UDC 637.5:004.356
DOI: 10.21323/2414–438X–2020–5–1–9–16
Review paper

POSSIBILITIES OF ADDITIVE TECHNOLOGIES IN THE MEAT INDUSTRY. A REVIEW

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Key words: *3D food printing, meat products, food design, process parameters*

Abstract
Three-dimensional printing (3D printing) is a rapidly developing market of digital technologies with a huge potential for food production, which gives an opportunity to create new food products with the improved nutritional value and sensory profile, and adapted for a particular consumer. The review presents historical aspects of the development of the additive technologies and their classification, examines advantages and drawbacks of the 3D food printing, discusses key aspects of safety of three-dimensional food printing and probable peculiarities of their labeling, analyzes potential possibilities of using the 3DP technology for meat processing and aspects influencing the possibility of printing and following processing of 3D printed meat products.

Introduction

Additive technologies (3D printing) are one of the youngest and actively developing directions in the field of the creation of three-dimensional objects, including industrial culinary. Marketing experts believe that the prospects of this industry are extremely high. Additive printing allows combining food raw materials and three dimensional printing to produce complex shapes, texture and even tastes, which are considered either too complex for manual production or completely infeasible.

The use of 3D printing in food science includes different goals such as the novelty/enjoyment/creative activity, convenience and efficiency, health/nutrition, reduction of waste and increase in sustainability as well as reduction of hunger in the world [1].

Activation of the growth rate of additive food technologies is determined by the demand for mass adaptation for a certain consumer.

Food customization includes determination of the precise composition of particular nutrients. Consumers only have to order products that were created in strict correspondence to the requirements of their daily diet. In addition, it can allow taking into consideration specific individual requirements, for example, in case of difficulties in chewing and swallowing due to combination of different food ingredients and printing methods. Three-dimensional printing also reduces time consumption and labor costs in food manufacturing.

Additive manufacturing (AM) is the layer-by-layer building and synthesis of an object by computer 3D technologies.

Additive fabrication (AF) or technologies of the layer-by-layer synthesis is one of the most dynamically developing directions of digital production. AF (or AM) is abbreviation of a phrase accepted in the English technical lexicon, which means manufacturing products by adding material [2].

As any new technology, 3D printing has both positive and negative sides. Key problems associated with adoption of 3D food printing include definition of the term «food» by the new technology, the method of food manufacturing and limits of manipulation of edible ingredients [1,3].

The aim of the review is to show the possibilities of the 3D printing technologies with consideration for their advantages and risks for meat product development based on the assessment of the rheological and mechanical properties of raw material components and selection of technological regimes that affect possibilities of printing and the following processing of 3D printed meat products.

Main part

1. Historical aspects of the additive technology development

Two original technologies appeared in the 19th century are considered to be precursors of the modern AF-technologies [2]. In 1890, Josef E. Blanther proposed the method for making contour relief-maps — three-dimension maps of the locality surface. The essence of the method was as follows: fragments corresponding to the supposed horizontal section of an object were cut from thin wax plates along the contour lines of a topographic map; then, these plates were placed one on another in a certain order and stuck together. The «layer-by-layer synthesis» of a hill or ravine was obtained. After that, paper was placed over the obtained figures and a relief-map of an individual element of landscape was formed, which afterwards was placed in the paper form according to the initial map. This idea found practical application in the LOM-technology (Lamination Object Manufacturing) — layer-by-layer lamination or gluing of thin sheet materials with the sheet thickness of 0.051–0.25 mm.

In 1979, prof. Nakagawa from Tokyo University proposed to use this technology for quick production of molds, in particular, with complex geometry of cooling channels.

The second technology (photosculpture) was proposed by the French François Willème in 1890. Its essence was as follows: photo cameras were placed around an object or subject (Willème used 24 cameras at intervals of 15 degrees) and simultaneous photos were made with all cameras. Then

FOR CITATION: Gorbunova N.A. Possibilities of additive technologies in the meat industry. A review. *Theory and practice of meat processing.* 2020;5(1): 9–16. DOI 10.21323/2414–438X–2020–5–1–9–16

each image was projected onto a semitransparent screen and an operator outlined the contour with a pantograph. The pantograph was connected with a cutting instrument, which removed a model material (clay) according to the profile of the current contour. In 1904, the German Carlo Baese proposed to use photo sensitive gelatin, which expanded upon treatment by water depending on the degree of illumination (exposure), in order to reduce labor intensity of this process [2].

In 1935, Isao Morioka proposed a method that combined topography and photosculpture. The method assumed the use of structured light (combination of black and white bands) to create a topographic «map» of an object — a set of contours. After that, contours were cut from the sheet material, placed in a certain order and, in such a way, a three-dimensional image of an object was generated. Also, these contours could be projected onto a screen as in the method by François Willème for the following creation of a three-dimensional image by a cutting instrument [2].

The first approximation to stereolithography in the modern sense was the idea of Otto Munz (1956), who proposed a method for selectively (layer-by-layer) exposing transparent photo emulsion. A contour (section) of an object was projected on a layer.

In 1977, Wyn Kelly Swainson proposed a method for obtaining three-dimensional objects by solidification of a photosensitive polymer at the intersection of two laser beams. Approximately at the same time, the technologies for the layer-by-layer synthesis from powder materials began to appear. In 1981, R. F. Housholder proposed a method for formation of a thin layer of a powder material by its application on a planar plate. Then, leveling was carried out up to a certain height with the following fusion of the layer. In the same year, Hideo Kodama published the results of the work with the first functional systems of photo-polymerization using ultraviolet lamp and laser. In 1982, A. J. Herbert published the work on creation of the three-dimensional models using X-Y-plotter, UV-lamp and a system of mirrors [2].

The technology of three-dimensional printing appeared at the end of the 1980s. A forefather of the industry was Charles W. Hull, a founder of the 3D Systems — a company, which became the first in the commercial activity in the field of the layer-by-layer synthesis. In 1986, Charles W. Hull proposed a method for the layer-by-layer synthesis by ultraviolet irradiation, focused on a thin layer of photopolymer resin. He also introduced into use the term stereolithography. In the same year, the engineer made the world's first stereolithographic 3D printer SLA (Stereolithography Apparatus), due to which digital technologies made a huge leap forward [2].

Approximately at the same time, Scott Crump, who later founded the company Stratasys, introduced the world's first FDM apparatus. Since then, the market of three-dimensional printing began quickly grow and was supplemented by new models of unique printing equipment. Up to the middle of the 1990s, they were used mainly in the research and development activities associated with the defense industry. The first laser machines, initially stereolithographic machines (SLA machines) and then powder machines (SLS machines), were extremely expensive and the range of the model materials was quite limited. In 1995, however, the turning point came making additive methods of production generally accessible. Jim Bredt and Tim Anderson, graduate students at the Massachusetts Institute of Technology, incorporated the technology for the layer-by-layer synthesis into an inkjet printer. That is how Z Corporation was founded. For a long time, it was considered a leader in the sphere of common printing of 3D objects. Widespread acceptance of digital technologies in the field of design (CAD), engineering (CAE) and manufacturing (CAM) stimulated the explosive character of the development of the 3D-printing technologies. At present, it is extremely difficult to indicate a field of material production, where 3D printers are not used to one degree or another [2].

2. Classification of additive technologies

In 2012, the American Society for Testing and Materials (ASTM), created standard ASTM/ F2792–12a, which gave a definition of «additive technologies». However, their rapid development required a revision of the existing standard and creation on its base of a new international standard that would allow combining world experience and creating a unified terminological and classification base. In 2015, ASTM in cooperation with the International Organization for Standardization (ISO) developed international standard ISO/ASTM 52900:2015 [4].

Standard ISO/ASTM 52900:2015 became a foundation for the first Russian standard GOST R57558–2017 «Additive manufacturing processes. General principles. Part 1. Terminology», which came into force from December 1, 2017 and contains the basic technical terms.

Technical classification is performed according to the following traits:

A. Method of article production.

For example, ASTM F2792.1549323–1 (USA) divides AT into seven subgroups:

1. Material Extrusion — material pushing
2. Material Jetting — material dispensing, jet technologies
3. Binder Jetting — binding agent deposition
4. Sheet Lamination — sheet material binding
5. Vat Photopolymerization — photopolymerization in a vat of liquid photopolymer resin
6. Powder Bed Fusion — fusion of material in a preformed layer
7. Directed energy deposition — direct energy supply immediately in the place of building.

Similar classification is given in GOST R57558–2017.

The processes of additive manufacturing are classified depending on the used material and printing type.

Liquid processes include stereolithography, fused deposition modeling and inkjet printing.

Powder materials are used in such technologies as 3D printing, selective laser sintering, direct metal laser sintering, selective laser melting, electron beam melting, direct metal deposition and laser engineered net shaping.

Taking into consideration the peculiarities of the food industry, the scientists of the K. G. Razumovsky Moscow State University of Technologies and Management believe that the most feasible in the food industry are the following technologies that have their own specific characteristics in terms of the simplicity of implementation, basic possibilities of using one or another raw material and commercial use at present and in the future [5]:

— FDM (fused deposition modeling) — modeling by the method of layer-by-layer deposition / fusing

The essence of the method is as follows: printers eject material (sauce, glaze, cheese, dough, chocolate, puree) layer by layer through a dispensing nozzle. It is possible to use several cartridges with different materials; respectively, several heads for printing will be used.

— PBP (powder binder printing) — powder-binding («drop-on-powder») printing

The essence of the method is as follows: an inkjet print head moves across a layer of powder and selectively deposit liquid binding material. Then, a thin layer of powder is evenly deposited on the treated surface and the process is repeated. With each new layer, the particles of powder adhere to each other. When the printing process is finished, unbound powder is automatically and/or manually removed and remaining powder can be reused.

In the original implementations, starch and sugar are used as a powder and water and food additives (regulators of viscosity and surface tension, dyes (for color printing)) as binding material.

— SLS (selective laser sintering)

The essence of the method is a successive sintering of powder material layers using high power lasers, which ensures partial fusion necessary for material sintering. Sintering is achieved by laying out contours incorporated in a digital model using one or several lasers. After scanning is finished, the powder bed is lowered and a new layer of material is deposited. The process is repeated until formation of a complete model. Before the beginning of printing, the consumable material can be heated to a temperature slightly below its melting point to make the process of sintering easier.

Foreign specialists also regard the above mentioned methods as the most reasonable for using in the food industry [6,7,8].

However, it is necessary to take into account that the process of three-dimensional (3D) food printing includes much more factors than the classical methods of additive manufacturing from thermoplastics considering a diversity of rheological properties of food raw materials and ingredients.

3. Advantages and problems of application of 3D food printing

Possibilities of using 3D printing in the food industry have been widely studied in the world with different goals. At present, 3D food technologies are directed at the following [1,9,10]:

— satisfaction of the human need for cognition, novelty, creativity, entertainment, enjoyment, convenience and efficiency [8,10],

— extension of sources of available food materials due to the use of non-traditional food components such as insects, high-fiber plant raw materials and by-products of plant and animal origin [8,9,11,12,13],

— development of healthy nutrition products and personalized foods with certain nutritional properties adapted to the particular human needs. Individuals with swallowing difficulties (dysphagia), which may be a result of intracerebral hemorrhage or another condition, can be classified as a targeted group. Researchers developed a method for printing different dishes (for example, cooked potato, carrot and chicken) in well-known shapes but with the texture that was specifically adapted to the needs of these patients. Printed dishes of this type can be incorporated with additional nutrients such as protein, vitamins or minerals also with consideration for patient's needs. Foreign researchers believe that his method will allow building complete individual diets that will be used, for example, by patients with special nutritional needs due to their diseases, sportsmen, the military and others [8,9,12,14];

— search for meat substitutes and methods for creating foods using alternative protein sources. Jasper L. Tran and Payne, C.L.R. [3,11] summarizing publications in the periodical press give the following citation: «To fully raise a cow for meat, you have to feed a cow 20,000 gallons of water and 10,000 pounds of grain in its lifetime. Then there's the cost of slaughtering, shipping and packaging. Our grandkids will say, that was insane. Instead, imagine the possibility of going to one's kitchen to have a 3D printer print out a customized burger.»

— use of technologies to implement the non-waste production philosophy (researchers give an example of applying additive technologies to increase food production profitability without the need to manufacture and store too many food), reduce waste, enhance environmental sustainability and prevent climate change;

— solution to the problem of food deficiency. According to Dr. Jason Clay, Senior Vice President for Market Transformation at the World Wildlife Fund «we have to produce as much food in the next 40 years as we have in the last 8,000 … By 2050 we're going to have to produce twice as much food as we do today. We need to find a way to do this more sustainably. The biggest threat to the planet is to continue producing food in a business-as-usual fashion» [3].

— reduction of transport volume in the whole world, reform of logistics facilities, logistics cooperation, reconstruction of the global supply chain [15].

Food printing dramatically changes a concept of food production and preparation as its use can change the whole process eliminating several stages from buying products to food preparation. An absence of food production and preparation means that: (1) labor costs of production are reduced, which leads to a decrease in food cost and (2) food becomes more «autonomous» as people can make any kind of food in comfortable conditions of their own kitchens being independent of food manufacturers or restaurants.

Scientists and the industry believe that is will lead to destruction of the production rules set in the epoch of the First Industrial Revolution. 3D printing and other methods of digital manufacture together will facilitate implementation of the Third Industrial Revolution. The social, economic and technical revolution of 3D printing is coming. Entrepreneurs, politicians and the society in general will face unforeseen possibilities and problems [16].

Monostori L. et al. think that when new technologies are applied, the traditional rigid, centralized and hierarchical way of production will change. They suggested that the future of the production and logistics system should be dynamic, open and reconfigurable [17].

Taking into consideration new possibilities and advantages of 3D food printing, it is necessary to note that the development of this direction also brings many new problems.

The biggest problems in 3D printing of food products are a choice of an ingredient mixture with account for their rheological properties, retention of structure precision in printing and stability of a shape of a created product, compatibility with the traditional food technology (for example, baking and drying) and printing speed. For example, traditional ingredients in cookie recipes are compatible with 3D printing, but when a recipe contains a high amount of fat, they do not retain their shape and structure after the final technological processing stage (for example, baking) [18].

Other problems with 3D printed food products are their safety and labeling [3]. The safety issues are linked with the assessment of whether 3D products can cause food poisoning of individuals or mass poisoning. Moreover, at present, there are no studies on the effect of long-term consumption of 3D printed products, which could lead to inevitable changes in the human body to adapt to a new diet of constant consumption of 3D printed food.

It is assumed that labeling of 3D-printed food will likely face problems similar to those linked with labeling of genetically modified organisms (GMO). Regardless of whether 3D-printed food is safe or not, it is not easy for consumers to identify the origin of this food. Thus, the question arises: do consumers have a right to know where their food comes from? Labeling should give an answer to the question of possible food imitation and exclude economic falsification (i. e., misleading consumers).

At the same time, it is necessary to take into account that people can be reluctant to eat 3D-printed food because they perceive it not as good as traditional food. It is quite natural that people have a cautious attitude to such sharp alterations in food production and necessary changes in their taste preferences. It is assumed that after a while the majority of people most likely will adapt themselves to new taste so as not to notice the difference. However, until the choice of access to traditional food is not completely excluded, the opposite could also be observed: people can get tired to eat only 3D printed food and return to traditional food [3].

This is a reason to raise a question: what is a probability of retention of high-quality traditional food in the future and their availability for a consumer?

Several specialists suggest that the wide use of 3D printing does not mean disappearance of the traditional technology. In the real production process, new and traditional technologies should be combined [12,15].

4. Possibilities of 3D printing in the meat industry (for meat product development)

4.1. How to create 3D-products?

In a cattle carcass, cuts that are considered suitable for production of high value steaks account only for 7.2%; other carcass parts are sold as less valuable [9]. Therefore, meat and meat product manufacturers are in constant search for new technologies aimed at improving utilization and value of meat cuts [19] to increase profitability and global competitiveness.

3D printing can present a wonderful possibility to use low value cuts and meat by-products for manufacturing personalized meat products [9].

However, to produce a 3D printed meat product with the required design, sensory profile and nutritional value, it is necessary to assess the suitability of meat paste for three-dimensional printing. The suitability of any food material for three-dimensional printing is its ability to be processed and spread by a 3D printer in a structure of a free shape after deposition, which depends on the conditions of printing and rheological properties of materials [7,9,12].

Meat and slaughter by-products are fibrous materials by their nature and are not suitable for 3D printing. They require the modification of their rheological and mechanical properties by adding flow enhancers to produce the paste-like material.

The emulsifying and gel-forming properties of food ingredients are of utmost importance for changing rheological and mechanical properties of meat paste for 3D printing. Cold-swelling hydrocolloids, such as xanthan gum, guar gum and gum tragacanth, which ensure production of heat-resistant gels, can be used to achieve modification of both rheological and mechanical properties. It is possible to use of heat-resistant binders (such as blood proteins and soy proteins), which can be added into the meat batter to improve its mechanical properties, mainly during its deposition and following processing. Their contribution to changes in the rheological characteristics of meat paste still needs to be widely studied [9].

As a fibrous material, raw meat has to be finely minced into a paste form with the controlled particle size to ensure extrusion through the nozzle. As a rule, a particle size of paste ingredients should be significantly lower than the intended diameter of the 3D printer nozzle to prevent clogging.

It is recommended to use additives, which are necessary to easily extrude meat paste, as well as binding components to ensure adhesion of the subsequent layers after deposition. For example, gelatin added to a chicken, pork and fish slurry enhances its printability [9].

Lipton et al. (2010) assessed the suitability of turkey meat with addition of transglutaminase (TGase) as a binding material and bacon fat as a flavor enhancer for 3D printing. Transglutaminase was added to meat puree immediately before 3D printing to retain its rheological properties. Transglutaminase was investigated as a food additive that can enable creating complex geometries out of meat. Puree from turkey with transglutaminase was printed as a truncated dome and cooked using sous-vide methods. The organoleptic assessment showed that meat after cooking had proper taste and texture, but the shape was slightly distorted. In addition, the same meat paste was used to print a cube that contained a celery fluid gel [18]. Also, chicken, pork and fish in a slurry form with addition of the gelatin solution as a viscosity enhancer were 3D printed, although the ability to retain the shape after processing was not assessed [9].

Lipton et al. (2015) established that food texture can be changed either by combining materials with different textures in patterns or by changing porosity of the product printed mesostructure, while the nutritional composition is regulated by changes in its recipe [20].

For example, meat products can be printed using a multi-head printer and include different ingredients placed in target locations/layers of meat paste (Figure 1), such as salt, garlic, fatty slurries and so on, which facilitate various mouthfeels and flavors.

Figure 1. Multi-material computer-aided design (CAD) model [9]

Similarly, it is possible to obtain different food designs with modified texture and the appetizing appearance that resemble the original meat product as an alternative to traditional meat products for people with chewing and swallowing difficulties.

Three hypothetical designs (Autodesk, Inc.), such as sausage, steak and beef patty, can be presented as an example (Figure 2). In such a way, recombined meat products, such as steaks, can be 3D printed as models from soft meat paste, fatty slurry and other food ingredients that ensure approximation to the taste and nutrient content of a beefsteak [9].

At present, there are many difficulties from the technical point of view, which prevent mass production of 3D printed meat products. Nowadays, the technology of meat production using a 3D printer is consisted in structuring meat products with various characteristics from basic meat blocks.

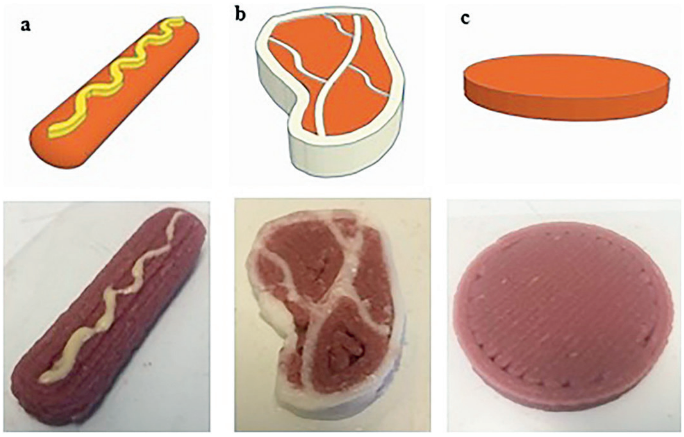

Figure 2. Hypothetical food designs for age care homes: (a) sausage, (b) steak 'recombined meat', and (c) patty [9]

Researchers from the School of Agriculture and Food Sciences, the University of Queensland (Australia) studied an effect of infill density (50%, 75%, and 100%) in the rectangular prism (40x40x10 mm) filled with a meat composition and its fat content determined by the number of layers of minced lard (0, 1, 2, and 3 layers) in the structure of the 3D meat product on the parameters of final processing of meat products cooked by the sous-vide method [21].

The meat paste base consisted of 85% minced beef and 15% water with addition of 1.5% NaCl and 0.5% guar gum used for increasing the viscosity and elasticity of a product to unsure effective 3D printing and retain the finished product structure. The printing process was performed at ambient temperature (23 ± 1 °C) using a dual nozzle model 3D printer (Shinnove, Hangzhou Shiyin Technology, China). The printing settings were determined based on preliminary experiments, as follows: 1.95 mm layer height, 1.5 mm first layer height for extruder 1 (meat paste), 1 mm layer height for extruder 2 (minced lard), 2 vertical shell perimeters, 2 solid layers on top and bottom, 20 mm/s speed, and 100% flow rate. Therefore, lard layers were printed inside a shell from meat paste to reduce fat losses during cooking.

The results of the study showed that after thermal treatment infill density had no significant effect on changes in sizes of the 3D samples of the finished meat product. The maximum values of deviations from the designed length and width were 0.6mm and 0.7 mm, respectively. The fat content did not influence the sample length and width deviation, which can be linked with the fact that the layers of minced lard were printed inside the sample perimeter minimizing the fat loss during sous-vide cooking. At the same time, significantly larger deviation for both dimensions was observed when the infill density was increased to 100%, which can be explained by a denser structure of the deposited material and consequently by an increase in the product weight. Also, an increased amount of meat paste in the product structure can facilitate deviation from the chosen configuration (shape) due to the 'extrude swell phenomenon', which may be influenced by the springiness of the material.

The infill density did not influence the deviation from the product designed height, while an inverse relationship was found when the fat content was increased. This can be explained by the lower mass of the extruded lard layer compared to the mass of meat paste, as the lard layer was deposited by the nozzle with a smaller diameter (1 mm) and a lower density of fat (0.9 g/mL (FAO/WHO Food Standards Programme, 2001)) compared to a density of the meat paste (1.106 g/mL), which was extruded using the nozzle with a diameter of 2 mm [21].

These multi-layer 3D printed samples of meat products were cooked by the sous-vide method. All samples retained their internal and external structure after heat treatment; however, partial inwards contraction was observed in the samples having two and three layers of lard and the initial fat content in a range of 8.21% to 12.65% and 14.76% to 18.97%, respectively.

In general, an increase in the fat content (or its layers) in a product led to higher cooking losses, shrinkage, increased cohesiveness, and lower indices of fat binding and moisture binding, hardness, and chewiness. In the future, the authors [21] intend to continue studying the feasibility of creating 3D printed composite multi-layer meat products with different cooking methods and conditions, analyzing microstructural changes during cooking of 3D food in order to elucidate the sensorial and textural effect on the final product.

In New York, Modern Meadows company has been working on creation of a biomaterial lineage using a 3D printer, for example, leather and, in the long-term, meat products that do not require animal slaughter [22].

Modern Meadows has proposed the new ecologically clean technology for 3D printing of meat and leather, which is much more productive and cleaner than the traditional method of animal raising.

The essence of the technology is as follows [23]. At first, living cells are taken from donor animals. The obtained material is placed into a bioreactor for multiplication. Then, the growth medium is eliminated from the «bioink» and remaining cells are put into a 3D printer to form multi-layer objects, which are again placed into a bioreactor, at this point, for maturation and generation of muscle tissue. This stage takes several weeks, after which grown meat is ready for food production.

The specialists of Modern Meadow have already achieved the first success: they printed on a 3D printer, cultivated in a bioreactor and then fried and ate a pork chop with a size of 2 × 2 cm and a height of 0.5 cm.

It should be acknowledged that printed meat products are not fully vegetarian as animal cells are used for their production. Nevertheless, bio-printing is a more humane method than animal slaughter [23].

Along with 3D -printed meat products, Modern Meadow decided to focus its efforts on the creation of artificial leather with properties of natural products, produced from animal hides. To implement its idea, the company raised $10 million for research and development.

Creation of artificial leather is quite a long process. For example, «growing» a cloth with a size of 30.5 × 30.5 cm will take about 1.5 months (Figure 3). Although, when comparing this time to 2–3 years necessary to raise an animal, this new technology appears quite attractive and promising. Moreover, as printed leather will be devoted of hair and the tough external layer, it will be completely ready for production of clothes and shoes in contrast to animal hides, which require complex multi-stage processing. The first samples of 3D printed leather were created by specialists of Modern Meadow as far back as 2012. Recently, the company has stated that it can produce leather of any kind of animals whether it is a calf, alligator or python using corresponding cells as the consumable material for a 3D printer.

Dr. Keith Belk, Professor of the Center for Meat Safety & Quality at Colorado State University, said in the interview with the portal Global Meat News that if «3D printing of meat products becomes mainstream and becomes economically and practically feasible, it can really create quite serious problems for traditional meat production» [22].

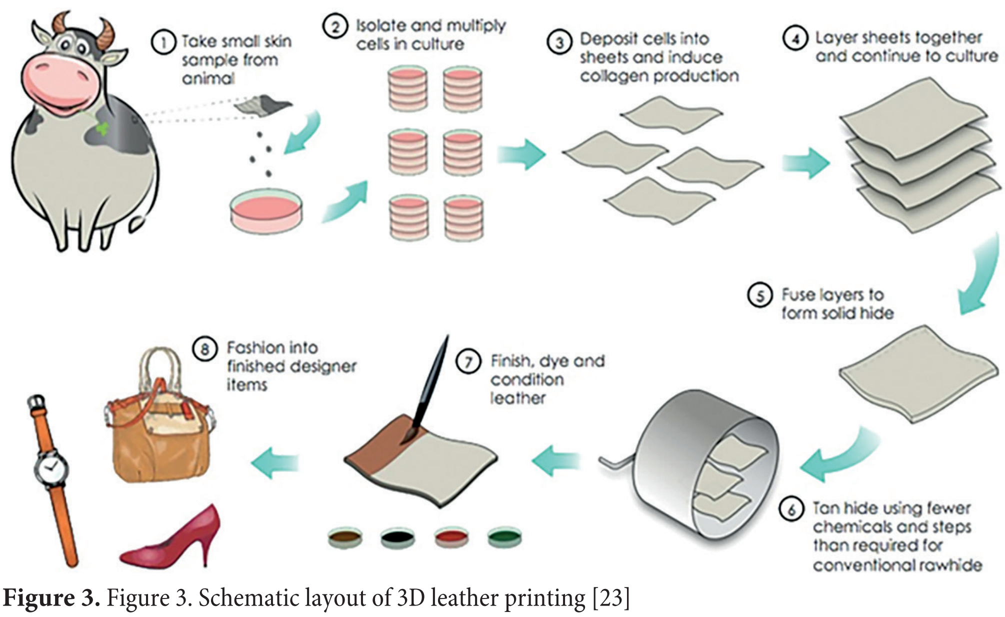

Figure 3. Figure 3. Schematic layout of 3D leather printing [23]

Dr. Joseph Sebranek, Distinguished Professor of Animal Science from Iowa State University noted that 3D printed meat products can become another category of meat products on the market along with traditional products. «While this might be an alternative,» he said, «I wouldn't expect it to replace the industry, especially with consumer interests in natural, organic products.» [22].

Prof. Keith Belk agreed that before the 3D meat printing technology can be implemented on a commercial basis, it would be necessary to solve a number of questions; although, Keith Belk noted that this technology will surely make it possible to «feed the masses,» [22].

Prof. Joseph Sebranek, however, is not so optimistic and said that one of the main problems of meat 3D printing can become «consumers' reluctance to accept 3D printed meat» rather than technical difficulties [22].

4.2. Selection of methods and conditions for quality assurance of 3D printed meat products

Several researchers determined requirements for 3D printers for meat product printing. Extruder-type 3D printers are the most acceptable for 3D printing of meat paste. It is very important to ensure the temperature control during printing, which should be less than 4 °C to prevent microbial growth. During meat printing, a temperature should be constantly controlled throughout the system — meat paste feeding, the hopper, the nozzle and the platform for meat paste deposition [9].

The critical parameters influencing the geometric accuracy of a printed construction are a nozzle speed, nozzle diameter, nozzle height (a height between the nozzle and a surface of the platform for deposition and/or a preceding food material layer), extrusion rate, and infill percentage. For example, a nozzle diameter > 2mm can facilitate extrusion of meat paste that contains bigger particle size components, such as connective tissue; however, the printing precision may be compromised due to the deposition of thicker layers. A nozzle diameter < 2mm allows production of more accurate and complex objects; however, fine emulsion-like meat pastes are necessary for extrusion through a nozzle with a lower diameter to prevent its clogging.

Likewise, an optimal nozzle height determines the accuracy and size of the printed meat product, and it is assumed that it should be equivalent to a nozzle diameter size. Due to the «extrudate swell phenomenon» [9], which is linked with meat paste springiness, a nozzle height lower than optimal can lead to scattering of the deposited flow resulting in expanded objects as compared to the desired shape. When this height is more than the optimal value it can lead to the dragging of the meat paste flow, which would not be accurately deposited on the top of the preceding layers facilitating the development of cavities inside the structure, which in turn can influence the quality of meat products after final technological processing.

If the nozzle speed and extrusion rate are not properly set, over-deposition and spreading of the meat paste flow can be observed. The nozzle speed determines the movement rate of the print head, and has to be adjusted in preliminary experiments or by calculation of the optimal nozzle speed. When a nozzle speed is optimal, the diameter of the deposited flow of meat paste is equal to the nozzle diameter. When a nozzle speed is too high, a thinner flow of meat paste is obtained and dragged, preventing the subsequent binding of layers and facilitating formation of cavities within the cross-section area of the final product. Moreover, when a nozzle speed is too low at a given extrusion rate, thicker flows are extruded and over-deposition can be observed. An extrusion rate determines the volume of the deposited material per unit time. An increase in the extrusion rate leads to production of denser products due to a higher amount of deposited meat paste [9].

Changes in the percent content of a filling material (meat paste) influence the total amount of a deposited material in the internal part of the printed product and the proportion of cavities in the final 3D printed meat product and, therefore, the conditions of the following processing. For example, the volume of cavities will determine the conditions of cooking to a certain degree of doneness as upon higher porosity in the structure, heat transfer during cooking is less intensive, which influences the moisture and fat release, and therefore, the texture of the cooked meat product [9].

By the percent content of a filling material is meant a volume (percent) of filling the chosen pattern of a three dimensional object with meat paste. For meat products, it is recommended to use 80–100%.

When choosing the above considered parameters necessary for geometric accuracy during 3D printing of meat, the economic aspect should be considered. For example, a lower printing speed and a lower nozzle diameter, as well as an increased infill percentage can lead to higher accuracy in reproduction of a product geometric shape, but longer printing time and an increase in energy consumption [9].

The other method of three-dimensional printing, which is possible to use in meat manufacture, is bio-printing. Bioprinting is a relatively novel technology based on tissue engineering and is aimed at generating raw meat tissue by printing cultured stem cells. In this method, an inkjet printer places cells into the agarose gel support structure, which is fused and forms artificial meat. After fusion, the agarose structure is removed and the tissue is subjected to low frequency stimulation in a bioreactor for maturation of meat fibers. Although, this method represents a great progress in terms of reducing slaughter of farm animals, it is still necessary to solve problems regarding its cost-efficiency, assurance of organoleptic characteristics of the final products and consumer acceptance [9].

Conclusion

3D food printing is one of the youngest technologies in the field of creating 3D objects; however, this does not prevent its development and improvement in different directions simultaneously. 3D food printing has several significant advantages such as creation of individual food designs, personalized nutrition, simplification of the supply chain and extension of available food raw materials and ingredients. Although studies of 3D food printing have been expanding today, there are still some problems that need to be solved including an increase in print precision and accuracy by regulating a printing speed, nozzle diameter, rheological characteristics of edible «ink» for 3D food printing and other parameters, organization of production of food with certain quality and nutritional characteristics, changes in the consumer attitude to 3D foods and so on.

Studies have been carried out regarding a possibility to print meat materials such as pork and poultry meat. These studies show that addition of different food hydrocolloids into meat paste can ensure modified rheological and mechanical properties due to different binding mechanisms, increasing its suitability for printing and viability after processing. At the same time, there are no data on beef. The results of the studies on recipes to correct rheological and mechanical properties of beef paste are necessary to better understand its printability, as well as 3DP settings and conditions of following processing of printed meat products. As soon as these problems are solved, the wider use of 3D food printing is expected.

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Completely prepared the manuscript and is responsible for plagiarism.

The author declare no conflict of interest.

Received 09.12.2019 Accepted in revised 25.02.2020 Accepted for publication 05.03.2020