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Prospects of 3D printing in the development of meat based products

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Abstract
A developing technology for food manufacturing, which offers the opportunity to design novel food products with improved nutritional value and sensorial profile is 3DP (Three Dimensional Printing). The emerging technology of 3D printing (3DP) has been recognized for its unprecedented capacity to fabricate food products with intricate structures and reduced material cost and energy. For sustainable 3DP of meat substitutes, the possible materials discussed are derived from in vitro cell culture, tougher meat cuts, trimmings or by products/waste, insects, and plants. These material-based approaches are analyzed from their potential environmental effects, technological viability, and consumer acceptance standpoints. The sustainability of 3DP using these raw materials as food inks could be enhanced by the utilization of generic/universal components or scaffolds and optimization of cell sourcing and fabrication logistics. Despite the availability of number of options animal based proteins as printing materials for inks and some start-up ventures attempting to fabricate food products, 3D printing of meat products remains a challenge. From various insects, powders, proteins (soluble/insoluble), lipids, and fibers are produced, which—in different combinations and at optimal concentrations—can potentially result in meat products constructs. Valuable materials derived from meat like meat trimmings or by products/wastes using low energy methods could reduce waste production and offset some greenhouse gas (GHG) emissions. Apart from printer innovations (speed, precision, and productivity), rational structure of supply chain and optimization of material flow and logistic costs can improve the sustainability of 3D printing. Irrespective of the materials used, perception-related challenges exist for 3D-printed food products. Consumer acceptance could be a significant challenge that could hinder the success of 3D-printed meat products.

Keywords: 3D printing, meat products, recombined meat, extrusion

Introduction
An emerging technology for the food industry, which represents a great opportunity to seize meat by-products for the fabrication of customized meat products, is three-dimensional printing (3DP). 3DP technology uses a computer-aided design (CAD) software assisting a digital manufacture machine in the generation of three-dimensional objects without any additional tool (Noorani, 2017) [16]. Besides already standing as a relevant technology in the medical, automotive, aerospace and fashion fields (Gross, Erkal, Lockwood, Chen, & Spence, 2014) [4], during the last decade, 3DP technology has also gained the attention of researchers in the food science field due to the potential advantages that 3DP could bring to the food industry in the future.
The application of 3DP in the food science field comprises various aims such as novelty/fun/creativity, convenience and efficiency, health/nutrition, reducing waste and enhancing environmental sustainability, and alleviating world hunger (Turner & Lupton, 2017) [21]. For instance, one of its most relevant applications relies on the design of personalized food meals aimed for elderly consumers dealing with swallowing and/or mastication difficulties. (RTDS Group, 2014) [17].
However, in order to manufacture a 3D printed meat product with a desired design, sensorial profile and nutritional value, first the printability of the meat paste needs to be assessed. The printability of any food material refers to its ability to be handled and dispensed by a 3D printer into a freeform structure after deposition (Godoi *et al*., 2016) [3], and is affected by the printing conditions and the rheological properties of the materials (Kim, Bae, & Park, 2017) [8].

Ingredients of Printing Inks

Based on the printability of food ingredients, three categories were identified by Sun, Zhou, Huang, Fuh, and Hong (2015) [19]: native printable food materials, non-native printable traditional food materials, and alternative ingredients.

A material with native printability has enough flow ability to be easily extruded from the nozzle without additional flow enhancers (Sun *et al*., 2015) [19]. Some natively printable materials, including cream cheese, cheddar cheese (Kim *et al*., 2017) [8], Vegemite and Marmite (Hamilton, Alici, & in het Panhuis, 2018) [5] have enough rigidity to uphold its structure after deposition, and are thus suitable for sophisticated 3D objects and general 3D printing system.

On the other hand, non-native printable traditional food materials require additional flow enhancers for ease of extrusion and/or post-cooking processes (Sun *et al*., 2015) [19]. Most traditional staple foods lack printability characteristics, requiring aided and controlled rheological and mechanical behaviour during printing and deposition. Therefore, the effect of flow and viscosity enhancers on the printability of food materials have been widely studied. Additives commonly used for 3DP applications include gelatin, xantham gum, starch, pectin and alginate (Vancauwenberghe, Katalagarianakis, Wang, Meerts, Hertog, Verboven, Moldenaers, Hendrickx, Lammertyn, & Nicolaï, 2017) [22].

Alternative ingredients refer to those emerging as novel sources of functional constituents aiming to customize nutrition, such as proteins and fibres isolated from insects, algae, fungi, bacteria, among others (Sun *et al*., 2015) [19]. These alternative ingredients are becoming of interest as potential supplements towards a balanced nutrition, complementing traditional food sources, such as cattle and crops, and can be formulated into a paste or powder suitable for 3D printing within a meat paste for the production of customized meals. For instance, the combination of entomogaphy (eating insects) with 3DP technology has been tested by adding edible insect powder from *Tenebrio molitor* to enrich the protein content of 3D printed wheat-based snacks (Severini & Derossi, 2016a) [18].

3D Printing process

Three-dimensional printing, also known as additive manufacturing (AM), is a process that generates freeform structures by introducing a prototype into a computer aided design (CAD) software, which is then converted into a STL file by a slicing software to be recognised and processed by 3D printers (Noorani, 2017) [16]. The technology involves a layer-by-layer deposition with predetermined thickness to create complex three-dimensional objects from different materials used as "inks", using strictly the necessary amount of material to consolidate the shape of the printed object. It has become a relevant technology with broad applications in the medical field for tissue engineering, automotive and aerospace fields for components design, as well as fashion and food design, among others (Gross *et al*., 2014) [4].

Through the combination of diverse food materials and 3D printing methodologies, the design of novel food products offering unique textures, nutritional value and eating experiences is conceivably unlimited in order to manufacture a printed food product with desired design and nutritional value, several aspects needed to be taken into account to ensure the required printing precision and accuracy. Some of these aspects, as reported in the literature, include but are not limited to the printing machines, methodologies, prototype design and software, food ingredients and additives, processing parameters, and post-processing suitability (Liu, Zhang, Bhandari, & Wang, 2017) [13] applied to each 3D printed food manufacturing process.

3D Printing of meat

To date, only a small number of studies account for the printability of fibrous-meat materials, through the assessment of the rheological properties of the meat "ink", as well as the post deposition and post-processing properties of the printed object. Lipton *et al*. (2010) [10] authored the first published work on 3D printing of meat. The authors demonstrated the suitability of 3D printed turkey puree for sous-vide cooking method. The turkey paste was added with TGase as a binder, and bacon fat as a flavour enhancer, and was printed in the shape of a truncated hemisphere using a Fab@Home extruder- type 3D printer. Also, the same slurry was used to print a cube containing celery fluid gel inside.

Likewise, gelatine was added to fibrous meats (pork, chicken, fish) as a viscosity enhancer to evaluate its printability and the applicability of a newly designed 3D printer for fibrous materials (Liu *et al*., 2018a) [12], although the post-processing viability was not assessed. Such introductory results in 3D meat printing show how this technology can further generate meat products with complex internal structure, containing on-demand functional ingredients and modified textures for enhanced eating experiences. In addition, during the 3D Food Printing Conference Asia-Pacific, Meat and Livestock Australia (2017) proposed the creation of an emulsified red meat ink from secondary cuts which was 3D printed into meat scrolls with a By Flow 3D printer that well-maintained their shape after frying. In addition, the printability of seafood materials has also been tested to some extent. Recently the printability of fish surimi gel was assessed by Wang *et al*. (2018) [25] using a screw-conveyor extruder type 3D printer. The effect of added NaCl (0%, 0.5%, 1%, 1.5%) to fresh silver carp fillet mince on the functional and rheological properties of the surimi gel was evaluated through the water holding capacity (WHC), gel strength, rheological behaviour, microstructure and distribution of water content within the gel; suggesting 1.5% NaCl as the optimal concentration for having suitable mechanical properties for 3D printing process. Furthermore, the authors evaluated the effect of printer settings on the geometrical precision and dimension of the deposited structures, although no objective comparison was performed among printed structures, such as the post-deposition and post processing properties.

Furthermore, aiming to develop pureed foods for people with swallowing difficulties, tuna puree was obtained by blending tuna in spring water for 5 minutes, and was further 3D printed into a tuna shape with pressure-controlled extrusion at 20 °C (Kouzani *et al*., 2017) [9]. Such processing temperature may compromise not only the material behaviour, but also the food safety risks, showing a limitation of 3D printers that still need to be addressed in order to be applicable for a wider variety of foods.

Different 3DP Technologies

The processes of additive manufacturing are classified based on the material used and printable material which usually involves liquid processes like stereo lithography, fused deposition modelling and inkjet printing. (Vithani *et al.*, 2019) [23] described following three main factors which have been primarily utilized in 3D printing of food viz. To design the layout of food with special textures to develop new nutrient rich food materials To enhance the appearance by planning the design the food in complex structures via controlling the development of structures at micro- and macro levels.

Different 3DP technologies have been applied to process the vitamins, additives, and flavours to propel food properties with tailor-made chemical, structural characteristics and to extend the shelf-life of food with increase demand to satisfy the exceptional need of individuals are explained in general.

Extrusion, binder jetting, selective sintering and inkjet are the four main types of 3D printers. A number of food printers have been developed that meet the specific printing requirements of different food products, including ChefJet, Foodini, f3d, Choc Creator, Discov3ry Extruder, NASA printer, 3D Fruit Printer, Cake and Chocolate Extruder, 3D Everything Printer, Original Food Printer and Palatable-Looking Goop Printer (Bhat, Morton, Bekhit, Kumar, & Bhat, 2021f) [1]. Printing of animal protein-based products is most commonly done by using extrusion-based 3D printers using meat, fish, egg, cheese and dairy ingredients and mostly used to evaluate physical and rheological properties of food inks and constructs.

Printing conditions to enable 3D printing of meat

Several studies demonstrate the effect of varying printing processing parameters on the printability of food materials and hence, the quality of the final printed objects. The component settings that include nozzle speed, nozzle height (layer height), nozzle diameter, extrusion rate, and infill percentage, are suggested as critical parameters affecting the geometry accuracy of the printed construct (Hao *et al*., 2010) [6]. While different mechanical properties of the 3D printed meat paste can be obtained by varying the critical printing parameters, each of them affect the accuracy of the printed geometry in individual and/or combined ways.

In this way, the selection of the nozzle diameter should take into account the desired accuracy of the printed structure and the food components within the meat paste.

A nozzle diameter >2mm may facilitate the extrusion of the paste containing bigger particle size components, such as connective tissue but the printing precision may be compromised by the deposition of thicker streams. Whereas a nozzle diameter <2 mm allows the production of more accurate and intricate objects but the formulation may be compromised, as fine emulsion- like pastes are required for the extrusion through the narrow nozzle without the occurrence of clogging.

Similarly, an optimal nozzle height determines the accuracy and dimensions of the printed meat product, and it is suggested to be equivalent to the dimension of the nozzle diameter. Due to the extrudate swell phenomenon (Kim *et al*., 2017) attributed to the springiness of meat paste, a nozzle height lower than optimal may result in scattering of the deposited stream, thus producing expanded objects as compared to the desired design. Whereas the opposite situation, a larger than optimal nozzle height, may result in the dragging of the meat paste stream since it is not properly deposited on top of the former layers contributing to the void fraction within the structure which in turn, can affect the postprocessing changes in the meat product. In addition, springiness of the meat paste can contribute to dimensional deviation of the printed structure and may affect the printing accuracy of tall designs. When extruding the material with a predetermined nozzle diameter, the springiness may affect the actual deposited stream diameter and hence vary the actual nozzle height, as the deposited object height significantly increases in comparison to the initial design. Likewise, dragging, under- and over- deposition on the meat paste stream may be observed if the nozzle speed and extrusion rate are not properly set. The nozzle speed determines the movement rate of the print head, and needs to be adjusted with preliminary trials or by calculating the optimal nozzle speed (Hao *et al*., 2010) [6].

The extrusion rate (flow) determines the volume of deposited material per unit time (Wang & Shaw, 2005) [24]. At an optimal nozzle speed, the stream diameter equals that of the nozzle (Khalil & Sun, 2007) [7]. If the nozzle speed is too high, a thinner stream of meat paste is obtained and dragged, preventing the subsequent binding of layers and producing inaccuracies in the final product since voids remain within the cross-section area, and under deposition may occur. In addition, if the nozzle speed is too low at a given extrusion rate, thicker streams are extruded and over deposition may be observed. Furthermore, an increase extrusion rate produces more dense products due to higher amount of deposited materials and thus reduces the void fraction.

Similarly, varying infill percentages will affect the total amount of deposited material in the internal part of the printed structure, affecting the void fraction within the final 3D printed meat product and thus the post-processing conditions. For instance, the void fraction would determine the cooking conditions for a specific degree of doneness since as more porosity remains within the structure, less heat transfer occurs during cooking, affecting the moisture and fat releases and thus the texture of the cooked meat product. In addition, the setting of the infill pattern actuate the stability of the printed meat product. For instance, a rectilinear or honeycomb pattern will provide more anchor points within the structure to allow the meat paste deposited as infill to bind with the vertical shell or perimeter due to the particular stickiness of the meat paste. On the contrary, unless an 80-100% infill percentage is used, the concentric pattern lack of anchor points between the infill material and the vertical shell in which the meat paste can bind to provide stability to the structure.

In general, while adjusting the above reviewed parameters essential for geometrical accuracy during 3D printing of meat, the economical aspect should also be considered. For instance, lower printing speed and nozzle diameter, as well as increased infill percentage, may result in higher accuracy, but longer printing times and energy consumption.

Formulating the meat for enhancing its printability

3DP by extrusion requires non-Newtonian fluids showing shear-thinning behaviour in order to retain the desired printed shape (Lipton, 2017) [11]. The extrusion of meat paste involves the application of mechanical and shear stress in order to produce a strain that allows the transport of the material along the hopper and through the nozzle (Yang *et al*., 2018) [26]. Therefore, the assessment of the meat paste's rheological and mechanical properties helps to predict its behaviour during printing and deposition, and aids the setting of printing parameters. The printability of any food material refers to its ability to be handled and dispensed by a 3D printer as a freeform structure (Godoi *et al*., 2016) [3]. Printability is affected by several factors including temperature, printing parameters, and the rheological properties of food materials (Kim *et al*., 2017), making it challenging to describe the printability of a particular ink under varying printing conditions.

Although several studies reveal the assessment of different methodologies and foodstuffs in order to 3D print food products with diverse properties, one of the biggest challenges is the development of printable food formulations. A fine combination of an appropriate food formulation with suitable processing parameters must hinder the printability and structure stability issues.

Meat ingredients, which fit in the category of non-native printable traditional food materials, require a modification into a meat paste with suitable viscosity in order to be extruded from the nozzle and still be able to hold its structure upon deposition. Therefore, the expected printability, stability, and post-processing conditions need to be taken into account when designing the formulation.

First, as a fibrous material, the raw meat needs to be finely comminute into a paste form with controlled particle size to enable the extrusion through the nozzle of mm to micron size. The degree of comminution will depend on the type of the product to be printed and its textural characteristics. Meat mincing aids the extractions of myofibrillar proteins that assists the formation and stability of the batter emulsion through its interaction with other emulsion constituents. When working with off-cuts as raw material, the amount and particle size of connective tissue, as well as other non-meat tissues have to be considered, since it may affect the printability of the paste. In general, the particle size of the paste ingredients needs to be lower than the intended nozzle diameter for the printer to avoid clogging.

Additives, such as plasticizers may be required for the meat paste to be easily extruded, as well as binding components to adhere the subsequent layers once deposited. For instance, gelatine was added to a chicken, pork and fish slurry to enhance its printability (Liu *et al*., 2018a) [12]. Likewise, slow cooking and frying of 3D printed turkey and scallop pastes into complex structures was feasible with the addition of TGase right before extrusion, acting as a heat-stable cold-set binder (Lipton *et al*., 2010) [10].

Potential viscosity enhancers and binders for printable meat paste

The viscosity of the paste has to be low enough to flow easily through the nozzle and high enough to maintain the deposited shape (Godoi *et al*., 2016) [3], and further support the subsequent layers on top. In order to control the viscosity of the paste, flow enhancers such as hydrocolloids and fats can be added. The use of hydrocolloids, including polysaccharides and proteins from plant, animal and microbial sources, is widely known in the meat processing industry where they act as thickeners, gelling and binding agents, syneresis controllers, emulsifiers, textures stabilizers, etc. (McArdle, Hamill, & Kerry, 2011) [15].

Merits of 3DP

The texture and organoleptic attributes of a product is very important for determining its acceptability in the market. Novel meat products having unique flavour combinations, intricate and attractive designs, eating experience, on-demand modified nutritive value and texture, three dimensional designs etc. are having great potential in meat sector and can open unlimited opportunities in near future. The development of such products is possible by using 3D printing technology. Due to the potential advantages of 3D printing technology in food industry in near future, it has gained interest by researchers and academicians of food industry. It is possible to formulate novel food products with higher nutritional value, complex shapes and unique textures by using different food ingredients and various printing technologies. The 3D printing is a sustainable and energy efficient technology. It has inherent advantages such as efficient utilization of food ingredients with minimum or no waste, on demand inclusion of functional ingredients, improving eating experience, automation, saving on labour, lower energy and transportation cost, easier supply chain, increase scope of ingredients used for food, shifting of food manufacturing in proximity to consumers, etc (Dick *et al*., 2019) [2].

In food science, 3D printings finding its application in improving efficiency of operations, composite and designer foods, developing novel and convenient functional products, on-demand nutritional food, waste utilization and alleviating global hunger and ensuring food security, developing of specific or personalized food products for particular sections such as for elderly person having problem in swallowing or mastication, etc. For wide popularization and application in industry at large scale, the issue of high capital investment at the beginning, time consumption, issue of limited printable materials, safety issues, accuracy and surface finish of the food material should be sorted out at earliest.

Conclusions

Production of customized 3D printed animal products is still at a conceptual stage and will require significant improvement before becoming a commercial reality. Production of 3D printed meat products currently involves reduction of particle size and dilution of meaty and savoury flavour that is generally associated with reduction of value. This will limit the use of 3D printing for production of meat products from inferior and tougher cuts of meat. However, this technology may have a better future in production of cultured meat products and may successfully cater to the needs of people on special diets. Extensive research is required to develop unique animal-based products with functional and nutraceutical value to draw the attention of the consumers. This will help the growth of this sector and will add a new dimension to 3D printing that goes beyond designing complex shaped foods. Special 3D printed meat products could be used as delivery systems for nutrients or drugs to tackle malnutrition or to meet the requirements of people with health problems. Furthermore, adequate 3D printer for meat products is suggested to be extruder-type consisting of screw conveyor or syringe system with uninterrupted temperature control throughout the feeding system, the hopper, the nozzle and the platform itself in order to reduce food safety risks and controlling the material's rheology during the printing process.

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