REVIEW

Application of 3D food printing in meat production

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Abstract

Three-dimensional printing (3D) also known as additive manufacturing (AM) is a developing technology for food manufacturing, which offers novel food products with unique, complex and personalized design geometries, elaborated textures and tailored nutritional content. Today, 3D printing is being applied in military and space food, elderly food and sweets food. This technology offers a potential solution to overcome weaknesses of currently used food techniques, such as lower production efficiency and high manufacturing cost. Main aim of this review is to analyze the potential applications of 3D printing technology for meat processing including 3D printers, meat formulation and several aspects affecting the printability and post processing feasibility of 3D printed meat products.

Key words: additive technology; 3D food printing; meat printing; food design

Introduction

Additive manufacturing (AM) method involves the deposition of various materials layer by layer for building physical objects (Pinna et al., 2016; Rayna and Striukova, 2016). Due to the ability to create various food design by using different ingredients, 3D printing brings revolution to the food industry. Additive technologies are the answer to the dynamics of today's industry and provide personalized food produced according to the wishes and needs of an individual. First it was introduced to food sector from Cornell University researchers by using (Fab@home) (Periard et al., 2007). Up today, scientists have created foodstuffs such as chocolate, various desserts, breads, pasta, crackers and pizzas, in order to potentially commercially implement 3D printing (Lipton et al., 2010; Yang et al., 2015). One of the main advantages of this technology is the reduction of the produced waste in food production as well as the maximum utilization of raw materials and the possibility of producing edible packaging and cutlery.

The design of food which meets the unique demand of special consumer categories, such as, elderly, children and athletes, has raised the need for new technologies usable in the processing of additives, flavors and vitamins with tailored chemical and structural characteristics, and longer shelf-life properties. 3D printing is not only a novel approach to food fabrication, but also an economical and powerful technique for mass customization. The development of health and well-being products, as well as novel food interactions may be triggered trough 3D food printing.

According to past researches, 3D printing technology has all the requirements for creating environmentally friendly and sustainable nutrition habits. The production of functional food by using additive technology is a new field of development

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in the food industry. By adding special recipes tailored to the individual's nutritional needs of the individual (avoidance of allergens, animal products, religious restrictions, weight control), a new branch of personalized diet develops (Lupton and Turner, 2016). In order to enrich the nutritional composition of the food, alternative valuable raw materials such as insects, algae, seeds husks, animal proteins grown in the laboratory or protein of plant origin are introduced, along with consumers needs for appealing food design and ethically acceptable production (Lupton and Turner, 2016).

Customized foods are currently designed and made by specially-trained artisans using techniques, which may involve assembling the various prefabricated components to meet customers' preferences. The cost for producing a limited number of customized pieces is significantly high and to achieve mass customization in an economic way an innovative method for fabricate customized foods had to be developed. Digital gastronomy brings in cooking knowledge into food fabrication so that our eating experiences can go beyond merely taste and cover all the aspects of gastronomy (Van Bommel and Spicer, 2011).

Novel meat products demand combination of nutritionally balanced ingredients which can be shaped into a multi-material 3D model that meets special needs, such as chewing and swallowing difficulties. About 15 to 25 percent of people over the age of 50 years old suffer from difficulties in swallowing (Sun et al., 2015a).

In order to obtain specific meat cuts based on customer specifications, trimmings and off-cuts with varying composition and quality are remained and often, either sold as low-value by-products, or even considered waste. Only 7.2 % in weight of a cattle carcase accounts for cuts that are considered suitable for high-value steaks (Conroy et al., 2010). Also meat is known of its high carbon footprint values that heavily impact environment. By increasing yield of meat cuts use, can also help reducing carbon footprint.

Although it is unlikely to wipe out the conventional practices for meat production, in a near future unconventional protein sources (vegetable, insects, milk, etc.) are likely to represent an increasing competitive alternative for inferior meat cuts and processed meats made from meat by-products. Leftovers from meat trimmings and highly valuable off-cuts can be further processed into a paste and 3D printed in order to make it suitable for dysphagia patients with chewing, swallowing and digesting difficulties and still retain pleasing visual appearance of the printed personalized food. 3D food printing allows consumers to keep eating experiences (visual, textural, nutritive, etc.) and food enjoying while consuming prepared meals.

3D food printing – 3dp

A food printing platform consists of an X-Y-Z three axis stage (i.e., a Cartesian coordinate system), dispensing/sintering units, and a user interface. Material feeding system is controlled by software, that allows food fabrication in real time. Several 3DP methods has been used for food printing, such as extrusion, inkjet printing, binding deposition, and bioprinting (Godoi et al., 2016), which are commonly applied to paste-like materials, liquid and powder-based foods. The most applicable technology for food materials is 3DP by extrusion, which consists of ejecting the material through the nozzle in a digitally controlled way. The material stream is deposited through cross-sectional assembling layers according to a designed pattern, until a 3D solid structure is obtained (Sun et al., 2018).

In the screw-based extrusion process, food materials are put into the sample feeder and transported to the nozzle tip by a moving screw. This process is not suitable for the food slurry with high viscosity and high mechanical strength, thus the printed samples do not gain proper mechanical strength to support the following deposited layers which result in the object deformation and poor resolution (Liu et al., 2017). The air pressure-based extrusion is suitable to conroyprint liquid or low viscosity materials, where food materials are pushed to the nozzle by air pressure (Sun et al., 2017). The syringe-based extrusion unit is suitable to print food materials with high viscosity and high mechanical strength, to fabricate complex 3D structures with high resolution. The air pressure-based extrusion and syringe-based extrusion do not allow the continuous feeding of food materials during printing. The viscosity of the soft-material should be both low enough to be easily extruded through a fine nozzle and high enough to hold the subsequently deposited layers (Godoi et al., 2016). However, 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 applied to each 3D printed food manufacturing process (Liu et al., 2017).

There are several challenges and factors that influence on 3D food printing: 1) printing precision and accuracy 2) process productivity and 3) production of multi-flavor, multi-structure products, while using adequate rheological and thermodynamic properties, binding mechanisms and proper pre- and post-processing methods.

The highly desirable materials for 3D food printing should not only possessed suitable yield stress (τ0) and elastic modulus (G′) to be capable of maintaining printed shapes, but also had relative low consistency index (K) and flow behavior index (n) to be easily extruded out from nozzle in extrusion-based type printer. help to strength of the construct (An et al., 2017). For stronger material structure after printing are also crucial the crystallization state and glass transition temperature (T_g) of material (Godoi et al., 2016). To achieve strong 3D structures, rheological modifiers, such as hydrocolloids and soluble protein, can be added but must comply with food safety standards.

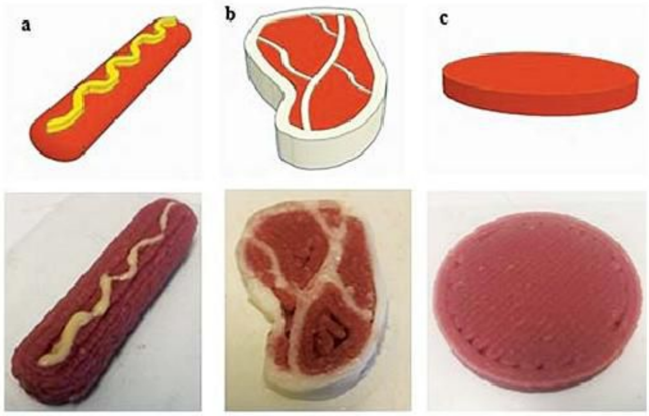
3D printing of meat

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. There are three categories based on the printability of food ingredients native printable food materials, non-native printable traditional food materials, and alternative ingredients (Sunet et al., 2015b). Meat and its by-products are fibrous materials non-printable by nature (Liu et al., 2018), which require the modification of its rheological and mechanical properties through the addition of flow enhancers to obtain an extrudable paste-like material.

3D printing of meat products consists of building the desired geometry from a slurry material, which requires controlled temperature below 4 °C, calling for liquid-based methodologies, such as extrusion and/or inkjet printing (Figure 1).

Figure 1 Hypothetical food designs: (a) sausage, (b) steak 'recombined meat', and (c) patty (Dick i sur., 2019)

Slika 1. Mogućnosti dizajna mesnih proizvoda: a) kobasica, b) odrezak (različitog sastava) i c) pljeskavica (Dick i sur., 2019.)



To date, only few studies about 3D printing of fibrous materials, such as meat and seafood have been reported. Lipton et al. (2010) assessed the suitability of 3D printed turkey meat added with transglutaminase (TGase) and bacon fat for conventional post-processing (sous-vide cooking). Liu et al. (2018) were able to 3D print chicken, pork and fish in a slurry form with the addition of gelatine solution. Still most of the printed food were seafood based with various additives. The printability of fish surimi with added NaCl was assessed by Wang et al. (2018), whilst blended canned tuna with spring water was 3D printed as part of a meal designed for people with swallowing difficulties (Kouzani et al., 2017).

One of the biggest challenges is the development of a fine combination of an appropriate food formulation with suitable processing parameters (the printability and structure, stability issues).

Formulation for 3DP

A fibrous material like 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 (Dick et al., 2019). Fragmentation will depend on the type of the product to be printed and its textural characteristics. Myofibrillar proteins are extracted during mincing that assists the formation and stability of the batter emulsion. The amount and particle size of connective tissue, as well as other non-meat tissues have to be considered, while working with off-cuts since it may affect the printability of the paste. To avoid clogging, the particle size of the paste ingredients needs to be lower than the nozzle diameter for the printer.

Addition of binding components like gelatin, including polysaccharides and proteins from plant, animal and microbial sources may be required for the meat paste to be easily extruded and to adhere the subsequent layers once deposited. Gelatine was added to a chicken, pork and fish slurry to enhance its printability (Liu et al., 2018). In order to modify the rheological and mechanical properties of the meat paste for 3DP, the emulsifying and gelling properties are of primary importance.

Cold-set binders that provide heat-resistant gels may be used to attain the modification of both, rheological and mechanical properties. While, heat-set binders can be added to the paste to enhance its mechanical properties mostly during post-deposition and post-processing operations. Microbial TGase (mTGase) is enzyme system applicable for meat cold binding mechanisms based on the covalent cross-linking of glutamine and lysine in protein molecules (Payne, 2009), resulting in the modification of physical and chemical properties of food products, such as viscosity, firmness, thermal stability, elasticity and water holding capacity. The addition of different food hydrocolloids to the meat paste can provide modified rheological and mechanical properties through varying binding mechanisms, enhancing its printability and post-processing viability. An adequate 3D extruder type printer for meat products with screw conveyor and temperature control throughout all system, would help reducing food safety risks and controlling the material's rheology during the printing process.

Potential technologies applicable to food printing

In addition to 3D printing technologies, there is a need to enhance the printing process, by combining established techniques like electrospinning and microencapsulation. The applications of electrospinning and microencapsulation include extracting fibers and encapsulating nutrition, thus providing additional material sources for printing (Sun et al., 2015b). These technologies can also be directly integrated into the food printing process through multi-print head platform, to control fibers and nutrition dispensing. They have been embedded into bioprinter design for structural coating and microsphere fabrication (Xu et al. 2013; Yu et al. 2014).

Electrospinning

Electrospinning is capable of producing thin, solid polymer elements ranging from 10 to 1000 nm in diameter. It can produce food materials with preferred size and structure, thus generating healthier foods (lower fat and lower salt) with appropriate sensory properties and novel ingredients (Neethirajan and Jayas, 2011). These thin, micro fibers can provide stronger structure and desired texture to food products with a pleasant taste experience, such as muscle fibers in meat, cellulose fibers in vegetables, and citrus fibers in low-fat full-taste mayonnaise.

Microencapsulation

Microencapsulation can pack minerals, vitamins, flavors, and essential oils within another material for the purpose of protecting active ingredients from the close environment. Integrating such technology into food printing can be achieved by using a multi-print head system, where at least one print head generates and dispenses microcapsules in the fabricated food products. This would help delicate and complex materials (e.g., probiotics and bioactive ingredients) survive in processing and packaging conditions, stabilize the shelf life of active ingredients, and create appealing aroma release, taste, odor, and color masking. This method simplifies the current functional food manufacturing process, enhances functional ingredient stability and realizes controlled release of flavorings and nutrients.

Conclusion

Even though 3DP technology has been applied for numerous types of food materials, very few studies refer to the printability of fibrous meat materials, such as pork, turkey, chicken and fish, while no data is available for beef meat. As reviewed, the design of 3D meet products through additive manufacturing is strongly dependent on the material properties and binding mechanisms.

For a better understanding of its printability, as well as the 3DP settings and post-processing conditions of the printed product is required to optimize formulation through the rheological and mechanical properties for beef paste. Further research may be conducted with beef materials in order to improve its nutritional value and sensorial profile by means of addition of bioactive ingredients and including complex internal structures, respectively. Analyzing and understanding how the essential constituents of food (carbohydrates, proteins and fat) behave during printing processes bring useful insights into the additive manufacturing of food structures and helps with the optimization of printable multicomponent mixtures. Applying new technologies to 3D food printing like electrospinning and encapsulation can help improving 3D printed meat products and become a potential way to fabricate on demand products.

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Primjena 3D ispisa hrane u proizvodnji mesa

Sažetak

Trodimenzionalan ispis (3D), odnosno aditivna proizvodnja (engl. *Additive Manufacturing*, AM), je tehnologija u razvoju koja se upotrebljava u proizvodnji hrane, a omogućava razvoj novih prehrambenih proizvoda s jedinstvenim, složenim i personaliziranim geometrijama dizajna, razrađenim teksturama i prilagođenim nutritivnim sadržajem. Danas se 3D ispis primjenjuje u proizvodnji hrane za posebne namjene (za vojnike, astronaute, starije osobe) te u konditorskoj industriji. Ova tehnologija predstavlja potencijalno rješenje za otklanjanje problema postojećih tehnika procesiranja hrane s posebnom namjenom, poput niže učinkovitosti i visokih troškova proizvodnje. Glavni je cilj ovoga rada analizirati potencijalne primjene tehnologije 3D ispisa u preradi mesa, uključujući 3D pisače, mesne formulacije i druge aspekte koji utječu na mogućnost ispisa i naknadne obrade 3D ispisanih proizvoda od mesa.

Ključne riječi: aditivna tehnologija, 3D ispis hrane, ispis mesnih proizvoda, dizajn hrane

Anwendung des 3D-Lebensmitteldrucks in der Fleischproduktion

Zusammenfassung

Der dreidimensionale Druck (3D) (engl. *Additive Manufacturing*, AM) ist eine Technologie in der Entwicklungsphase, die in der Lebensmittelproduktion eingesetzt wird und die die Entwicklung neuer Lebensmittelprodukte mit einheitlichen, komplexen und personalisierten Designgeometrien, erarbeiteten Texturen und einem angepassten Nährwertgehalt ermöglicht. Heute wird der 3D-Druck bei der Produktion von Lebensmitteln für Soldaten und Astronauten, ältere Personen und für Nachtische verwendet. Diese Technologie stellt eine potentielle Lösung für die Beseitigung von Schwierigkeiten auf, die sich aus der Verwendung von modernen Techniken der Lebensmittelprozessierung ergeben, wie zum Beispiel die geringere Effizienz und hohe Produktionskosten. Der Schwerpunkt dieser Arbeit ist es, die potentielle Anwendung der 3D-Drucktechnologie bei der Fleischbearbeitung zu prüfen, einschließlich der 3D-Drucker, Fleischformulationen und sonstigen Aspekte, die sich auf die Möglichkeiten des Drucks und der Nachbearbeitung der 3D gedruckten Fleischerzeugnisse auswirken

Schlüsselwörter: additive Technologie, 3D-Lebensmitteldruck, Druck von Fleischerzeugnissen, Lebensmitteldesign

Impresión 3D de alimentos en la producción de la carne

Resumen

La impresión tridimensional (3D), también conocida como manufactura por adición (en. *Additive Manufacturing*, AM), es tecnología en desarrollo usada en la producción de alimentos que facilita el desarrollo de nuevos productos alimenticios con geometrías del diseño singulares, complejas y personalizadas, texturas elaboradas y el contenido nutritivo individualizado. Hoy en día la impresión 3D de alimentos se usa en la producción de la comida para los soldados y astronautas, personas mayores y para los postres. Esta tecnología representa una solución potencial para eliminar las dificultades que surgen en las técnicas modernas del procesamiento de alimentos, como la baja eficiencia y los costos altos de la producción. El objetivo principal de este trabajo fue analizar las aplicaciones potenciales de la tecnología de la impresión 3D en el procesamiento de la carne, incluyendo las impresoras 3D, formulaciones de carne y otras dimensiones que pueden influir sobre las posibilidades de la impresión y sobre el procesamiento posterior de los productos cárnicos imprimidos por la impresión 3D.

Palabras claves: tecnología aditiva, 3D impresión de la comida, impresión de productos cárnicos, diseño de productos alimenticios

Applicazione della stampa 3D per alimenti nella produzione della carne

Riassunto

La stampa tridimensionale (3D), nota anche con il nome di produzione additiva (in inglese *Additive Manufacturing*, AM), è una tecnologia in via di sviluppo che si utilizza nell'industria alimentare, consentendo lo sviluppo di nuovi prodotti alimentari con un design dalle geometrie uniche, complesso e personalizzato, con consistenze elaborate e contenuti nutrizionali adatti caso per caso. Oggi la stampa 3D trova applicazione nella produzione di prodotti alimentari in ambiente militare e per gli astronauti, per gli anziani e per la produzione di dessert. Questa tecnologia rappresenta una potenziale soluzione per la rimozione di ogni problema che discende dall'uso di tecniche all'avanguardia del processo alimentare, come la bassa efficienza e gli alti costi di produzione. L'obiettivo principale di questo studio consiste nell'analizzare la potenziale applicazione della tecnologia della stampa 3D nella lavorazione della carne, comprese le stampanti 3D, le formule a base di carne e gli altri aspetti che incidono sulla possibilità di stampa e di ulteriore elaborazione dei prodotti di carne stampati in 3D

Parole chiave: tecnologia additiva, stampa 3D per alimenti, stampa di prodotti di carne, design degli alimenti