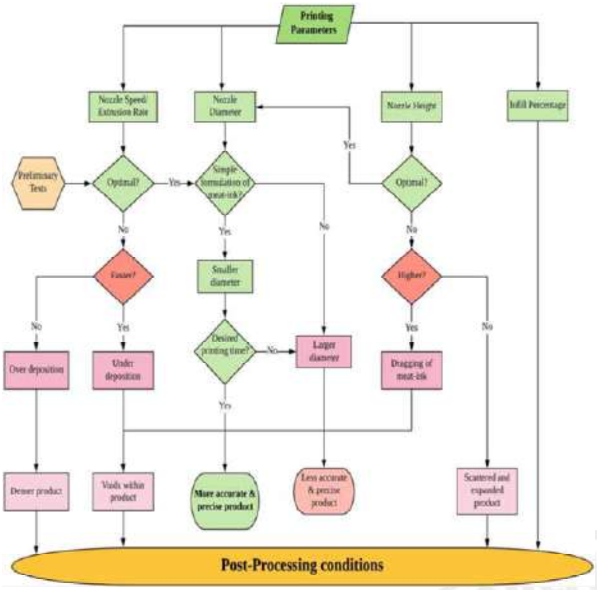
Post Bioprinting

Post processing feasibility includes the analysis of internal and external designs of 3D printed product. The infill densities at different layers of animal fat plays an important role in strength, stability and thereby structure and textural properties of printed meat (Dick *et al*., 2019). The major post processing parameters include cooking loss, moisture retention, fat retention and shrinkage along with textural changes in the 3D printed product. The nutritional profile of the 3D printed sample is obtained using proximate analysis.

TABLE 3

Commercially available 3D bio printers

Name	Technology	Materials	Price (Indian Rupees)
3D Bio plotter Envision TEC	Syringe based extrusion	Hydrogel, Chitosan, Silicone	1.47 crores
Novogen MMX Organovo	Syringe based extrusion	Cellular hydrogel	1.85 crores
3D discoveryRegen HU	Syringe based extrusion	Bio inks	1.46 crores
BiobotBiobot	Syringe based extrusion blue light technology	Agarose, alginate, poly ethylene glycol	7.3 lakh
InkredibleCell ink	Syringe based extrusion	Bio inks	3.6 lakh
Bio assemble bot Advance solutions	Six axes syringe based extrusion	Cellular hydrogel	1.2 crores
Bio scaf folderGesim	Syringe based extrusion	High viscosity paste materials, Protein solution	1.3 crores



(Handral *et al*., 2020)

Fig. 4 : Flowchart of important printing parameters to consider to obtain suitable product

3D Bioprinting in Agriculture

3D bioprinting is having many potential applications in agricultural field. Shakti *et al*., 2020 has reviewed about the applications of 3D bioprinting in plant science field. The sub cellular responses to different physiological requirements such as accuracy of fragmentation, fusion, rearrangement of organelles, interaction and assembly of different components of cell wall can be determined with nanoscale accuracy and a better understanding of geometrical properties and spatial relations of cellular components during shape attainment and binding of cells is possible using 3D printed constructs (Shakti *et al*., 2020). The plant root inspired CAD models can be converted to printed ones for better investigation of root penetration and navigation to soil, cellular interaction with soil matrix and root dependent soil confinement which can further contribute to increased yield and sustainability of ecology and soil resources (Shakti *et al*., 2020). The nature-inspired examples for plant cell-based and plant-inspired constructs that provide low-cost solutions for biomedical or scientific applications to study plant-environment interactions are given in Fig. 5.

3D Bioprinting of Plant Tissue-Based Food

Plant tissues are of important interest in the field of 3D bio printing because of their properties related to both their particular porous structure and the turgor

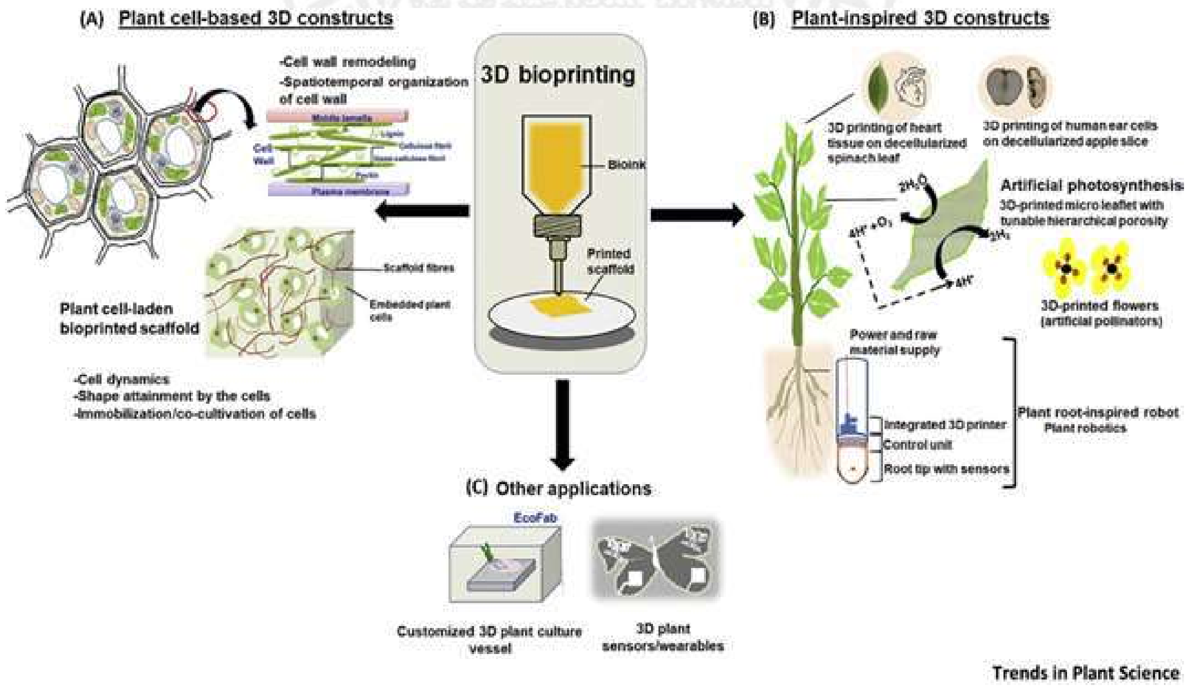
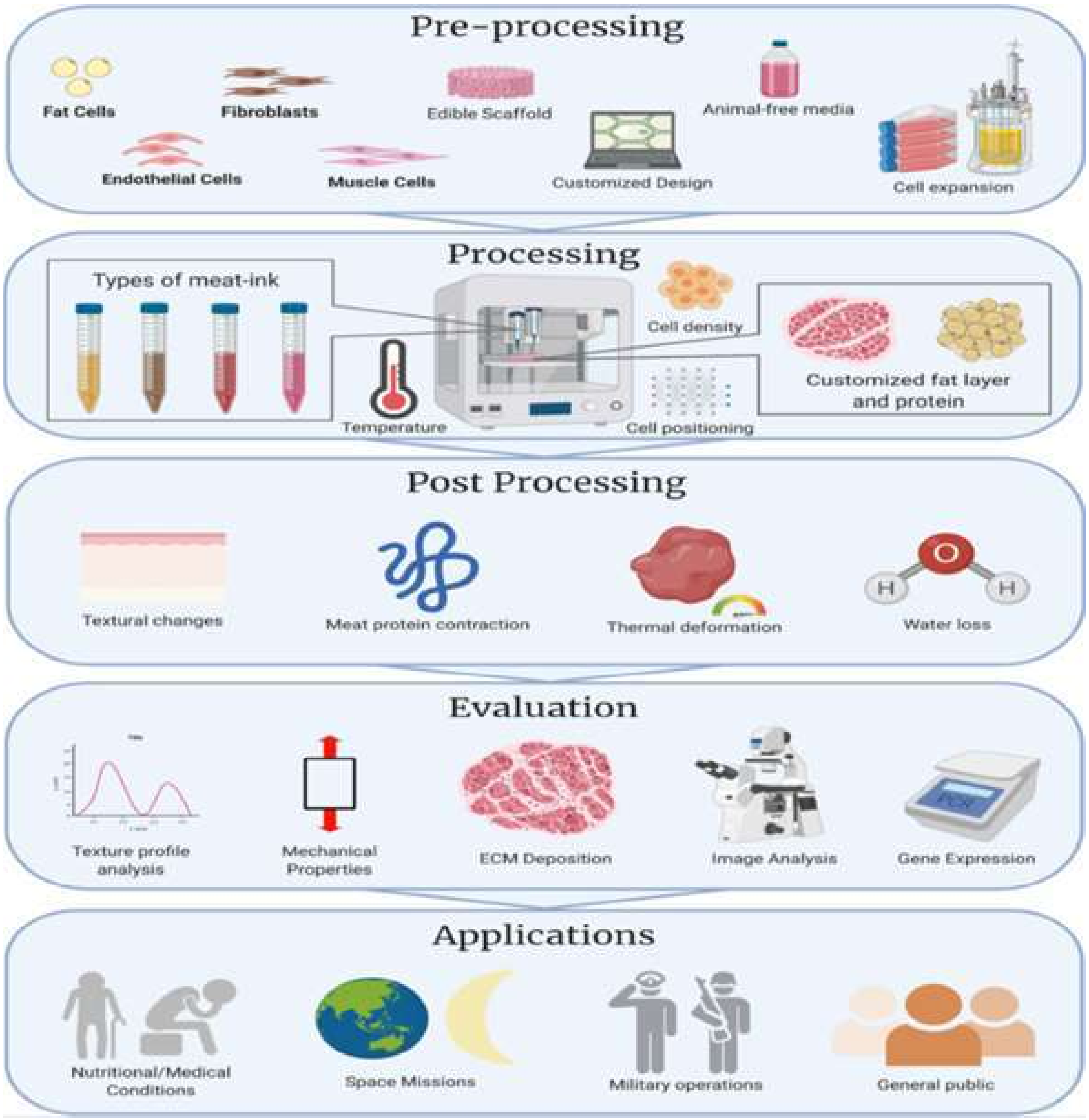


Fig. 5: Trends and Scope of 3D Bioprinting in Plant Science Research. (A) Plant cell-based 3D constructs (B) Plant-inspired 3D constructs (C) The design and development of customized plant culture systems

pressure of cells (Wicaksono and da Silva, 2015). 3D bioprinting of plant tissues have the potential to create new possibilities in texture and flavor of personalized food (Vancauwenberghe *et al*., 2019). Nordlund *et al*., 2018 validated the possibility of using plant cell culture technology as plant-based food production. The cell lines derived from cloud berry, stone berry and lingonberry showed fresh and berry like characteristics in terms of visual and sensory aspects. The protein content ranged from 13.7 to 18.9 per cent which showed *in vitro* digestibility by hydrolysis by digestive enzymes (Nordlund *et al*., 2018). The results showed suitability of material for 3D food printing and the 3D printed objects from plant tissues enabled the reproduction of inherent texture and nutritional composition of actual foods. Callus based food inks were found to reproduce edible artificial cellular



(Handral *et al*., 2020)

Fig. 6 : Schematic diagram of major steps considered for 3D bioprinted meat products, their evaluation and potential applications

tissue similar to natural food texture (Park *et al*., 2020). The carrot callus tissues embedded in alginate hydrogel matrix showed varying printability and structural conformity in accordance with the cell density. Excessive cell density found to disrupt 3D printed scaffold (Park *et al*., 2020). The research can be considered as a major break through for the simulation of real textured food using plant tissue regeneration in the food engineering.

3D Bio Printing of Meat

3D bio printing of meat can be considered as the only developed sector under the 3D food bioprinting. Modern meadows has created raw meat tissue from cultured stem cells in which an inkjet bioprinter deposit cells into an agarose support structure to get fused and the tissue is matuarated in a bioreactor (Forgacs *et al*., 2014). But the constraints such as cost effectiveness, sensorial attributes and consumer acceptance need to be addressed yet (Dick *et al*., 2019). 3D printing of meat is difficult due to the fibrillar nature of the meat. The printability of chicken meat can be enhanced by the addition of wheat flour (Anila *et al*., 2020). The major steps involved in the production of 3D bioprinted meat is shown in Fig. 6.

Challenges in the Market

The success of a technology or a product in the market lies with the acceptance of the same in the market by the consumers. Lupton and Turner, 2018 conducted a survey in Australia to know about the consumer behavior towards 3D printed, cell based and insect-based foods. Eventhough there are a few consumers who would like to accept the recent advancements, the majority of them found it difficult to understand the concept mainly due to a lack of knowledge. Many of them believe that screwing with nature is wrong and think that the technology can adversely affect the livelihood of farmers and meat producers. Vegetarian people are reluctant to have the product since the meat products are printed from animal cells itself. Even if people go for trying meat alternative, they expect same taste, low fat and much cheaper product, for which the technology should prosper even better. It is difficult to convince people who think why go for pureeing of veggies, meat and other materials just to convert it into original shape by printing. The major constraint is getting approval from a central agency on which the consumers believe (Lupton and Turner, 2018). Further, the acceptance of products can sometimes vary with labels and description and therefore it is necessary to educate people and create awareness (Siegrist and Hartmann, 2020).

3D bio-printing is a technology with bright future in food and agriculture. The various problems existing in market including short buying power and deprived access to food resources can be resolved to some extent for the future generations by adopting mass customization through 3D printing process. The future of the technology can be bio-printers integrated with post processing systems such as those for drying, cooking or even for packaging to reduce handling (Portanguen *et al*., 2019). Since the printing times for the existing bio-printers are long, careful maintenance of immediate environment is necessary, thus facilitating the serving of biologically, chemically and nutritionally stable food at room temperature. The 3D bio-printed products just like normal 3D printed foods have potential benefits and applications in military and space. Further research is needed to improve the nutritional profile and sensory attributes of bioprinted product and to improve control of tissue development. The technology can be widely utilized for nutraceuticals, functional foods and customized foods. Above all this, the acceptance from consumers need to be assured by properly briefing the processes involved and the benefits being offered.

REFERENCES

ANILA, W., ANUKIRUTHIKA, T., MOSES, J. A. AND ANANDHARAMAKRISHNAN, C., 2020, Customized shapes for chicken meat-based products : Feasibility study on 3D-Printed nuggets. *Food. Bioproc. Tech*., **13** (11) : 1968 - 1983.

AZAM, S. M. R., ZHANG, M., BHANDARI, B., AND YANG, C., 2018, Effect of different gums on features of 3D printed object based on vitamin-d enriched orange concentrate. *Food biophysics*, **13** (3) : 250 - 262.

CANTINOTTI, M., VALVERDE, I. AND KUTTY, S., 2016, Three - dimensional printed models in congenital heart disease. *Int. J. Card. Imaging*, **32** (1) : 1 - 8.

CERNENCU, A. I., LUNGU, A., STANCU, I. C., SERAFIM, A., HEGGSET, E., SYVERUD, K. AND LOVU, H., 2019, Bioinspired 3D printable pectin-nanocellulose ink formulations. *Carbohydr. Polym*., **220** (18) : 12 - 21.

CHANG, C. C., BOLAND, E. D., WILLIAMS, S. K. AND HOYING, J. B., 2011, Direct-write bioprinting three-dimensional biohybrid systems for future regenerative therapies. *J. Biomed. Mater. Res. Part B. Appl. Biomater.,* **98** (1) : 160 - 170.

CHEN, H., XIE, F., CHEN, L. AND ZHENG, B., 2019, Effect of rheological properties of potato, rice and corn starches on their hot-extrusion 3D printing behaviors. *J. Food. Engg*., **244** (5) : 150 - 158.

CRISOSTOMO, J. B. AND DIZON, J. C., 2021, 3D printing applications in agriculture, food processing and environmental protection and monitoring. *Adv. Sus. Sci. Engg. Tech. (ASSET),* **3** (2) : 1 - 11.

CUI, X., BOLAND, T., LIMA, D. D. AND LOTZ, M. K., 2012, Thermal inkjet printing in tissue engineering and regenerative medicine. *Recent. Pat. Drug. Deliv. Formul*., **6** (2) : 149 - 155.

DATAR, I. AND BETTI, M., 2010, Possibilities for an *in vitro* meat production system. *Innov. Food. Sci. Emerg. Technol*., **11** (1) : 13 - 22.

DAVIES, K. M. AND DEROLES, S. C., 2014, Prospects for the use of plant cell cultures in food biotechnology. *Curr. Opin. Biotechnol*., **26** (2) : 133 - 140.

DERBY, B., 2012, Printing and prototyping of tissues and scaffolds. *Science*, **338** (6109) : 921 - 926.

DESSELS, C., POTGIETER, M. AND PEPPER, M. S., 2016, Making the switch : Alternatives to fetal bovine serum for adipose-derived stromal cell expansion. *Front. Cell Dev. Biol*., **4** : 1 - 10.

DICK, A., BHANDARI, B. AND SANGEETHA, P., 2019, Post processing feasibility of composite layer 3D printed beef. *Meat. Sci*., **153** (7) : 9 - 18.

FORGACS, G., MARGA, F. AND JAKAB, K. R., 2014, Engineered comestible meat. Apr. 22. US Patent No : US 8703216B2.

GUILLEMOT, F., SOUQUET, A., CATROS, S. AND GUILLOTIN, B., 2010, Laser assisted cell printing : Principle, physical parameters versus cell fate and perspectives in tissue engineering. *Nanomedicine*, **5** (3) : 507 - 515.

GUVENDIREN, M., LU, H. D. AND BURDICK, J. A., 2012, Shear thinning hydrogels for biomedical applications. *Soft Matter*, **8** (2) : 260 - 272.

HANDRAL, K. H., TAY, S. H., CHAN, W. AND DEEPAK, C., 2020, 3D printing of cultured meat products. *Cri. Rev. Food. Sci. Nut*., DoI : 10.1080/10408398.2020.1815172.

IWANAGA, S., ARAI, K. AND NAKAMURA, M., 2015, Inkjet printing, Chapter IV: Essentials of 3D biofabrication and translation. Academic press, USA.

KADIM, I. T., MAHGOUB, O., BAQIR, S., FAYE, B. AND PURCHAS, R., 2015, Cultured meat from muscle stem cells : A review of challenges and prospects. *J. Integr. Agric*., **14** (2) : 222 - 233.

KIM, J. D., CHOI, J. S., KIM, B. S., CHAN CHOI, Y. AND CHO, Y. W., 2010, Piezoelectric inkjet printing of polymers : Stem cell patterning on polymer substrates. *Polymer*, **51** (10) : 2147 - 2154.

LIU, A., ZHANG, M., BHANDARI, B. AND YANG, C., 2018, Impact of rheological properties of mashed potatoes on 3D printing. *J. Food Eng*., **220** (5) : 76 - 82.

LIU, L., MENG, Y., BHANDARI, B., DAI, X., CHEN, K., ZHU, Y. AND SANGEETA, P., 2019, 3D printing complex egg white protein objects: Properties and optimization. *Food. Bio. pro. Tech*., **12** (2) : 267 - 279.

LIU, Z., BHANDARI, B., SANGEETA, P., MANTIHAL, S. AND ZHANG, M., 2019, Linking rheology and printability of a multicomponent gel system of carragee nan-xanthan-starch in extrusion based additive manufacturing. *Food. Hydrocoll*., **87** (2) : 413 - 424.

LIU, Z., ZHANG, M. AND YANG, C., 2018, Dual extrusion 3D printing of mashed potatoes / strawberry juice gel. *LWT - Food. Sci. Tech.,* **96** (10) : 589 - 596.

LUPTON AND TURNER, 2018, Food of the future? Consumer responses to the idea of 3D-printed meat and insect-based foods. *Food Foodways*, **26** (4) : 269 - 289.

MACQUEEN, L. A., ALVER, C. G., CHANTRE, C. O., AHN, S., CERA, L., GONZALEZ, B., O'CONNER, B., DRENNAN, D. J., PETERS, M. M. AND MOTTA, S. E., 2019, Muscle tissue engineering in fibrous gelatin : Implication for meat analogs. *NPJ Sci. Food*, **3** (1) : 1 - 12.

MALDA, J., VISSER, J., MELCHELS, F. P., JUNGST, T., HENNINK, W. E. AND DHERT, W. J., 2013, 25th anniversary article : Engineering hydrogels for biofabrication. *Adv. Mater*, **25** (36) : 5011 - 5028.

MELOCCHI, A., PARIETTI, F., MARONI, A., FOPPOLI, A., GAZZANIGA, A. AND ZEMA, L., 2016, Hot-melt extruded filaments based on pharmaceutical grade polymers for 3D printing by fused deposition modeling. *Int. J. Pharm*., **509** (13) : 255 - 263.

MODULEVSKY, D. J., LEFEBVRE, C., HAASE, K., AL-REKABI, Z. AND PELLING, A. E., 2014, Apple derived cellulose scaffolds for 3D mammalian cell culture. *PLoS One*., **9** (5) : e97835.

MORONI, L., BURDICK, J.A., HIGHLEY, C., LEE, S. J., MORIMOTO, Y. AND TAKUECHI, S., 2018, Biofabrication strategies for 3D in vitro models and regenerative medicine. *Nat. Rev. Mater*, **3** (5) : 21 - 37.

MURPHY, S. V. AND ATALA, A., 2014, 3D bioprinting of tissues and organs. *Nat. Biotechnol*., **32** (8) : 773 - 785.

NOORANI, R., 2017, 3D printing: technology, application and selection. CRC Press, Milton, United Kingdom.

NORDLUND, F., LILLE, M., SILVENTOINEN, P., NYGREN, H., SEPPANEN - LAAKSO, T. AND MIKKELSON, A., 2018, Plant cells as food-A concept taking shape. *Food Res. Int*., **107** (5) : 297 - 305.

PARK, S. M., KIM, H. W. AND PARK, H. J., 2020, Callus-based 3D printing for food exemplified with carrot tissue and its innovative potential for innovative food production. *J. Food. Eng*., **271** (8) : 1 - 8.

PEREIRA, R. F., SOUSA, A., BARRIAS, C. C., BARTOLO, P. J. AND GRANJA, P. L., 2018, A single component hydrogel bio ink for bioprinting bioengineered 3D constructs for dermal tissue engineering. *Mater. Horiz*., **5** (6) : 1100 - 1111.

PORTANGUEN, S., TOURNAYRE, P., SICARD, S., ASTRUC, T. AND MIRADE, P., 2019, Toward the design of functional foods and biobased products by 3D printing : A review. *Trends. Food Sci. Technol*., **86** (4) : 188 - 198.

ROBERTS, R. M., YUAN, Y., GENOVESE, N. AND EZASHI, T., 2015, Livestock models for exploiting the promise of pluripotent stem cells. *ILAR J*, **56** (1) : 74 - 82.

RORHEIM, A., MANNINO, A., BAUMANN, T. AND CAVIOLA, L., 2016, Cultured meat : An ethical alternative to industrial animal farming. *Policy paper by Sentience politics*, **1** : 1 - 14.

SCHUTYSER, M. A. I., HOULDER, S., DE WIT, M., BUIJSSE, C. A. P. AND ALTING, A. C., 2018, Fused deposition modelling of sodium caseinate dispersions. *J. Food. Engg.,* **220** (5) : 49 - 55.

SHAKTI, M., SMITA, K., VIKAS, S., TAIJSHEE, M. AND BHARTENDU, N. M., 2020, 3D Bioprinting in plant science: An interdisciplinary approach. *Trends Plant Sci*., **25** (1) : 9 - 13.

SIEGRIST, M. AND HARTMANN, C., 2020, Consumer acceptance of novel food technologies. *Nat. Food*, **1** (6) : 343 - 350.

THEAGARAJAN, R., MOSES, J. A. AND ANANDHARAMAKRISHNAN, C., 2020, 3D extrusion printability of rice starch and optimization of process variables. *Food Bioproc. Tech*., **13** (6) : 1048 - 1062.

VANCAUWENBERGHE, V., MBONG, V., VANSTREELS, E., VERBOVEN, P., LAMMERTYN, J. AND NICOLAI, B., 2019, 3D printing of plant tissue for innovative food manufacturing : Encapsulation of alive plant cells into pectin based bio-ink. *J. Food. Engg*., **263** (24) : 454 - 464.

VIJAYAVENKATARAMAN, S., JERRY, Y. H. AND FENG LU, W., 2017., 3D printing and 3D bioprinting in pediatrics. **4** (3) : 63-73.

WANG, L., ZHANG, M., BHANDARI, B. AND YANG, C., 2018, Investigation of fish surimi gel as promising food material for 3D printing. *J. Food. Engg.,* **220** (5) : 101 - 108.

WANKHADE, U. D., SHEN, M., KOLHE, R. AND FULZELE, S., 2016, Advances in adipose-derived stem cells isolation, characterization and application in regenerative tissue engineering. *Stem Cells. Int*., DOI: 10.1155/2016/3206807.

WARNER, E. L., NORTON, I. T. AND MILLS, T. B., 2019, Comparing the viscoelastic properties of gelatin and different concentrations of kappa-carrageenan mixtures for additive manufacturing applications. *J. Food. Engg*., **246** (7) : 58 - 66.

WEINSTOCK, P., PRABHU, S. P., FLYNN, K. AND ORBACH, D. B., SMITH, E., 2015, Optimizing cerebro vascular surgical and endovascular procedures in children *via* personalized 3D printing. *J. Neurosurg. Pediatr*., **16** (5) : 584 - 589.

WICAKSONO AND DA SILVA, J. A., 2015, Plant bioprinting: novel perspective for plant biotechnology. *J. Plant Dev*., **22** (1) : 135 - 141.

YANG, F., ZHANG, M., BHANDARI, B. AND LIU., 2018, Investigation of lemon juice gel as food material for 3D printing and investigation of printing parameters. *Food. Sci. Tech*., **87** (1) : 67 - 76.

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