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3D printing based on meat materials: Challenges and opportunities

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ABSTRACT

Three-dimensional (3D) printing, as an emerging technology, is driving great progress in the food industry. In the meat field, 3D printing is expected to replace the traditional food industry and solve the problems of raw material waste and food contamination. Nevertheless, the application of 3D printing in meat still faces many challenges. The rheological properties of the ink, such as shear thinning behavior, viscosity, and yield stress, are critical in determining whether it can be printed smoothly and ensuring the quality of the product. Meat materials are complex multi-phase colloidal systems with unique fibrous structures that cannot be printed directly, and improving the printability of meat colloids mainly limits meat printing. The complexity of meat colloidal systems determines the different heat requirements. In addition, at this stage, the functionality of the printer and the formulation of a single nutritional and organoleptic properties limit the implementation and application of 3D printing. Moreover, the development of cultured meat, the full application of by-products, and the emergence of new technologies provides opportunities for the application of 3D printing in the meat industry. This review highlights the current challenges and opportunities for the application of 3D printing in meat to provide new ideas for the development of 3D printing.

1. Introduction

Meat is a nutrient-rich food containing many trace elements such as iron, zinc, and B vitamins and is the primary source of complete protein in most people's diets. Throughout history, humans have consumed meat without interruption, and anthropologists believe that adequate meat intake leads to the evolution of larger brains. As the economy and population grew, human demand for meat continued to grow(Roser, 2017). However, this development is considered environmentally unfriendly and unsustainable, because many problems are encountered in raising livestock and meat production processes. First, livestock breeding requires large amounts of land and forage, which degrades pastures and drastically reduces forest cover. Moreover, the UN data show that global greenhouse gas emissions from livestock farming account for approximately 15% of total global emissions and are part of an extensive carbon emission system, which is not conducive to a benign global climate(K. Handral, Hua Tay, Wan Chan & Choudhury, 2022). In addition, during the production of raw materials, meat is cut and trimmed to varying degrees to suit consumer preferences, and despite possessing the same nutritional value, at least 30% of the meat is usually sold as a low-value by-product or even discarded as waste, resulting in significant waste and food waste contamination(Dick, Bhandari & Prakash, 2019a; Welin, 2013; Zhao et al., 2021). Therefore, the meat industry urgently needs new technologies to link these problems.

3D printing, which is also known as additive manufacturing, is a technology-based on computer numerical technology, through three-dimensional modeling, model slicing, information processing, layer-by-layer printing, and other steps to form a 3D solid(Guo et al., 2019). Hull developed the first commercial 3D printer in 1986(Hull, 1986), and 3D printing began to enter the public consciousness and gradually became widely used in industrial design, model making, automobile, and aviation(Kelly et al., 2019; Lu et al., 2018). The original 3D printing technology was developed based on photo-hardened polymers to manufacture complex metal and ceramic plastic parts rather than food materials. In 2007, an extrusion-based printer (Fab@home) designed by researchers at Cornell University introduced 3D printing to the food industry(Malone and Lipson, 2007).

The 3D printing technology, as an emerging technology in the food industry, can be an excellent solution to the environmentally unfriendly and unsustainable challenges faced by the meat industry. The 3D

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printing technology that produces cell-cultured meat can obtain similar nutrition and taste to the meat while eliminating the need for farming, thus reducing land occupation and waste emissions. Moreover, the raw materials for 3D printing are often powders or pastes, which can produce custom-shaped food products in a relatively short period without complicated pre-processing and cutting, thus significantly reducing raw material waste and food waste pollution. In addition, 3D printing is efficient, economical, innovative, and personalized to meet the unique needs of children, pregnant women, the elderly, soldiers, and other special populations nutritional need(Bulut and Candoğan, 2022; Prakash et al., 2019).Accordingly, it has received wide attention.

However, the meat materials used for 3D printing can be regarded as a polyphase colloid system with water as a continuous phase and protein, carbohydrate, and inorganic salt as the dispersed phase. This system has a complex rheological properties and is not naturally printable, resulting in great challenges to 3D printing. Therefore, this paper first summarized the challenges faced by 3D printing in the meat industry, including printability, simultaneous precision cooking, 3D printer development, and product nutritional sensory limitations, and discussed the methods and research directions that can be used to deal with these challenges. Then, the application opportunities of 3D printing in the meat industry were introduced in detail, the research status of cell-cultured meat was reviewed, the feasibility of developing meat by-products by 3D printing was discussed, and the latest technology for evaluating meat printability was summarized. This review describes in detail the application of food 3D printing technology in meat materials in terms of challenges and opportunities and introduced some ideas for the reasonable design of printable materials and accelerating the development of meat printing materials.

2. 3D printing of traditional meat materials

The leading 3D printing methods include selective laser sintering, binder jetting, inkjet printing, and extrusion printing (Demei et al., 2022). Extrusion 3D printing is the most appropriate technology for food materials and has been widely used compared with other technologies (Varvara et al., 2021). Extrusion-based 3D printing is performed via computer-controlled extrusion of ink from a nozzle and builds up layer by layer on the printer base (Fig. 1). During printing, the path of the nozzle motion is controlled by a preset 3D model, allowing the extruded print material to produce a specific shape after curing(Sun et al., 2015; Sun et al., 2018). According to the printing characteristics, the food can be divided into raw printable food materials (e.g., chocolate(Kim et al., 2017), cheese, and mashed potatoes(He et al., 2020)) and non-raw printable food materials (e.g., meat, vegetables, and fruits). The unique fibrous structure of meat adds to the challenge of printing, thus requiring pre-treatment or additives to allow the ink to extrude smoothly from the nozzle and maintain good self-support and formability. Limited studies have looked into the development of 3D printed meat products, and most of these studies have focused on surimi materials with good adhesion, gelation, and softness(Chen et al., 2021; Oyinloye and Yoon, 2022; Wang et al., 2018; Xie et al., 2022). A few studies have focused on meat with solid fiber structure and low viscosity (beef, chicken breast, etc.). Therefore, further development of printable raw materials and expansion of printable meat types are necessary for the application of 3D printing to meat products.

3. Challenges of 3D printing in meat material

3.1. Poor printability

Improving the rheological properties of meat materials is a key challenge for meat printing. Meat is a complex polyphase colloidal system that exhibits complex rheology and is usually plastic or pseudoplastic (shear thinning). Complex structural units result from the interactions between particles in the dispersed phase and with other colloidal molecules that are added to control the properties of the system, such as the addition of gelatin to chicken, to improve its rheological properties and gelation ability(Bulut et al., 2022). For extrusion-based 3D printing, the rheological properties of the material (e.g., shear thinning behavior, viscosity, and yield stress) are critical in determining whether it can be printed successfully and ensuring product quality (Jiang et al., 2019). The control of rheology is very important for processing and the control of texture and sensory perception. The 3D printing process is divided into four stages, namely, start-up flow, continuous extrusion, recovery stage, and deposition stage. Generally, the 3D printing ink must have good extrusion, recovery, and self-supporting ability. The yield stress reflects the minimum force required to initiate fluid flow and is closely related to the extrusion performance of the ink during 3D printing. The minimum pressure required to start the flow of ink with yield stress can be described as follows:

$$p_{min} = \left(\frac{4L}{D}\right)\tau_{yield} \tag{1}$$

where $P_{\min}$ indicates the minimum pressure required, L indicates the nozzle length, D indicates the nozzle diameter, and τ_{yield} indicates the yield stress of inks.

During the extrusion phase, the shear force at the nozzle suddenly

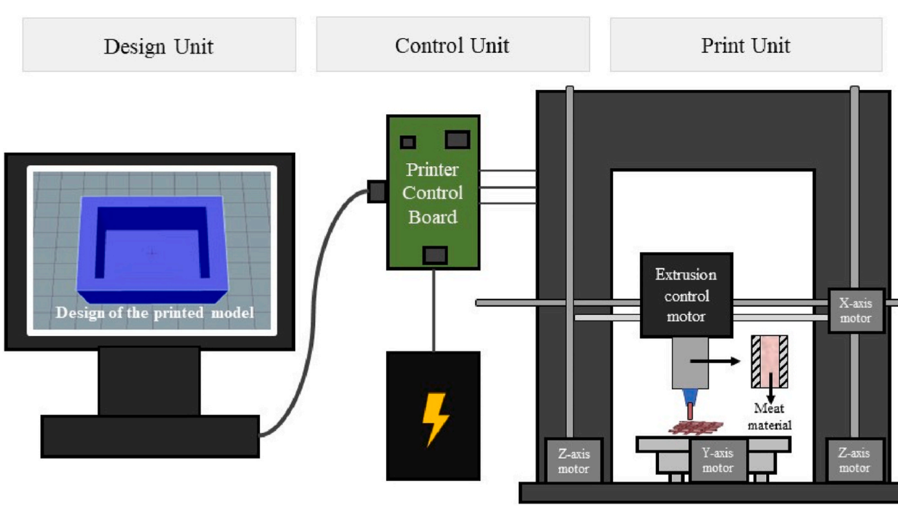

Fig. 1. Schematic diagram of 3D printing of meat.

becomes high, and the material under gravity experiences low shear action again after extrusion. The ink should therefore have shear thinning properties with high shear recoverability, exhibit low viscosity during extrusion for smooth extrusion, and have sufficiently high viscosity after deposition to adhere to the previously deposited ink layer. The shear-thinning behavior of the sample is evaluated by fitting a power-law model to the obtained viscosity measurements (Equation (2)) as expressed below:

$$\eta = \kappa \cdot \gamma^{n-1} \tag{2}$$

where η is the material viscosity (Pa·s), γ is the shear rate (s^{-1}), k is the consistency index (Pa·s^n), and n is the flow behavior index(Paxton et al., 2017). For fluid shear thinning with $n < 1$, a smaller n indicates higher shear thinning behavior.

The recovery stage is the transition phase prior to a deposition where the ink undergoes a change from high to low shear. Ideally, the ink should have the ability to recover viscosity and resist deformation immediately after extrusion. Researchers often simulate the extrusion to the recovery process by alternating strain scans to evaluate the shear recovery behavior of inks(Zeng et al., 2021). During deposition, the ink layers stack up but do not merge and collapse between the layers, thus requiring good self-supporting capabilities. The main rheological parameters involved in the deposition stage are the yield stress, complex modulus (G^*), storage modulus (G'), and elastic modulus (G'') at the deposition temperature. The yield stress at the deposition stage reflects the resistance of the ink to external stresses, such as the gravity and forces exerted by its top material layer, at ambient temperature. G^* indicates solid-like properties, which reflect the resistance to compressive deformation and mechanical strength. G' and G'' reflect the viscoelasticity of the ink. The results of the present study indicate that materials with a highly structured or more solid-like behavior have a good self-supporting ability (Fig. 2).

Extruded 3D printed food materials need to maintain a low viscosity and yield stress during extrusion flow to ensure their smooth extrusion. After extrusion, these materials need to have sufficient viscosity and yield stress to retain their shape and support and connect other layers. Finally, the ink must provide strong mechanical support and gel strength to maintain the stability of the spatial structure(Chen et al., 2022), thus preventing the product from collapsing over time. As a complex colloid system, meat does not have the original printing ability. A good 3D printing effect can be obtained by improving the rheological and gel properties of meat paste in the process of ink development. At present, the printability of meat materials was improved mainly through pre-treatment to promote the interaction between colloids in the minced meat system or to add other colloids to meat. Notably, when adjusting the ink formulation, the ability of the ink to resist post-treatment should be considered. Ideally, the product should be able to transfer mass evenly, maintain its full shape, and have minimal steaming losses during maturation.

3.1.1. Pre-processing to improve printability

3.1.1.1. Pre-ultrasound treatment. As an emerging technology, ultrasound has been widely used in the food industry. Mechanical effects such as cavitation, agitation, and turbulence that are produced by ultrasound destroy muscle fibers contribute to the release of viscous substances (e.g., meat protein, fat, and glycogen) and increase the degree of fiber swelling, thus improving the water retention, softness, and viscosity of meat(Amiri et al., 2018). The protein and fat in meat may dissolve and disperse into small molecules under the action of ultrasound and interact with each other through electrostatic action and van der Waals force. This interaction increases the stability of the whole colloid system. As the main protein of meat, myofibrillar protein determines the functional properties of meat products(Chang et al., 2012; Li and Sun, 2002; Sun et al., 2021; Wang et al., 2021). Alarcon-Rojo et al. found that ultrasound enhances the rheological and gel properties of the myofibrillar protein(Alarcon-Rojo et al., 2015). Zhang et al. found that ultrasound synergistically treated with endogenous transglutaminase (TGase) can remarkably improve the gel strength of surimi(Zhang et al., 2011). Therefore, ultrasound treatment could be used as a simple and efficient pre-treatment method for 3D printing inks to improve the printability of minced meat. Besides, ultrasound participates in enhancing mass transfer, improving heat transfer during cooking, and reducing cooking losses and cooking time(Leal-Ramos et al., 2011; Pohlman et al., 1997).

3.1.1.2. Microwave treatment. Microwave heating (MH) absorbs microwave energy and simultaneously converts it into heat by electromagnetic induction of materials(Sumnu, 2001). Microwave heating is a promising method for 3D printing material pre-treatment and post-treatment because of its fast-heating speed, high energy efficiency, non-contact, and hygienic properties(He et al., 2020). Microwave has been used to improve the printability of materials such as soy protein (Bhattacharya and Jena, 2007) and potato starch(Przetaczek-Rożnowska et al., 2019). The thermal effect of microwave denatures the proteins in the minced meat system and reversibly associates them to form soluble aggregates, thus changing some of the proteins from sol to gel and increasing the self-supporting capacity of the meat filling(Bohr and Bohr, 2000; Cai et al., 2018; Sun et al., 2020). By controlling the time and power ratio of sol and gel through microwave control, the fluidity and mechanical strength of the meat filling can be changed. In 3D printing of meat products, microwave pre-treatment is seldom studied, and studies have mainly focused on surimi materials. Zhao et al. used a synergistic approach of microwave-focused heating and TGase to achieve the self-gelatinization of surimi during printing. Solid products with high resistance to deformation were obtained under

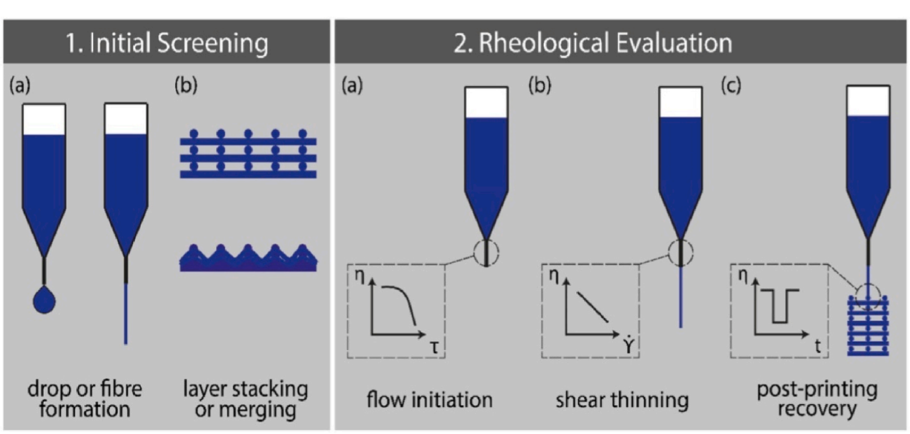

Fig. 2. Outline of the proposed research method to assess bio-ink printability. 1. Initial screening of ink formulations to establish (a) fibre formation as opposed to droplet formation and (b) successful layer stacking without merging between layers. 2. Rheological evaluations are employed to characterise (a) the flow initiation properties and yield stress, (b) degree of shear-thinning to predict the extrusion process and cell survival and (c) recovery behaviour of the inks after printing(Paxton et al., 2017).

these conditions(L. Zhao et al., 2021). The results of these studies imply that microwave heating can effectively induce gels in 3D printing.

3.1.1.3. High-pressure treatment. High-pressure treatment has been a promising area of research in meat processing because of its potential to prolong meat shelf life and improve meat quality(Chattong, Apichartsrangkoon & Bell, 2007). In addition, pressure treatment leads to changes in the constituent molecules of meat, affects the structural and functional properties of proteins, promotes protein adsorption at the fat droplet/water interface to improve ink emulsification, increases the thermal stability of proteins, promotes gelation, and fixes free water, resulting in dense and uniform gels(Wang et al., 2020; Yang et al., 2021; Zhou et al., 2018). In addition, high pressure can improve the texture and printability of meat by increasing elasticity, water retention, and adhesion. Limited studies have applied high pressure to meat product printing, and the role of high-pressure technology in 3D printing needs to be further developed.

3.1.2. Adjusting formulations to improve printability

The rheological properties of raw materials (e.g., shear-thinning properties, viscosity, and yield stress) remarkably affect the 3D printing process and the quality of the printed product. Protein, fat, and carbohydrates are essential components of a balanced diet, and they have different rheological properties and gelation characteristics(Liu et al., 2019; Liu et al., 2018; Liu et al., 2020). Therefore, the rheological characteristics of raw materials need to be understood for an effective 3D printing. By altering the proportion of meat to non-meat ingredients in ink formulations, the rheology and printability of the ink can be improved, and nutrient-rich goods can be developed.

3.1.2.1. Lipids. Lipids (also translated as lipid-like) are a class of bioorganic molecules that are poorly soluble in water and highly soluble in non-polar solvents. Most lipids consist of esters and their derivatives formed from fatty acids and alcohols. The chain length and saturation of the fatty acids also affect the physical and functional properties of the lipids, and thus the 3D printing results. Notably, raw meat comes with animal fat, and the fat content and composition vary greatly depending on the type and part of the meat. During meat ink processing, meat pieces are crushed and sheared to form minced meat. At this time, the fat is sheared into microspheres and evenly adsorbed on the protein surface. When the ink is heated, the proteins therein are denatured and cross-linked to form a 3D gel network, while the fat fills the network pores or co-polymerise with the protein to form an emulsified gel. Therefore, lipids in meat products can improve the flow behavior of meat materials, reduce the viscosity, and increase the ink flow and extrudability. During gel formation, lipids play an excellent filling role, forming emulsion gels with proteins in meat with a uniform structure and good formability and self-supporting properties. Wu et al. found that fat globules interact with proteins through disulfide bonds, thus affecting the formation of gel networks and improving gel hardness and water retention(Wu, Xiong, Chen, Tang & Zhou, 2009a). The addition of functional lipids to 3D printing provides a new idea for the design of nutritious and healthy personalized foods. However, too much fat will lead to the fluid behavior of meat paste, thus increasing cooking loss and deformation. Arianna and others found that beef ink's cooking loss and shrinkage are proportional to the lard content. Moreover, the addition of fat makes the ink show viscous fluid behavior; although this condition is conducive to extrusion, it affects the continuity of extrusion and self-supporting(Dick, Bhandari & Prakash, 2019b). Therefore, lipids and other materials should be chosen to improve the printability of meat ink. Xie et al. produced cod protein ink with high thixotropy by blending flaxseed oil with inulin/soybean dietary fiber(Xie et al., 2022a,b).

3.1.2.2. Hydrophilic colloid. Hydrocolloids, also known as edible gums, are a heterogeneous group of long-chain polymers, which mostly include polysaccharides and a few proteins. These compounds are soluble in water and can be fully hydrated under certain conditions to form viscous dispersions and/or gels. The addition of hydrocolloids in meat products can improve the water retention of gels, enhance the mechanical strength of gels, and promote the stability of hybrid dispersion systems (Liu and Xu, 2019; Perez-Mateos et al., 2001; Ramirez et al., 2002; Wang et al., 2018). In 3D printing, the addition of exogenous colloids interacts with macromolecules in the minced meat, thereby enhancing the stability of the meat colloids and improving its rheological properties. Hydrocolloids mainly acts as thickening and gelling agents. The thickening effect mainly affects the continuity and homogeneity of the ink during extrusion. Hydrocolloids have a certain viscosity, because their molecular structure contains more hydrophilic groups, such as hydroxyl and carboxyl. The presence of these groups makes the protein or polysaccharide partly dissolved in the solution, forming a viscous colloidal solution. Based on Stokes' law, the greater the viscosity, the smaller the settling rate of colloidal particles, the smaller the degree of mutual agglomeration between molecules, and the more stable the system. High-viscosity inks show good deposition and self-supporting properties in 3D printing, and they can clog the nozzle tip and prevent extrusion. Low-viscosity inks may interrupt flow and agglomerate solid particles, and they have poor mechanical solids properties that make them difficult to mold(Müller et al., 2020). Therefore, hydrocolloids should be added to adjust the extrudability of meat materials.

Gelling mainly improves the self-supporting properties of the ink. The hydrophilic groups in hydrogels form gels through hydrogen bonding, hydrophobic association, and cation-mediated cross-linking physical association. These gels can be classified as cold-curing, heat-curing, and cation-mediated gels in terms of their gelation-forming mechanism (as shown in Table 1). For example, starch as a cold-curing hydrogel has a high viscosity and shear stability, and considering the interaction between starch molecules, intermolecular interactions are enhanced at high starch concentrations and the probability of forming hydrogen bonds increases. This phenomenon contributes to the formation of a denser gel network and enhanced self-supporting properties of the ink(Goldstein et al., 2010). Starch can be used as an additive to other food materials to make them printable(Feng et al., 2019). Beef, chicken breast, and other meats usually have very low viscosity, are not printable, and are often used in combination with starch and lipids to blend into printable inks.

However, the effect of hydrogels in meat systems is not always positive, and the effect is related to the type of hydrocolloid and the way and amount of addition. The addition of xanthan gum, k-carrageenan, and alginate alone may sometimes deteri0orate the texture of meat products(Hachmeister and Herald, 1998; MITTAL & BARBUT, 1994). The addition of small amounts (0.2% and 0.5%) of horny gum may increase gel elasticity. However, higher concentrations of carrageenan can lead to a decrease in sausage elasticity(Ayadi et al., 2009). In addition, the combination of several hydrocolloids usually results in new rheological properties to the food, improves product quality, and has the advantage of fat and cost reduction. Cross-linking may occur between different hydrocolloids, leading to precipitation or gelation. Hydrocolloids with opposite charges may join and form precipitates. By using the synergistic effect of gels, gel structures can be enhanced at lower addition levels(Fan et al., 2020; Yasin et al., 2016).

3.1.2.3. Transglutaminase (TGase). TGase is an extracellular acyltransferase that catalyzes the formation of a non-disulfide covalent bond between the ε-amino group of a lysine residue and the γ-carboxamide group of the glutamine residue on the heavy chain of myosin. This reaction changes the physical and chemical properties of the meat matrix (Cando et al., 2016). Dong et al. found that microbial transglutaminase (MTGase) catalyzes the acyl transfer reaction during the manufacture of surimi to improve surimi's printability and form a tight and uniform gel structure(Dong et al., 2020). TGase, as a temperature-dependent

Table 1
Hydrocolloids in meat products.

Gel conditions	Hydrocolloids	Functional Class	Application	References	Example
Cooling	Gelatin (triple helix)	Thickeners, Gelling agent	Chicken	Wang et al. (2018)	 3D printed chicken mince (Yang et al., 2022)
	Agar	Stabilisers, Thickeners, Gelling agents	Canned food, fish, poultry	Banerjee & Bhattacharya (2012)	
	Starch	Stabilisers, Thickeners	Minced fish, minced shrimp, pork ham	(Li and Yeh, 2003); (Pan et al., 2021); (Dong et al., 2019)	
	Collagen	Gelling agents	Minced fish	(Eilert, Blackmer, Mandigo & Calkins, 1993); (Shi et al., 2022)	
Cooling and salt	Carrageenan	Stabilisers, Thickeners, Gelling agents	Beef, sausage	(Dick, Bhandari & Prakash, 2021); (Cao et al., 2022)	 3D printed chicken mince (Dick et al., 2019b)
	Cold-junction gum	Gelling agents	Chicken, sausage	Li et al. (2019)	
	Guar gum	Emulsifier, Stabilisers, Thickeners	Beef	(Dick et al., 2019b); (Ramí;rez, Barrera, Morales & Vázquez, 2002)	
Heating	Soy protein	Gelling agents	sausage	(Patana-anake & foegeding, 1985); (Kang et al., 2021)	 Photos of 3D printed pork after cooking(Dick, Bhandari, Dong & Prakash, 2020b)
	Ovalbumin	Gelling agents	Beef	Pietrasik (2003)	
	Methylcellulose	Thickeners	Ostrich meat	Chattong et al. (2007)	
Salt (Specific binding)	Alginate	Chelating agent, Stabilisers, Thickeners	Pork, cold-cut duck	Kim et al. (2020)	
Synergistic effects	Xanthan Gum + Galactomannan	Gelling agents Thickeners	Pork	(Ramí;rez et al., 2002); (Dick, Bhandari, Dong & Prakash, 2020)	

enzyme, has a dynamic temperature range of 0–60 °C and a pH activity range of 4.5–8.0. The reaction temperature and pH can be adjusted using other processing techniques to control the cross-linking effect and the reaction process(Kieliszek and Misiewicz, 2014). For example, Zhao et al. synergistically treated surimi with TGase and microwave heating and found that ϵ-(γ-Glu)-Lys was produced by the synergistic effect of microwave, and TGase mainly resulted in gel enhancement(Z. Zhao et al., 2021). Trespalacios studied the effect of simultaneous application of MTGase and high pressure on the functional properties of chicken gels. Significant improvements in hardness and chewiness were observed(Trespalacios and Pla, 2007). In addition, MTGase is usually synergized with NaCl or phosphate in the 3D printing of meat to obtain sufficient protein substrate to enhance protein cross-linking levels (Sadeghi-Mehr et al., 2018).

3.2. Meat-related 3D printers need further development

3.2.1. Lack of capacity to ensure food safety at all links

Meat materials increase the demand for the development of 3D printers. For example, microbial growth can be inhibited and spoilage of meat products can be prevented during printing by setting a printing temperature of less than 4 °C at all times. However, cooling during printing results in energy consumption, thus deteriorating the sustainability in large-scale food production. Therefore, the development of energy-efficient and environmentally friendly automatic temperature-controlled 3D printers may be used as the basis for the commercialization of food 3D printing. In addition, during printing, the ink comes into contact with several parts of the printer, such as the extruder, nozzle, and piston, which are located inside the printer, making them difficult to clean. Subsequently, this configuration may promote the growth and colonization of different microorganisms, such as *Staphylococcus aureus* and *Escherichia coli*(Severini et al., 2018). Muro-Fraguas et al. have developed acrylic acid and tetraethyl orthosilicate coatings applied by plasma polymerization to reduce the biofilm formation of *Pseudomonas aeruginosa*, *E. coli*, and *Listeria monocytogenes* on 3D printing contact surfaces(Muro-Fraguas et al., 2020). However, antimicrobial surfaces may form a layer of dead cell surface debris after some time, thus remarkably decreasing the lethality efficiency of the antimicrobial surface. The fabrication of self-cleaning surfaces is one of the most anticipated alternatives to slow down the rate of bacterial adhesion to surfaces. The application of superhydrophobic-based systems in 3D printers is highly desirable. Superhydrophobic materials have considerable surface roughness(Yoon et al. 2014), which forms cavities when water comes in contact with the surface. This property repels aqueous residues, spills, and droplets that carry bacterial suspension, thus reducing the actual effective contact area between the suspension(Oh et al., 2019) and the coated surface and improving the efficiency of disinfection and cleaning of devices and surface(Ghasemi and Niakousari, 2020). Meat colloids are hydrophilic colloidal systems with water as the dispersed phase, and superhydrophobic coatings can effectively reduce ink adhesion and enhance the hygienic design of 3D printers (Fig. 3).

The balance between printer printing efficiency and cost should be focused on. Most current printers are single or dual printheads, and the feed tube and cartridges can only hold a small amount of food material and do not have the capacity for large-scale batch production. The high price of printers makes them unaffordable for small food factories and home kitchens. Therefore, continuous feeding systems and multi-jet printers should be developed to improve the practicality of printers. Most printers simply give the ink its characteristic shape, and raw meat products not only rely on special pre-treatments and formulations to achieve the proper extrusion viscosity but also require post-processing by using traditional convection or conduction methods, thus limiting the ability of combining multiple materials in a single food object (Hertafeld et al., 2018). In response to these limitations, the combination of 3D printing technology with advanced thermal processing or texture modification technologies for the development of printers with pre-and post-processing capabilities can maximize the benefits of 3D printing(Demei et al., 2022). Gunduz et al. combined high-frequency amplitude ultrasound on 3D printing nozzles to enable the 3D printing of high-viscosity materials without pre-processing the recipe to adjust the viscosity(Gunduz et al., 2018). However, only a few specialized studies have integrated 3D printing with new technologies, and limited data are available to support the need to fully consider food safety and production economics to address the potential problems in the application of these technologies(Dankar et al., 2018).

3.2.2. Lack of simultaneous precision cooking ability

Post-processing issues are among the main challenges that face the 3D meat printing industry today. The need for simultaneous maturation capabilities provides new challenges for printer development. Unlike chocolates and candies, most meat materials cannot be eaten raw and need to be processed using traditional convection or conduction methods after printing, thus limiting their ability to combine multiple materials in a single food object. Traditional cooking methods tend to cause damage to the print shape and cooking loss(De Pilli and Alessandrino, 2020; Dick et al., 2021), and the steaming process moisture, as a heat transfer medium, can over-penetrate the ink and damage its structure and shape(Dankar et al., 2020; Dong et al., 2019). The loss of surface moisture and excessive protein denaturation caused by baking can lead to uneven heating and affect the taste of the product(Severini et al., 2016). The traditional heating method can only heat a certain area and cannot precisely control the heating object. When printing complex multi-layer products, the heating time and conditions required are different for different layers of printing materials, and the traditional printing method cannot precisely locate the heat required for cooking. The combination of modern cooking technology with the printer to achieve simultaneous maturation during printing can meet the heat requirements of different food materials. Laser cooking technology allows for heat targeting and transfer, thus providing more uniform and efficient heating than conduction without physical contact with the food. Therefore, this technique is an ideal cooking method for 3D printing(Anonymous et al., 2021; Blutinger et al., 2019; Blutinger et al., 2021; Ma and Tao, 2005; Vaskoska et al., 2020). By incorporating a blue laser (λ = 445 nm), near-infrared (NIR) laser (λ = 980 nm), and mid-infrared (MIR) laser (λ = 10.6 μm) into the printer, the researchers laser-cooked food with approximately 50% less cooking loss than oven-baked food and enabled layer-by-layer cooking (Fig. 4). Hertafeld et al. integrated an infrared light heating mechanism into the printer, thus allowing the printer to selectively cook and print multi-material food objects, thereby creating complex food patterns with more compositional complexity(Hertafeld et al., 2018). However, many difficulties are encountered in the application of synchronous cooking technology to 3D printing. The control of cooking space and laser intensity needs to be improved, and the synchronous cooking method suitable for meat and the safety of the new technology need to be studied.

3.3. Improvement of nutritional and sensory properties

Ideally, 3D printed products should have the same or even better sensory properties and nutritional values than traditional foods to replace traditional foods in the market gradually. However, limited studies have focused on the sensory evaluation of 3D printed products and have primarily focused on the improvement and evaluation of texture and formability of single meat raw materials (e.g., chicken, beef, and pork). At the same time, mixed material printing with high nutritional value is lacking(Pant et al., 2021). Therefore, the currently developed printed products can only meet a single requirement. For example, the development of geriatric foods only focuses on the improvement of soft texture, with emphasis on hardness and chewiness, while the sensory evaluation of color and flavor is lacking. In addition, printability is not the only criterion that determines product quality. Post-treatment methods remarkably influence structural stability and consumer acceptability. Traditional post-treatment methods such as frying, steaming, and baking can alter the structure (e.g., shrinkage and steaming loss) and functionality (e.g., protein denaturation and vitamin loss) of the product to some extent. When cold-curing gels are used in printing to maintain the structure, the high temperature of the post-treatment often leads to gel melting and structural collapse. Therefore, the ink printability must be considered along with the stability of the post-treatment and the final product's sensory properties. Studying a personalized and nutritionally balanced diet is the prominent advantage of 3D printing. Many bioactive substances such as curcumin (Chen et al., 2021) and anthocyanin have been applied in the 3D printing of plant-based materials, while meat materials are rarely involved. Therefore, nutritional health and flavor need to be combined for the development of more functional meat products(Ghazal et al., 2021; Ghazal et al., 2019).

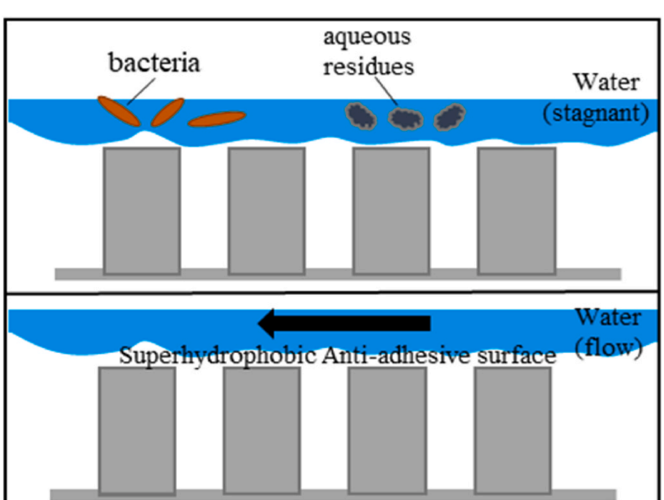

Fig. 3. Principle of superhydrophobic surface antibacterial and self-cleaning.

4. Opportunities of 3D printing in meat applications

4.1. 3D printing of cultured meat products

The 3D printing of complex structures such as muscles, skin, bones, and cartilage with biomaterials is called bio-printing. Bio-printing is a new technology that is based on tissue engineering, and this field is still being developed for food applications. Unlike cell-cultured meat, the 3D printing of cultured meat is more complicated, which achieves tissue maturity by accurately adhering to and growing stem cells and biomaterials in scaffolds, thus forming cultured meat(Ramachandraiah, 2021). The 3D printing of meat is mainly composed of the initial cells, culture medium, and scaffold. Initially, cells need to have the ability of self-renewal, infinite proliferation, and differentiation to develop and form the cells (e.g., muscle cells, fat cells, and chondrocytes) needed for meat. The medium mainly drives cell growth, multiplication, and differentiation and is responsible for providing nutrients for cell growth, leading to tissue regeneration and maturation. Growth factors and animal serum are important components of the growth medium for tissue maturation, which are often obtained from animal embryos(Andreassen et al., 2020; Andreassen et al., 2020; Kolkmann et al., 2020). The 3D scaffold is essential to the structure of cultured meat, which determines the physiological similarity between cultured meat and real meat. Therefore, the scaffold used in 3D printing must have good sensory quality and food safety and ensure the sufficiency of surface area and porosity to support cell adhesion and proliferation(Datar and Betti, 2010). Ben-Arye et al. used soybean protein as a 3D scaffold to support cells and imitate extracellular matrix to create bovine muscle tissue, thus replicating the feeling and texture of meat(Ben-Arye et al., 2020). Fibrinogen, gelatin, and collagen are 3D printing scaffolds that can improve tissue stiffness and meet the requirements of meat fiber characteristics(Ahmad et al., 2021; Duan et al., 2013; MacQueen et al., 2019). In the future, 3D printing of cultured meat may be able to solve the problems of land, resources, and environment in the farming process, bringing new opportunities for the development of the meat industry.

a b

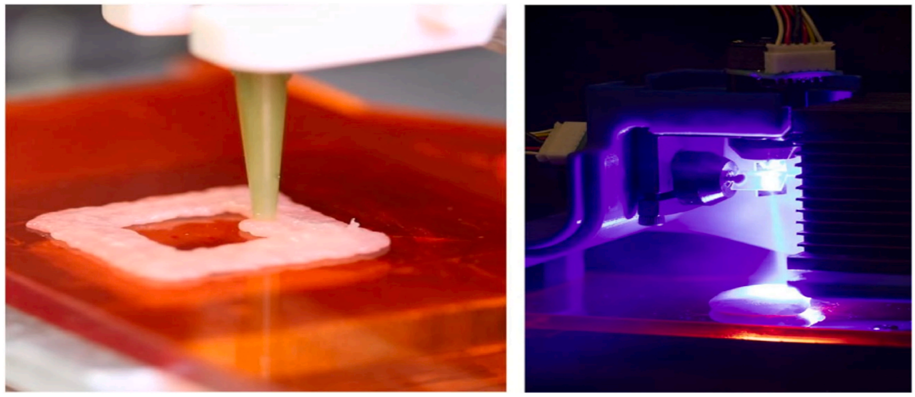

Fig. 4. Close up of raw chicken printed by a general food printer (a); Close up of a printer with a blue laser printing and synchronizing cooked chicken (b)(Blutinger et al., 2021).

4.2. Exploitation of meat by-product ink

The exploitation of meat by-products and trimmings is a crucial challenge for meat printing. Meat by-products mainly include body parts other than muscle, such as offal, skin, feet, and fat, accounting for 52% and 66% of the live weight of cattle and pigs, respectively. Some of these by-products, such as heart, liver, and kidney, have high nutritional value but have an unpleasant fishy taste and are generally unacceptable to consumers, making them low-value products in the market(Zou et al., 2021). The unpleasant smell in the liver is mainly caused by the release of iron bound to the proteins, which produces a metallic smell, and the decomposition of proteins and lipid oxidation, which produces a large number of alcohols, aldehydes, ketones, amines, low-grade fatty acids and sulfides, and other organic substances with a particular smell(Xiong et al., 2017). Undesirable flavors can be well removed by chemical methods such as antioxidant method(Liu et al., 2021) and acid-base salt treatment(Yarnpakdee et al., 2012), physical methods such as β-cyclodextrin adsorption(Yu et al., 2016), microencapsulation(Serfert et al., 2010), and fermentation, and enzyme treatment methods(Li et al., 2020), but these methods require the destruction of liver tissue. 3D printing can customize paste ink into various shapes, indicating that the inclusion of various deodorizers in the raw material handling process has unique advantages. Thus, the use of 3D printing technology has great potential in the development of consumer-acceptable meat by-products. Notably, in addition to parts such as liver, some trimmings can be used as low-value products or even discarded because of the presence of large amounts of sinew and the connective tissue or poor meat quality, such as beef neck meat. The presence of these connective tissues directly affects the uniformity and adhesion of the ink, thus limiting their application in 3D printing. The problem of raw material waste in the meat industry can only be solved by solving the problem of by-product development. Subsequently, ring sustainability can be improved, and the value of 3D printing can be realized.

4.3. New technology combined with modeling methods to improve printing accuracy

4.3.1. Predicting ink extrusion behavior using computational fluid dynamics (CFD)

CFD refers to computers for building mathematical models to simulate and studying the motion of fluids in a specific geometry with boundary conditions(Oyinloye and Yoon, 2021). The evaluation criterion is the agreement between numerical simulation results and experimental results performed under specific conditions. CFD has been used to simulate food-processing operations such as drying, cooking, sterilization, and freezing(Norton and Sun, 2006; Singh and Muthukumarappan, 2017). CFD can also be used to predict chemical reactions, mechanical motions, phase changes, and heat and mass transfer in food processing(Jiang et al., 2021). In 3D printing processes, CFD techniques have been used to explore the effects of material formulation and printing parameters on the extrusion behavior to predict the optimal deposition formulation. CFD mainly involves the selection of suitable methods to discretize the simulation of the fluid continuum, which mainly includes finite difference (FD), finite element (FE), and finite volume (FV) (Oyinloye and Yoon, 2021). In meat 3D printing, the finite element method (FEM) is widely used because of its ability to solve problems that involve non-Newtonian fluids and nonlinear flow. Oyinloye et al. successfully optimized the parameters of surimi 3D printing using FEM. They demonstrated that the nozzle diameter significantly affects the fluid properties (e.g., pressure, velocity, and shear rate) in the flow field and the residual stress and deformation of the printed sample(Oyinloye et al., 2022).

4.3.2. Improving ink printing accuracy with low field nuclear magnetic resonance (LF-NMR)

As the most critical chemical components in meat and meat products, the water content and water holding capacity are directly related to the edible quality of meat and meat products, such as color, tenderness, juiciness, and flavor(Guanghong, 2008). As a fast and non-destructive testing method, LF-NMR can detect much information about moisture in meat and meat products by analyzing the spin relaxation characteristics of hydrogen core (oil/gas/water) in the magnetic field. The relaxation time and corresponding peak area of food ink obtained by LF-NMR are closely related to its shear-thinning and viscoelastic properties(Phuhongsung et al., 2020; Xu et al., 2020). Therefore, LF-NMR is often used as a routine method for ink printability analysis in 3D printing. Many researchers have applied LF-NMR parameters to polynomial regression models to predict 3D printability, and high correlation coefficients (R^2) were obtained for both 3D printing accuracy and stability. Therefore, LF-NMR is an excellent non-destructive tool for the fast and accurate prediction of rheological properties and the assessment of 3D printability of food inks(Liu et al., 2022). Although LF-NMR has been widely used in predicting the printability of non-meat materials (Phuhongsung et al., 2020), meat materials have not been studied in detail. Therefore, the application scope should be increased, and strong technical support should be provided for enriching meat inks.

4.3.3. Predicting ink printability using NIR spectroscopy

NIR light is an electromagnetic wave with wavelengths between ultraviolet and visible spectrophotometer (UV–vis) and middle infrared (MIR). NIR correlated with sample rheological properties, modeled using appropriate methods, have proven to be effective in predicting ink printability and improving printing accuracy. First, the NIR spectroscopy technology obtains the spectra of the samples containing hydrogen groups by absorbing the frequency doubling and combining frequencies of the vibrations of hydrogen groups (–CH, –NH, and –OH) (Alexandrakis et al., 2012; Ammor et al., 2009). Then, other traditional analytical methods are used to determine the properties or data of the samples, and the correction model can be obtained using stoichiometric methods, such as principal component analysis, partial least square method, and multiple linear regression to correlate the spectra with the data. According to the established calibration model, the composition or content of the sample can be predicted by combining it with the NIR spectrum of the sample. At present, NIR spectroscopy has been widely used for the quantitative analysis of meat products, including the prediction of meat water holding capacity, tenderness, and shear force (Samuel et al., 2011), which are strongly related to rheological properties. In comparison with low field nuclear magnetic resonance and rheological properties detection, NIR spectroscopy has the advantages of fast and easy operation. It shows a good correlation in predicting rheological and printing properties of purple sweet potato past(Phuhongsung et al., 2020). Therefore, NIR spectroscopy can be applied for the prediction of the printability of meat inks in the future. Based on the models of partial least squares, principal component regression, and artificial neural networks, the rheological properties of slurries can be well predicted using appropriate NIR spectral parameters. Thus, the 3D printability of slurries can be predicted indirectly but quickly.

5. Conclusion

As reviewed, meat materials are non-native printable materials, which need to be pretreated or formulated to improve printing characteristics. Pre-treatment technology provides the feasibility of direct printing of “additive-free” raw materials, and grafting pre-treatment technology (e.g., ultrasound, infrared) onto 3D printers can achieve the rapid printing various materials and meet consumer demand for "additive-free" printed products. However, limited studies have focused on pre-processing technologies, and the lack of valid data require more in-depth research. Many scholars have conducted extensive research on printable meat formulations and have developed various products such as minced fish, chicken snacks, and beef burgers. However, the current research has many limitations, which are mainly in terms of single-ingredient composition, low product innovation and functionality, and lack of post-processing and sensory evaluation. In the future, convenient and rapid detection technologies will provide new opportunities for the development of 3D printing inks. Evaluation techniques such as LF-NMR, NIR spectroscopy, and CFD have already played an essential role in the development of meat inks, although only a few studies on the 3D printing of meat materials have been published. With the development of new technologies, the development of printable inks will no longer be a problem.

CRediT authorship contribution statement

Hualin Dong: Ideas, Conceptualization, Writing – original draft, Writing – review & editing. **Peng Wang:** Conceptualization, Funding acquisition, Writing – review & editing. **Zongyun Yang:** Conceptualization, Writing – review & editing. **Xinglian Xu:** Conceptualization, Funding acquisition, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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