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MINI REVIEW

Additive manufacturing food: technology and materials

[1,*]Ghazali, M.I.M., [1,2,8]Baharuddin A.S., [1,3]Alauddin M.S., [4]Dahlan, A., [5,6]Fuzi, S.F.Z., [1]Shaarani, S.M. and [7]Hanafi, M.A.

[1]SMART RG, Faculty Science and Technology, Universiti Sains Islam Malaysia, 71800, Nilai, Negeri Sembilan, Malaysia
[2]Faculty of Syariah and Law, Universiti Sains Islam Malaysia, 71800, Nilai, Negeri Sembilan, Malaysia
[3]Faculty of Dentistry, Level 15, Tower B, Persiaran MPAJ, Jalan Pandan Utama, 55100, Kuala Lumpur, Malaysia
[4]DR. Group Holdings Sdn Bhd, No.2, Jalan Teknologi 3/5, Kota Damansara, 47810 Petaling Jaya, Selangor, Malaysia
[5]Faculty of Applied Sciences and Technology, Universiti Tun Hussein Onn Malaysia, 84000, Pagoh, Muar, Johor, Malaysia
[6]Oasis Integrated Group, Universiti Tun Hussein Onn Malaysia, 86400, Parit Raja, Johor, Malaysia
[7]Department of Food Science, Faculty of Food Science and Technology, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia
[8]Academy of Islamic Civilisation, Faculty of Social Sciences and Humanities, Universiti Teknlogi Malaysia, Johor, Malaysia

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Abstract

Industry Revolution 4.0 have revolutionized every industry worldwide where manufacturing technology became more automated and efficient, and the food industry is no different from other industries such as textile, machinery, electronics, and chemical. In the food industry, technology is very important in order to compete with the high demands for food production. In recent years technology such as genetically modified organisms (GMO), precision agriculture, unmanned vehicle systems (drones) for agriculture, and the internet of things have been developed to improve efficiency in manufacturing food. However, one technology that has the capability to disrupt the food industry is additive manufacturing or better known as 3D printing technology. The technology has become a new manufacturing technology for the food industry that provides freedom of customizing food in terms of structural, ingredients as well as automated cooking for a plethora of applications that suits the customer needs. Technology creates a new platform in gastronomy by changing the perspective on making food. This paper focused on the technological aspect of additive manufacturing technology in terms of the suitable printer's use, the variety of materials that are used as well as potential materials, the key challenges faced by additive manufacturing with regard to production, and the future opportunities that can be discovered. Although additive manufacturing for food is relatively new compared to other additive manufacturing applications, the potential of such technology is huge and can be explored.

1. Introduction

Industrial Revolution (IR) 4.0 has altered the landscape of the world by incorporating smart manufacturing which integrates physical manufacturing with digitalization technology to create a far more efficient business ecosystem that allows the increase of productivity, optimizes the usage of energy as well as satisfies the demand of consumers (Sherwani *et al*., 2020). With the nine-pillar (augmented reality, system integration, cloud computing, big data, internet of things, cyber security, robotics, simulation, additive manufacturing) set in IR 4.0, additive manufacturing or commonly referred to as 3D printing has become one of the technologies that revolutionize the manufacturing industry (Ashima *et al*., 2021). Additive manufacturing is a robotics-based machine that provides an alternative manufacturing process where materials are additively layered on top of each other to create precise three-dimensional (3D) objects with the usage of data computer-aided-design (CAD) as illustrated in Figure 1 (Lee *et al*., 2021). The growing interest in additive manufacturing is apparent with the increase in patents

*Corresponding author.
Email: *ifwat.ghazali@usim.edu.my*

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and article journals over the years in a plethora of fields including architecture and construction, healthcare and medical, aeronautics and space, textile and fashion, education, drones, robotics, automotive, and electronics (Ghazali *et al*., 2017; Alauddin *et al*., 2021; Baharuddin *et al*., 2021; Fadzli *et al*., 2021).

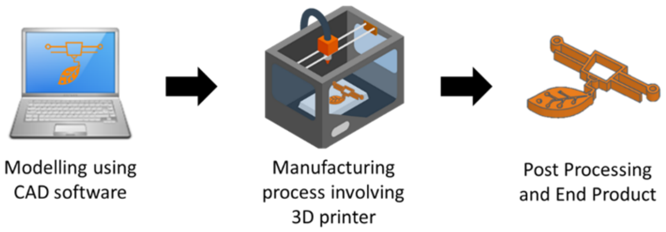

Figure 1. Illustration of the additive manufacturing process

Given its inherent capabilities, one of the emerging usages of additive manufacturing is the food industry. In the conventional food manufacturing process, two major technologies were used in manufacturing 3D structures which are the subtractive manufacturing process (computer numerical control machine machining) and formative manufacturing process (injection moulding) as shown in Figure 2. Nevertheless, there are several disadvantages to both technologies, for instance, both are only capable of fabricating or manufacturing simple geometries as complex structures needed to be done in several parts and combine the part to get the end product (Prakash *et al*., 2018). Furthermore, the cost of production would increase if the product required to be customized as each product requires adding new tools or mould structure. Another disadvantage comes in terms of the machinery which is very space-consuming, the tools are expensive and the learning curve to operate such machinery is high. On top of that materials wastages and energy consumption also play a major role in finding an alternative to such a manufacturing process.

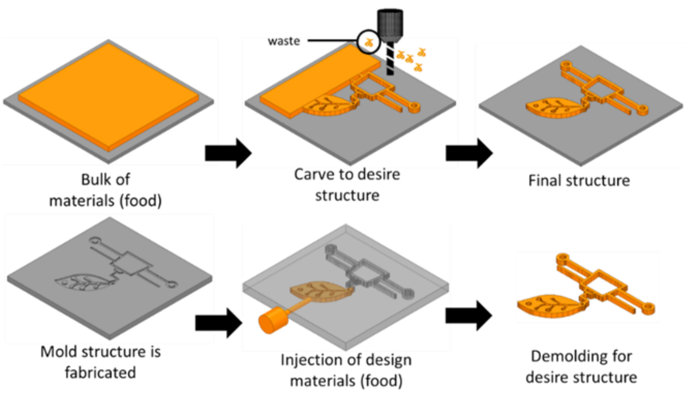

Figure 2. Illustration of the subtractive and formative manufacturing process

Additive manufacturing technology provides a breath of fresh air as the technology provides new possibilities in manufacturing food which leads to interest from researchers and industrial players. Compared to conventional manufacturing, additive manufacturing provides several advantages. One of the most appealing aspects of additive manufacturing is its capacity to reduce food wastage during production where sustainability is important with the growing concern for food security. Based on a study, an alarming statistic shows that 1.3 billion tons (approximately 4333 times the weight of the Kuala Lumpur Petronas Twin Towers) which is equivalent to one-third of all food produced for human consumption are turned into waste (Cristelo *et al*., 2020). Additive manufacturing can reduce the number by reducing the waste to the minimum as only the desired structure is printed throughout the printing process (Ghobadian *et al*., 2020). The amount of food ingredients is strictly parallel to the amount of structure wanted during the manufacturing.

Furthermore, by using additive manufacturing technology leftovers and unwanted food can be reused to create a new food product. Using the conventional way of cooking will create by-products for example potato peel, vegetable peel, and cooking oil which are usually thrown away. Additive manufacturing allows these by-products to be reused and become a new edible food products. One prime example of utilizing food waste and by-products by reconditioning the potato peel to make edible noodles and adding a nutrient-rich ingredient to add value to the food (Muthurajan *et al*., 2021). Additionally, the byproduct of meat can also be integrated into the additive manufacturing process to create customized meat structures that have all the typical meat structures including muscle, fat, skin, and tissue (Handral *et al*., 2022). This type of research has opened opportunities where a well-known brand company such as Kentucky Fried Chicken (KFC) is printing nuggets while IKEA is using additive manufacturing to print their meatballs.

Additive manufacturing of food also helps reduce the use of multi machinery or equipment to prepare the food. Conventional food production or preparation requires pots and pans, heavy machinery, and multiple heated pieces of equipment to cook the food, however, additive manufacturing technology can prepare such food products using a singular machine. The process of preparing the food is automated. In addition, customization of the product can be made easily. Artistic decorations with complex geometries can easily be created on a plate using the technology with any skills required by the chef or the decorator. Another customization is in terms of personalized nutrition. The ingredients can be printed according to the need of the consumer in terms of taste, nutrient level and texture (Sun *et al*., 2018). In this case, the data from the consumer can be analyzed to provide the optimal nutrition with regards to the preference based on medical

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as well as taste by creating a tailored made food.

In this paper, the major focus is on the technological element of additive manufacturing to manufacture food, as different technologies bring distinct advantages to additive manufacturing. Furthermore, the wide range of materials employed as well as possible materials are discussed in the paper. With huge potential and capability in additive manufacturing technology, the issues regarding manufacturing are evaluated and the prospect of the technology is identified.

2. Technological aspect uses for additive manufacturing of food

2.1 Technology

In additive manufacturing, the technology can be categorized into several categories which include vat polymerization, material extrusion, powder bed fusion, material jetting, binder jetting, direct energy deposition, and sheet lamination (Szymczyk-Ziółkowska *et al*., 2020). However, not all additive manufacturing technology is suitable to be used as 3D printing for food. Several considerations must be made for instance the extrusion method, the food materials, the accuracy of the printed structure, rheology, and the binder that hold the food materials together. Listed below are four additive manufacturing technology that provides the necessary capabilities for food 3D printing.

2.2 Material extrusion

The most popular additive manufacturing process for 3D printing food is material extrusion. Attributes that make this process commonly used are the availability of the machinery, cost-effectiveness, user-friendly, easy-to-comprehend printing, fast-printing speed relative to other printing methods, and low running cost. The material extrusion process is a process where the materials are administered selectively using a nozzle as shown in Figure 3. The state of material used in particular food 3D printing is usually in solid or semi-solid form. The material will be placed in a container usually in a cylinder structure where pressure is applied to force the material through the extruder. If solid materials are used, heat is utilized to liquidize the solid material so that the material can flow through the nozzle. Once the materials are extruded from the nozzle, the material will solidify due to the contact with the heated platform. There the desired structure of the 3D object is printed layer upon layer. The common type of materials for material extrusion is chocolate, dough, and puree (Mantihal *et al*., 2020).

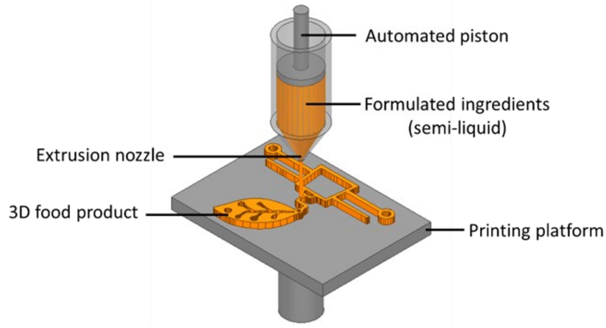

Figure 3. Material extrusion additive manufacturing technology

2.3 Selective Laser Sintering and Selective Hot Air Sintering and Melting

Figure 4 illustrates the Selective Laser Sintering (SLS) or Selective Hot Air Sintering and Melting (SHASAM) process as a viable option for 3D printing food. The materials used in these methods are mostly powder-based materials such as sugar or chocolate. The working principle of both techniques is similar; however, the slight difference is in the sintering mechanism. For SLS, a laser is applied to the powder-based material where the laser is fusing the materials to make a solidified structure. On the other hand, SHASAM uses a low-power heat mechanism to fuse the power-based materials. The procedure begins with a thin coating of powder being disseminated on top of the platform within a chamber. Next heat is exerted onto the powder just below or slightly over the melting point of the material. The materials are mechanically bound together to form a solid component or structure based on the design model. The next layer is created by the unfused powder used as the support to hold the structure to create the next layer of printing. The platform is gradually lowered, layer by layer, and the procedure is repeated until the entire printed construction is completed (Nachal *et al*., 2019).

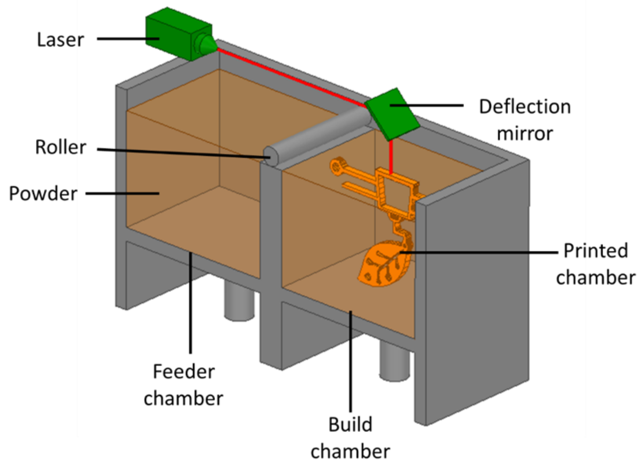

Figure 4. Illustration of selective laser sintering (SLS)

2.4 Binder jetting

Another additive manufacturing technology that is

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used in food production is binder jetting as illustrated in Figure 5 (Holland *et al*., 2019). The process uses powder -based materials where the powder is bonded together with a unique binder. The binder is deposited based on the design generated in a droplet manner in which the binder interacts with the powder which creates an adhesive bond. After the interaction, a heat source is exerted to enhance the adhesive bond creating a reasonable mechanical strength of the structure. The platform is lowered incrementally to form the needed thickness for each layer. The unbound powder is used as a supporting structure for the bounded material. The process is repeated until the whole final product is achieved. The materials which are commonly used in this process include sugar, starch, and flour.

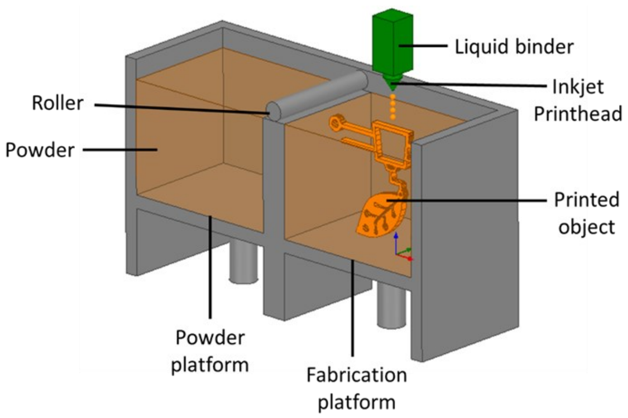

Figure 5. Binder jetting process

2.5 Inkjet printing

In additive manufacturing, inkjet printing is commonly used for electronics applications such as circuits and PCB processes. Therefore, the food industry has adapted the process to manufacture food. The mechanism of inkjet printing is dispensing of material in droplet form using a nozzle that is heated at a certain temperature. The heat is created using an electronic device called piezoelectric where the structure of the materials maintains in a liquid-based via acoustic vibration (Vadodaria *et al*., 2020). The droplets are selectively dispensed on demand creating a 3D structure of the desired shape or object. One of the advantages of this process is that the extruder nozzle does not touch the materials after being deposited. This element avoids the contamination which may occur in the nozzle. Another advantage of the process is the possibility of using multiple colour ink to provide an aesthetic and appetizing 3D printed food. Fruit puree, chocolates, and pizza sources are the food material used by the inkjet printing method.

3. Materials used in additive manufacturing of food

The types of ingredients used for additive manufacturing food are crucial in order to make the printing of the food successful. Such criteria needed for the ingredients are able to be printed, applicable to the additive manufacturing technology and the post-processing of the 3D printed food.

3.1 Meat

Meat is one of the candidates that suit the criteria of the material used in additive manufacturing food. In its natural state, meat is a non-printable material as meat is considered complex material; however, the meat may be mashed into a paste or batter to create an edible ink that can be extruded under certain printing conditions and remain mechanically intact. There are several meat forms that have been used as edible material. One prominent type of meat used in additive manufacturing is beef. A different aspect of beef meats is studied such as the use of hydrocolloids on the rheological properties to help the printability. The usage of a gelling agent with xanthan gum has been shown to be beneficial since the agent aids in water management during extrusion as well as shape retention following deposition and processing (Dick *et al*., 2021). Another meat used is chicken.

Similar to beef, chicken is non-printable in nature as the meat requires an additional enhancer. Refined wheat flour combined with grounded chicken meat ratio is optimized in aiming to produce a customized shape of the food product. Fish is also considered material in additive manufacturing food. One study shows the use of silver carp fillet was used to create a paste (surimi gel) as a potential material for 3D printing food. The addition of Sodium chloride (NaCl) helps the slurry to flow from the extruder and makes it viscous for printing (Wang *et al*., 2018).

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4.2 Meat analogue

Meat analogue is known by several names such as imitation meat and mock meat. Meat analogue is a meat-like product that is based on plants. The conventional ingredient for meat analogue is soy protein such as tofu and tempeh (Kaczmarska *et al*., 2021). Furthermore, studies regarding the use of reduced-fat soy protein emulsion gels as a replacement for oil are being conducted using different biosurfactants (Shahbazi *et al*., 2021). The research on meat analogue continues to develop with the introduction of texturized vegetable protein that is composed of wheat gluten and various other protein to form an elastic and spongy texture (Schreuders *et al*., 2022). This led to a food ingredient that mimics the texture of meat and provides similar nutrients to an animal protein. In addition, the meat analogue is less expensive compared to the meat in terms of resources and manufacturing. More so, the meat analogue is capable of doing the same food product as the conventional meat product. The integration of meat and meat analogue is done to provide a novel textured for soft hybrid meat analogues. A combination of pea protein isolate (PPI) and chicken minces is used. This research demonstrates that combining particular ratios improves printability and fibre structure (Shoaib *et al*., 2018).

4.3 Chocolates

Chocolates are one of the first materials used as edible ink for additive manufacturing. The main reason is that chocolate has the capability to easily be structured as the materials are melted during the extrusion process and easily solidify at room temperature. In addition, additive manufacturing of chocolates creates a simple process where the structure is automatically designed and can be customized depending on the desire of the consumer. In doing so, additive manufacturing chocolates have attracted companies to develop 3D printed machines such as Hershey's and Cadbury. Most of the studies being conducted in this field are related to optimizing the printability of chocolates. The effect of additives materials such as magnesium stearate (Mg-ST) powder enhances the properties of the chocolate by making the flow of the chocolate smoother during the extrusion process (Mantihal *et al*., 2019). Furthermore, the additive does not interfere with the thermal properties of the materials. Other factors are also being studied including the effect of printing velocity and the environment temperature during printing. The research shows that the condition is important in determining printability success (Rando *et al*., 2021).

5. Conclusion

Additive manufacturing technology is becoming a crucial manufacturing tool needed in a plethora of applications and food manufacturing is one of the sectors. Additive manufacturing of food provides several benefits in the food industry as the technology is able to reduce waste during the manufacturing process, create customizable and freedom in creating food structure, singular-based tools for manufacturing, reduce time consumption for human labour, be able to personalize the ingredients based on the needs of the consumer and provide new gastronomy area to be researched upon. Moreover, the development of various additive manufacturing tools such as SLS, material extrusion, binder jetting and inkjet printing will further increase the applicability of the technology in the food industry. Here technology can be modified to cater to the usage of different materials and enhance the speed, efficiency, accuracy, and stability of the 3D structure. Another critical aspect that can be explored is the materials used for additive manufacturing of food. Other raw materials can be explored to increase the materials library for technology. Furthermore, additives or combinations of several materials can help increase the potential of the food such as adding mechanical stability in terms of gelatin, adding nutrient value to a certain food in order to provide a healthier alternative, and adding specific components which allow for drug deliveries in form of food.

Conflict of interest

The authors declare no conflict of interest.

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References

Alauddin, M.S., Baharuddin, A.S. and Mohd Ghazali, M.I. (2021). The modern and digital transformation of oral health care: A mini review. *Healthcare*, 9(2), 118-130. https://doi.org/10.3390/healthcare9020118

Ashima, R., Haleem, A., Bahl, S., Javaid, M., Mahla, S.K. and Singh, S. (2021). Automation and manufacturing of smart materials in Additive Manufacturing technologies using Internet of Things towards the adoption of Industry 4.0. *Materials Today: Proceedings*, 45, 5081-5088. https://doi.org/10.1016/j.matpr.2021.01.583

Baharuddin, A.S., Wan Ismail, W.A.F., Abdul Mutalib, L., Hashim, H., Jusof, N., Mohd Ghazali, M.I., Alauddin, M.S. and Wan Harun, M.A. (2021). Halal Forensics Issues Involving Three-Dimensional (3D) Printing Technology of Cultured Meat. *Ḥalāl Reviews*, 1(1), 3–15. https://doi.org/10.55265/halalreviews.v1i1.7

Cristelo, N., Segadães, L., Coelho, J., Chaves, B., Sousa, N.R. and de Lurdes Lopes, M. (2020). Recycling municipal solid waste incineration slag and fly ash as precursors in low-range alkaline cements. *Waste Management,* 104, 60-73. https://doi.org/10.1016/j.wasman.2020.01.013

Dick, A., Dong, X., Bhandari, B. and Prakash, S. (2021). The role of hydrocolloids on the 3D printability of meat products. *Food Hydrocolloids*, 119, 106879. https://doi.org/10.1016/j.foodhyd.2021.106879

Dong, X., Pan, Y., Zhao, W., Huang, Y., Qu, W., Pan, J., Qi, H. and Prakash, S. (2020). Impact of microbial transglutaminase on 3D printing quality of *Scomberomorus niphonius* surimi. *LWT*, 124, 109123. https://doi.org/10.1016/j.lwt.2020.109123

Fadzli, S.D.N.M., Harun, M.A.W., Baharuddin, A.S. and Adnan, M.R.A.R. (2021). Produk Makanan Ubah Suai Genetik (GMF) Dalam Perspektif Konsep Halalan Toyyiban Berdasarkan Penilaian Maqasid Hifz An Nafs. *Malaysian Journal of Syariah and Law*, 9(1), 73-85. https://doi.org/10.33102/mjsl.vol9no1.284 [In Bahasa Malaysia].

Ghazali, M.I.M., Karuppuswami, S., Kaur, A. and Chahal, P. (2017). 3-D printed air substrates for the design and fabrication of RF components. *IEEE Transactions on Components, Packaging and Manufacturing Technology*, 7(6), 982-989. https://doi.org/10.1109/TCPMT.2017.2686706

Ghobadian, A., Talavera, I., Bhattacharya, A., Kumar, V., Garza-Reyes, J.A. and O'regan, N. (2020). Examining legitimisation of additive manufacturing in the interplay between innovation, lean manufacturing and sustainability. *International Journal of Production Economics*, 219, 457-468. https://doi.org/10.1016/j.ijpe.2018.06.001

Holland, S., Foster, T. and Tuck, C. (2019). Creation of food structures through binder jetting. In Fundamentals of 3D food printing and applications, p. 257-288). USA: Academic Press. https://doi.org/10.1016/B978-0-12-814564-7.00009-2

Handral, K., Hua Tay, S., Wan Chan, W. and Choudhury, D. (2022). 3D Printing of cultured meat products. *Critical Reviews in Food Science and Nutrition*, 62(1), 272-281. https://doi.org/10.1080/10408398.2020.1815172

Kaczmarska, K., Taylor, M., Piyasiri, U. and Frank, D. (2021). Flavor and Metabolite Profiles of Meat, Meat Substitutes, and Traditional Plant-Based High-Protein Food Products Available in Australia. *Foods*, 10(4), 801-817. https://doi.org/10.3390/foods10040801

Kim, H.W., Lee, J.H., Park, S.M., Lee, M.H., Lee, I.W., Doh, H.S. and Park, H.J. (2018). Effect of hydrocolloids on rheological properties and printability of vegetable inks for 3D food printing. *Journal of Food Science*, 83(12), 2923-2932. https://doi.org/10.1111/1750-3841.14391

Lee, J.Y., Nagalingam, A.P. and Yeo, S.H. (2021). A review on the state-of-the-art of surface finishing processes and related ISO/ASTM standards for metal additive manufactured components. *Virtual and Physical Prototyping*, 16(1), 68-96. https://doi.org/10.1080/17452759.2020.1830346

Mantihal, S., Prakash, S., Godoi, F.C. and Bhandari, B. (2019). Effect of additives on thermal, rheological and tribological properties of 3D printed dark chocolate. *Food Research International*, 119, 161-169. https://doi.org/10.1016/j.foodres.2019.01.056

Muthurajan, M., Veeramani, A., Rahul, T., Gupta, R.K., Anukiruthika, T., Moses, J.A. and Anandharamakrishnan, C. (2021). Valorization of Food Industry Waste Streams Using 3D Food Printing: A Study on Noodles Prepared from Potato Peel Waste. *Food and Bioprocess Technology*, 14 (10), 1817-1834. https://doi.org/10.1007/s11947-021

-02675-2

Nachal, N., Moses, J.A., Karthik, P. and Anandharamakrishnan, C. (2019). Applications of 3D printing in food processing. *Food Engineering Reviews*, 11(3), 123-141. https://doi.org/10.1007/s12393-019-09199-8

Prakash, K.S., Nancharaih, T. and Rao, V.S. (2018). Additive manufacturing techniques in manufacturing -an overview. *Materials Today: Proceedings*, 5(2), 3873-3882. https://doi.org/10.1016/j.matpr.2017.11.642

Rando, P. and Ramaioli, M. (2021). Food 3D printing: Effect of heat transfer on print stability of chocolate. *Journal of Food Engineering*, 294, 110415. https://doi.org/10.1016/j.jfoodeng.2020.110415

Schreuders, F.K., Sagis, L., Bodnár, I., Boom, R.M. and van der Goot, A.J. (2022). Non-linear rheology reveals the importance of elasticity in meat and meat analogues. *Scientific Reports*, 12, 1334. https://doi.org/10.1038/s41598-021-04478-z

Shahbazi, M., Jäger, H., Ettelaie, R. and Chen, J. (2021). Construction of 3D printed reduced-fat meat analogue by emulsion gels. Part I: Flow behavior, thixotropic feature, and network structure of soy protein-based inks. *Food Hydrocolloids*, 120, 106967. https://doi.org/10.1016/j.foodhyd.2021.106967

Sherwani, F., Asad, M.M. and Ibrahim, B.S.K.K. (2020). Collaborative robots and industrial revolution 4.0 (IR 4.0), 2020 International Conference on Emerging Trends in Smart Technologies. Karachi, Pakistan. https://doi.org/10.1109/ICETST49965.2020.9080724

Shoaib, A., Sahar, A., Sameen, A., Saleem, A. and Tahir, A.T. (2018). Use of pea and rice protein isolates as source of meat extenders in the development of chicken nuggets. *Journal of Food Processing and Preservation,* 42(9), e13763. https://doi.org/10.1111/jfpp.13763

Sun, J., Zhou, W., Huang, D. and Yan, L. (2018). 3D food printing: Perspectives. In Polymers for food applications, p. 725-755. Cham, Netherlands: Springer. https://doi.org/10.1007/978-3-319-94625-2_26

Szymczyk-Ziółkowska, P., Łabowska, M.B., Detyna, J., Michalak, I. and Gruber, P. (2020). A review of fabrication polymer scaffolds for biomedical applications using additive manufacturing techniques. *Biocybernetics and Biomedical Engineering*, 40(2), 624-638. https://doi.org/10.1016/j.bbe.2020.01.015

Vadodaria, S. and Mills, T. (2020). Jetting-based 3D printing of edible materials. *Food Hydrocolloids*, 106, 105857. https://doi.org/10.1016/j.foodhyd.2020.105857

Wang, L., Zhang, M., Bhandari, B. and Yang, C. (2018). Investigation on fish surimi gel as promising food material for 3D printing. *Journal of Food Engineering*, 220, 101-108. https://doi.org/10.1016/j.jfoodeng.2017.02.029

Wilson, A., Anukiruthika, T., Moses, J.A. and Anandharamakrishnan, C. (2020). Customized shapes for chicken meat–based products: feasibility study on 3D-printed nuggets. *Food and Bioprocess Technology*, 13(11), 1968-1983. https://doi.org/10.1007/s11947-020-02537-3

