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Potentials of 3D extrusion-based printing in resolving food processing challenges: A perspective review

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Abstract

Three-dimensional (3D) printing has promising application potentials in improving food product manufacturing, increasingly helping in simplifying the supply chain, as well as expanding the utilization of food materials. To further understand the current situation of 3D food printing in providing food engineering solutions with customized design, the authors checked recently conducted reviews and considered the extrusion-based type to deserve additional literature synthesis. In this perspective review, therefore, we scoped the potentials of 3D extrusion-based printing in resolving food processing challenges. The evolving trends of 3D food printing technologies, fundamentals of extrusion processes, food printer, and printing enhancement, (extrusion) food systems, algorithm development, and associated food rheological properties were discussed. The (extrusion) mechanism in 3D food printing involving some essentials for material flow and configuration, its uniqueness, suitability, and printability to food materials, (food material) types in the extrusion-based (3D food printing), together with essential food properties and their dynamics were also discussed. Additionally, some bottlenecks/concerns still applicable to extrusion-based 3D food printing were brainstormed. Developing enhanced calibrating techniques for 3D printing materials, and designing better methods of integrating data will help improve the algorithmic representations of printed foods. Rheological complexities associated with the extrusion-based 3D food printing require both industry and researchers to work together so as to tackle the (rheological) shifts that make (food) materials unsuitable.

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Practical Applications

As a processing technology with digital additive manufacturing methodology, 3D food printing over the decades has evolved greatly with the extrusion-based type increasingly studied. This perspective review scoped the potentials of 3D extrusion-based printing in resolving food processing challenges. In this work, we demonstrated how this extrusion-based technique increasingly contributes to situate the 3D food printing as among innovative technologies with an upscale dimension. To fully embrace the extrusion-based 3D printing, the food industry needs to primarily understand the potentials this technology would provide in enhancing food material properties/types.

1 | INTRODUCTION

Three-dimensional (3D) printing technology is believed to have emerged through a patent by Hull (1986) which was titled "an apparatus for the production of 3D objects by stereolithography." 3D printing, also known as additive manufacturing (AM), and solid freeform fabrication, made its way into the food sector through some Cornell University researchers that devised an extrusion-based printer (Fab@home) (Liu, Zhang, & Bhandari, 2017; Liu, Zhang, Bhandari, & Yang, 2018). Defining 3D printing technology hangs on the process where materials were added to make objects from 3D model data, otherwise called computer-aided design (CAD) models (Dankar, Haddarah, el Omar, Sepulcre, & Pujolà, 2018a; Feng, Zhang, & Bhandari, 2019; Li, 2016). Additive manufacturing, according to Sanchez et al. (2019), has allowed 3D parts/products to be realized directly from CAD without specific tools for such parts/products (Godoi, Prakash, & Bhandari, 2016). Typically, the 3D technology is characterized by a layer-by-layer material deposition and directly based on a pre-designed file (Liu, Zhang, Bhandari, & Yang, 2018; Liu et al., 2017) through nozzles and controlled by software to create novel food products with complex and exquisite shapes and designs. Several food printers have been manufactured to produce such food products as candy, meatballs, pizza, pasta, cookies, and burgers, etc. Essentially, these printers use cartridge tubes filled with edible food solid/semi-solid (dough, puree, paste, and powder), liquids, or gels made from substances such as sugar, meat, chocolate, flour, fruits, and vegetables (Lipton, Cutler, Nigl, Cohen, & Lipson, 2015; Liu et al., 2017; Liu, Zhang, Bhandari, & Yang, 2018; Lupton, 2017).

In the food sector, the common 3D printing techniques include binder jetting, extrusion-based printing, inkjet printing as well as selective laser sintering printing (SLS) (Dankar et al., 2018a; Feng et al., 2019; Jiang, Zhang, & Mujumdar, 2021). Furthermore, the 3D printing technology has increasingly gained attention because it has helped to simplify the supply chain, expand how existing food materials can be better utilized through the extension of shelf life, and provide an engineering solution for customized food design, and personalized nutritional value (Feng et al., 2019). To better the understanding regarding the current situation of 3D food printing in providing engineering solutions for customized food design, we checked relevant literature reviews conducted between 2017 and 2021, which we hereby present in Table 1, specific to their objective of synthesis and key sections. Areas reviewed include material property of food ingredients to design the 3D food matrix, relating between process parameters and resulting printed food properties (Yang et al., 2017), how to achieve accurate 3D food printing and its application in several food areas (Liu et al., 2017), how extrusion-based food printing technique had impacted on food texture design, and emergent related technical bottlenecks (Sun et al., 2018), how 3D food printing reaches compatibility between varieties of food ingredients and their corresponding best printing parameters (Dankar et al., 2018a), and 3D printing models and slices for optimizing the printing process to provide useful information for future research (Guo et al., 2019). The properties of 3D printing food material supplies and its effect on printing processes (Nachal et al., 2019), contents of printable edible inks, the effects of printable edible ink material properties on 3D print accuracy, and the impact of printing parameters on accurate printing (Feng et al., 2019), and status/possible directions in food ink research across five categories, (namely confectionery, dairy, hydrogels, plants, and meat), and roles of additives in these inks (Voon et al., 2019), as well as 3D printing requirements for estimating as well as improving the performance/self-supporting ability in the extrusion-based printing process, particularly those of rheological characteristics of (3D food printing) materials (Jiang et al., 2019) are also among the 3D food printing areas reviewed.

From Table 1 also, it appears that in the year 2020 alone, the conducted reviews included the effects as pre-(crushing, gelation, etc.)

TABLE 1 Recent reviews conducted on 3D food printing between 2017 and 2021, specific to their objective of synthesis and key sections

References	Objective of the review synthesis	Key sections of the review
Kewuyemi, Kesa, and Adebo (2021)	An overview of the 3D food printing process, discusses the major factors, with summary of available literature on extrusion-based 3D-printed foods for fermented and malted foods	(a) Overview of 3DFP process, factors affecting printability of 3D food products (b) The current state of research on 3D-printed foods and applicability for fermented and malted foods (c) Advantages and limitations in food product development with 3D printing
Wang et al. (2021)	To provide a more intuitive overview and guidance for future research on 3D printing of plant-based materials. Additionally, notable recent achievements and emerging trends involving the use of plant-based materials in extrusion-based food printing across three categories, namely, hot-melt (e.g., chocolate), hydrogel, and soft (e.g., cereal- and fruit/vegetable-based) materials were reviewed	(a) Requirements, classification, and binding mechanisms of extrusion-based food printing materials (b) Plant-based materials for extrusion-based food printing (c) Challenges and prospects
Zhao et al. (2021)	To systematically review the functional ingredients used for creating printable food formula and their functions, analyze the functions of internal structures used or developed during 3D printing (infill density/structure) and their effects on texture properties (of 3D-printed food), and introduce 4D food printing adding summary of its current advances	(a) Functional ingredients of 3D printing and its effects on the printing quality (b) Functions of internal structures and its effects on texture properties of 3D-printed food (c) 4D food printing
Tomašević et al. (2021)	To discuss 3D printing as novel tool for fruit-based functional food production	(a) 3D printing as novel tool for fruit-based functional food production (b) 3DP in functional food design (c) Impact of 3DP on food texture and rheology (d) Preservation of 3DP functional foods (e) Conclusion—Future perspective of 3D food printing
Zhang, Pandya, McClements, Lu, and Kinchla (2021)	To establish the development and characterization of "food inks" suitable for 3D printing of foods, highlighting main factors impacting successfully printed foods, including material properties and printing parameters	(a) Food materials for 3D printing (b) Major food ink constituents (c) Factors influencing 3D food printing (d) Future opportunities for characterizing 3D food
Jiang et al. (2021)	To discuss the printing characteristics/classification of food materials using four commonly used 3D printing techniques, and recent technologies to evaluate 3D-printed products	(a) Printability of different food materials (b) Characteristics of food materials for different 3D printing techniques (c) Novel evaluation technology of food material performance in 3D printing (d) Future scope
Mantihal, Kobun, and Lee (2020)	To categorize printability, productivity, properties of printable material and mechanism of 3D food printing techniques, and propose its future direction	(a) 3D food printing techniques (b) The application of food additives in 3D food printing (c) Printable food materials (d) 3D printing as the tool to fabricate food texture (e) Consumer perceptions about 3D food printing (f) 3D printing technology for food: Current status and future prospects
He, Zhang, and Fang (2020)	To analyze the effect of pretreatment technologies (crushing, gelation, etc.) and post-treatment technologies (cooking, drying, fast cooling technology, 4 D printing, etc.) on the accuracy/shape fidelity of 3D-printed food products	(a) Pretreatment of food 3 D printing materials (b) Post-treatment using drying and rapid-cooling (c) Challenges of food 3 D printing technology and prospects

(Continues)

TABLE 1 (Continued)

References	Objective of the review synthesis	Key sections of the review
Guo, Zhang, and Bhandari (2019)	To increase researchers' focus on 3D printing models and slices in order to optimize the printing process and provide some useful information for future research	(a) 3D model building (b) 3D models for some customized specific food printing areas applications (c) 3D model slicing (d) Numerical techniques for 3D printing
Jiang et al. (2019)	To establish the characteristics of raw materials or additives used during 3D printing, and requirements for estimating/ improving their printing performance and self-supporting ability in extrusion-based printing regarding rheological characteristics of 3D food printing materials	(a) Essential constituents and feasibility of food components for 3D printing (i.e., carbohydrates, fat, protein, dietary fiber, and emerging functional components) (b) Challenges and trends of 3D food printing (i.e., the impact of rheological properties, consumer attitude, superiorities and futures of/on 3D food printing)
Nachal, Moses, Karthik, and Anandharamakrishnan (2019)	To get the insight into the properties of printing material supplies and their effect on printing processes, globalization of customized printed foods, personalized nutrition, and applications in food packaging with respect to 3D printing applications in the food industry	(a) The concept of 3D food printing (b) 3D printing technologies (c) Material supplies and recipes (d) Role of food constituents (e) Potential 3D printing applications that can revolutionize the food industry (f) Market survey and consumer attitude toward 3D printing (g) Challenges in 3D food printing
Voon, An, Wong, Zhang, and Chua (2019)	To get the current status and possible directions in food ink research across five categories, (namely confectionery, dairy, hydrogels, plants, and meat), roles of additives in these inks, and remaining challenges/potential opportunities in 3D food printing	(a) Food inks for extrusion printing: Classification and status (b) Food inks in non-extrusion printing (c) Additives and their effect (d) Challenges and opportunities
Feng et al. (2019)	The contents of printable edible inks, the effects of printable edible ink material properties on 3D print accuracy, and the impact of printing parameters on accurate printing, current challenges, and recommendations for future research and development	(a) Printable edible inks (b) Ideal material properties of printable edible inks (c) 3D food printing process platform optimization (d) Challenges and future trends
Dankar et al. (2018a)	To analyze and compare published 3D food printing articles on how to reach compatibility between the huge varieties of food ingredients and their corresponding best printing parameters	(a) Why print food, uses and benefits of 3D food printing (b) 3D food printing technology (c) Available printing materials d) Challenges and barriers to overcome in 3D printing process (e) Optimizing a 3D printing process
Liu et al. (2018)	To collect and analyze the information on how to achieve a precise and accurate food printing, and review the application of 3D printing in several food areas, and provide proposals/critical insight into challenges/trends to 3D food printing	(a) 3D printing technologies and factors influencing printing precision and accuracy (b) Application of 3D printing in some specific food areas (c) Some proposals (d) Challenges and trends
Sun, Zhou, Yan, Huang, and Lin (2018)	To review published work pertaining to the extrusion-based food printing technique and determine its impact on food texture design, and identify any related technical bottlenecks	(a) Extrusion in 3D food printing (b) Extrusion mechanism and process parameters in food printing (c) Temperature in extrusion-based food printer design (d) Food design in extrusion-based printing (e) Challenges along the pathway of commercialization

TABLE 1 (Continued)

References	Objective of the review synthesis	Key sections of the review
Yang, Zhang, and Bhandari (2017)	To briefly introduce recent development of food printing and material property of food ingredients used to design the 3D food matrix, and investigate the relationship between process parameters and resulting printed food properties in order to establish a food manufacturing process toward optimization	(a) Principals and methods of 3D printing (b) Applications of 3D food printing (c) Opportunity to fabricate nutrient-dense innovative food materials (d) Improvement on appearance and texture of traditional food products (e) Trends and challenges in 3D printing of food products (f) Optimization of 3D printing process conditions with both high quality and high efficiency

and post-treatment technologies (cooking, drying, fast cooling technology, 4D printing, etc.) on the accuracy/shape fidelity of 3D-printed food products (He et al., 2020), as well as (3D food printing) techniques able to categorize printability, productivity, properties of printable material mechanisms (Mantihal et al., 2020). In the year 2021, however, the conducted reviews involved 3D food printing process overview with major factors and summary of available extrusion-based literature for fermented and malted foods (Kewuyemi et al., 2021), overview and guidance for future research on extrusion-based 3D printing for plant-based materials (Wang et al., 2021), printing characteristics/classification of food materials using four commonly used 3D printing techniques (Jiang et al., 2021), 3D printing as a novel tool for fruit-based functional food production (Tomašević et al., 2021), as well as development and characterization of “food inks” suitable for 3D printing of foods, highlighting main factors impacting successfully printed foods, including material properties and printing parameters (Zhang et al., 2021). Another review includes the functional ingredients used for creating printable food formula and their functions, analyzing the functions of internal structures used or developed during 3D printing (infill density/structure) and their effects on texture properties (of 3D-printed food) (Zhao, Zhang, Chitrakar, & Adhikari, 2021). From our conducted analysis of recent reviews published between 2017 and 2021 on 3D food printing, we authors opine that the emphasis given to extrusion-based type is not enough, and therefore, deserves additional literature synthesis. We have this opinion despite that, for example, the review of Sun et al. (2018) discussed how extrusion-based food printing technique had impacted food texture design, and Jiang et al. (2019) discussed 3D food printing estimating as well as improving (printing) performance and self-supporting ability in extrusion-based printing especially rheological characteristics of materials. Additionally, Kewuyemi et al. (2021) summarized available extrusion-based literature specific to fermented and malted foods, whereas that of Wang et al. (2021) discussed extrusion-based 3D printing specific to plant-based materials.

In the light of the above, the authors believe the further literature synthesis into the extrusion processes/mechanisms specific to 3D food printing would provide additional insights, especially how it functions within the food systems. Understanding better the various food/printer algorithm development and associated food materials/rheological properties is equally important. At the end, when the such state-of-the-art of 3D extrusion-based food printing is obtained, it would help to convince the agro-food product industry/sector more about how 3D extrusion-based printing possesses high promise in resolving its (agro-food product) processing challenges. To supplement existing information, therefore, this perspective review scopes the potentials of 3D extrusion-based food printing in resolving food processing challenges, and discussed as follows: (a) crux/essence of 3D food printing; (b) evolving trends of 3D food printing technologies; (c) fundamentals of extrusion processes, food printer and printing enhancement; (d) 3D printing in extrusion food systems; (e) 3D printing algorithm development and associated food rheological properties; (f) extrusion mechanism in 3D printing: some essentials for material flow and configuration; (g) extrusion-based 3D food printing: uniqueness, suitability, and printability of food materials; (h) food material types associated with extrusion-based 3D printing; as well as (i) essential food properties and their dynamics in 3D printing. Additionally, some bottlenecks/concerns still applicable to extrusion-based 3D food printing will be discussed.

2 | THE CRUX/ESSENCE OF 3D FOOD PRINTING: A PRIMER

The definition of 3D printing has been based on a technical process whereby a material (which can either be in form of plastic, ceramic, metal alloy, or food) is deposited layer-by-layer to form a product. It utilizes the same specification and design as that of the CAD (3D-CAD) model or scanned model of the product (Dankar et al., 2018a). Actually, before the printing process, the model has to be saved as an STL (Stereolithography) file, which is converted into a geometric code, popularly known as G-code for the 3D printer to understand. The movement of the printer head which is responsible for the release of material is controlled by the G-code. The information embedded in the G-code, when conveyed to the printer directly influences it to move in three (*X*, *Y*, and *Z*) axes—left to right, front to back, and up and down, respectively, as the object is being printed (Dankar et al., 2018a). This design information, which may be sent to the printer through a USB cable connected to the computer, or an SD card, is sliced into layers and assembled in the specified 3D pattern during printing. Therefore, 3D printing is also called AM because the material is laid down in layers (Godoi et al., 2016). Some workers have outlined factors they believed to influence 3D food printing, which included properties of food material, external influence of experimental design, as well as the parameters designed around the constituent food materials. Properties of food material would involve the concentration of ingredients, composition of food ink, rheology, and texture. External influence of experimental design would involve the design of print/printing, parameters of printing, processing techniques, as well as the 3D printing facility itself (Zhang et al., 2021).

There are potential benefits of 3D food printing related to automation of (food) manufacture and nutrition customization. An example of a food material that has found wide commercial application in 3D food printing is chocolate, whereby a 3D printer has been used to produce complex geometries of its products, which would be difficult to produce by hand or with the aid of a food mold. As a result, there is a greater possibility to fabricate complex food structures with personalized nutritional contents (Godoi et al., 2016; Yang, Zhang & Bhandar, 2017). Personalized nutrition, in terms of the development of a wide range of completely customized food products, sufficiently fits the consumers' (nutritional) history irrespective of their age, gender, occupation, and healthy lifestyles, by modifying the food composition and characteristics, and to suit consumer needs and preferences (Rodgers, 2016; Sher & Tutó, 2015). This will improve the usage of alternative food materials such as, insects, and unconventional fruits and vegetables, etc., for the development of food products with enhanced shelf life at low environmental cost and better quality (Sun, Peng, Yan, Fuh, & Hong, 2015). As a result, 3D food printing has the potential to simplify food manufacturing processes, establish high material use efficiency in terms of minimizing waste, portion control, and production of well-structured and tasty food products from food ingredients. Although food materials have complex structures with vast differences in physicochemical properties, some researchers (Sun, Peng, et al., 2015; Sun, Zhou, Huang, Fuh, & Hong, 2015) have attempted to widen the scope of 3D printing so as to accommodate varying food materials via the likes of fused deposition modeling (FDM) (also known as extrusion-based 3D printing), powder bed fusion and binder jetting (3D Systems, 2018; 3DigitalCooks, 2018; BeeHex, 2018; Byflow, 2018; CandyFab, 2006; Choc Edge, 2018; Createbot, 2018; Dovetailed, 2018; Edutechwiki, 2018; FoodJet, 2021; Itis3d, 2016; Krassenstein, 2014; Landoni, 2015; Lipton, Arnold, Nigl, Cohen, & Lipson, 2010; Lipton et al., 2015; Mmuse, 2018; Natural Machines, 2020; Ontwerp, 2021; Procusini, 2018; RIG, 2018; Van der Linden, 2015; Walters, Huson, & Southerland, 2011).

3 | EVOLVING TRENDS OF 3D FOOD PRINTING TECHNOLOGIES: KEY BRIEFS

The evolution of 3D food printers from commercial, open-source to printheads/extruders types, is depicted in Figure 1. These printers utilize the different methods of AM to process and design food materials. Also from Figure 1, it can be seen that prior to 2012, the 3D food printers appear to comprise FDM, as well as SLS. However, after 2012, there appears to be the further evolution of commercial printers having the FDM to combine with the binder jetting, coupled with the emergence of the rather cheaper Open-Source /multi-type FDM printers, and up to many others now available today. From Figure 1 also, it is clear that FDM, over the two decades, appears most widely used 3D printing method globally. Indeed, FDM is very popular with companies associated with consumer goods manufacturing (Black and Decker, Dial, Nestle). These companies utilize FDM in their manufacturing processes, product development as well as prototyping. Despite that Stratasys has been considered to be responsible for inventing FDM, it appears not the only company making profits from it (Palermo, 2013, website accessed May 8, 2021). On the other hand, SLS 3D printing, since its inception in the mid-1980s by Dr Carl Deckard and Dr. Joe Beaman (University of Texas, Austin-USA) has been adapted to work with range of materials, for example, ceramics, plastics, and various composite material powders. Besides,

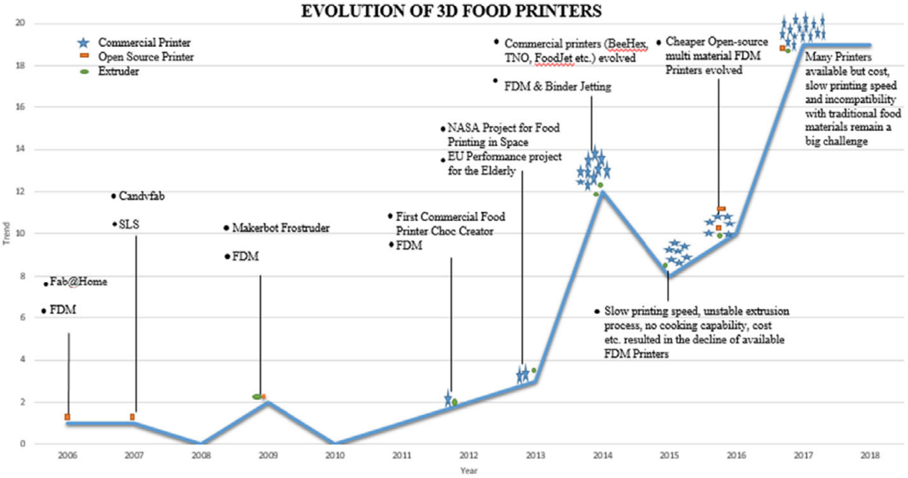

FIGURE 1 The evolution of 3D food printers from commercial/open source printers to printheads/extruders. FDM, fused deposition modeling, also known as fused filament fabrication (FFF); SLS, selective laser sintering; The trend axis is to signify the increase in competition as well as productivity of 3D food printers as they evolved over time

also available include the bench top (less expensive) and traditional industrial (more expensive) types (Formlabs, 2021b, Accessed May 9, 2021).

Extrusion-based 3D printing (similarly referred to as FDM) involves the deposition of food material from the heated or unheated nozzle (as in the case of cold extrusion of jellies) layer-by-layer (Sun et al., 2018). The extruded food material is usually heated to a temperature above its melting temperature, to ensure quick adhesion when a new layer is deposited onto the previous layer. This is believed as the most widely applied 3D printing technology for foods (Sun et al., 2018). FDM printers can also accommodate multiple extruders (more than two extruders), to facilitate simultaneous printing of several food components (Liu, Zhang, & Bhandari, 2018; Liu, Zhang, Bhandari, & Yang, 2018). The multi-printhead usually combined with interchangeable extruder designs enables the fabrication of intricate geometries using multiple ingredients, more easily than its other counterparts (Sun et al., 2018). Either selective laser sintering technology or powder bed fusion, on the other hand, is based on melting powder particles and fusing them layer-by-layer. The most suitable food materials are sugars or sugar-rich powders (Godoi et al., 2016). It is laser-oriented, given that the laser helps to fuse the powder, which makes it best for functional prototyping and end-use production (Formlabs, 2021a, Accessed May 8, 2021). Powders are evenly applied thinly on the bed, melted, and compacted together with the aid of a heat source, which may be a laser or hot air moving along the printing axes. Another layer of powder is applied and sintered similarly, and the same process is repeated continuously till the final product is formed, then cleaned from excess loose powder, which serves as structural support. However, this technology does not require post-processing like drying, unlike extrusion-based printing (Godoi et al., 2016).

For binder jetting, a uniform layer of powdery materials is also applied on the bed and fused using liquid binder sprays, which is a combination of powder bed and Ink-jet printing principles, the process resembling selective sintering technology. There is a continuation application of powder layers until the final product emerges, and the excess powder can be removed. Despite this, a finishing process is required, including cleaning and improvement of the connection layers, due to the use of the liquid binder (Dankar et al., 2018a). The application of heat employed in selective sintering and powder bed printing methods renders these methods unsuitable for the printing of traditional food ingredients. The particle size of powders used as raw materials must meet certain specifications required for a good quality product, and this accounted for the use of mostly sugar and sugar-rich powders in these methods (Dankar et al., 2018a). Moreover, the extrusion-based 3D printing method is mostly used because it is adaptable for a wide variety of food ingredients such as sugars, proteins, and carbohydrates (Sun, Peng, et al., 2015). Besides, there are a number of reasons why 3D food printing has been considered needful, according to Dankar et al. (2018a). Some of the key reasons include: (a) Creating personalized food products for a wide variety of consumers; (b) Enhancing the process of production; (c) Novel food structuring using a broad range of alternative food ingredients; (d) Environmentally friendly and sustainable technology; as well as (e) Promoting higher social bonding through food messaging.

4 | 3D PRINTING: FUNDAMENTALS OF EXTRUSION PROCESSES, FOOD PRINTER, AND PRINTING ENHANCEMENT

4.1 | Fundamentals of extrusion processes in 3D printing

Typically, the extrusion concept is underpinned when a material is prepared and fed to an extruder for modification/shaping to bring about a new product. Giles, Wagner, and Mount (2005)described the process in great detail, regardless of whether the process entails single or twin-screw type. First, there has to be a raw material supplied, for instance, a polymeric (raw)material such as resin. Besides the fact that it has to be stored properly, there are critical properties that could influence the final product performance, like color, long-term heat aging, tensile properties as well as viscosity. Material blending with additives and the drying process are very important stages. For instance, over-drying might contribute to characteristic/developmental losses in the emergent products. After being fed into the extruder, the emergent material product will depend on the feeding strategy, whether it is crammer, flood, melt, or starve, because the shaping and drawing, solidification, and cooling will certainly influence the output type. Giles, Wagner, and Mount (2005) further pointed out that, prior to the final inspection, which is largely by gaging or visual approaches, the dimensions of the final product would vary largely because of the extruder, owed to such challenges as surging, power input variations, slippage on the screw, poor feeding, etc. All these have been depicted in Figure 2, which displays the schematic flow of typical extrusion process of a given food material, and how it can easily locate itself within the 3D printing domain. It is well known that 3D emanates from AM, wherein the extrusion-based process occupies a useful part (Dankar et al., 2018a; Sanchez et al., 2019; Sun et al., 2018; Yang et al., 2015).

By studying the interchangeable head based on variable section screw applied to desktop 3D printers, Neto, Noritomi, Silva, Freitas, and Silveria (2014)discussed some considerations about the extrusion process. These workers pointed out two principles, largely applicable to highly viscous liquids, which include: (a) positive displacement pumps that allow fluids to fill up enclosed chambers, where parts of the machine move forward mechanically; and (b) drag flow pumps where the fluid would fill a region between the two surfaces, wherein only one is in motion. In these, there is a need for a more robust study that would look into the behavior of extrusion processes, which should involve an estimate of thermo-physical parameters, like its geometry, polymer rheology, and processing conditions, as it largely relates to the screw (Neto et al., 2014). For emphasis, the processing zones to a single screw are shown in Figure 3. We can see the feed zone, compression zone, and the flow control (Chung, 2000; Manrich, 2005; Neto et al., 2014). The optimization of the screw design can substantially help to improve the performance of the extrusion process, which with the latter is found the design parameters that can include acceleration, density, thread ratio, pressure gradient, Young modulus,

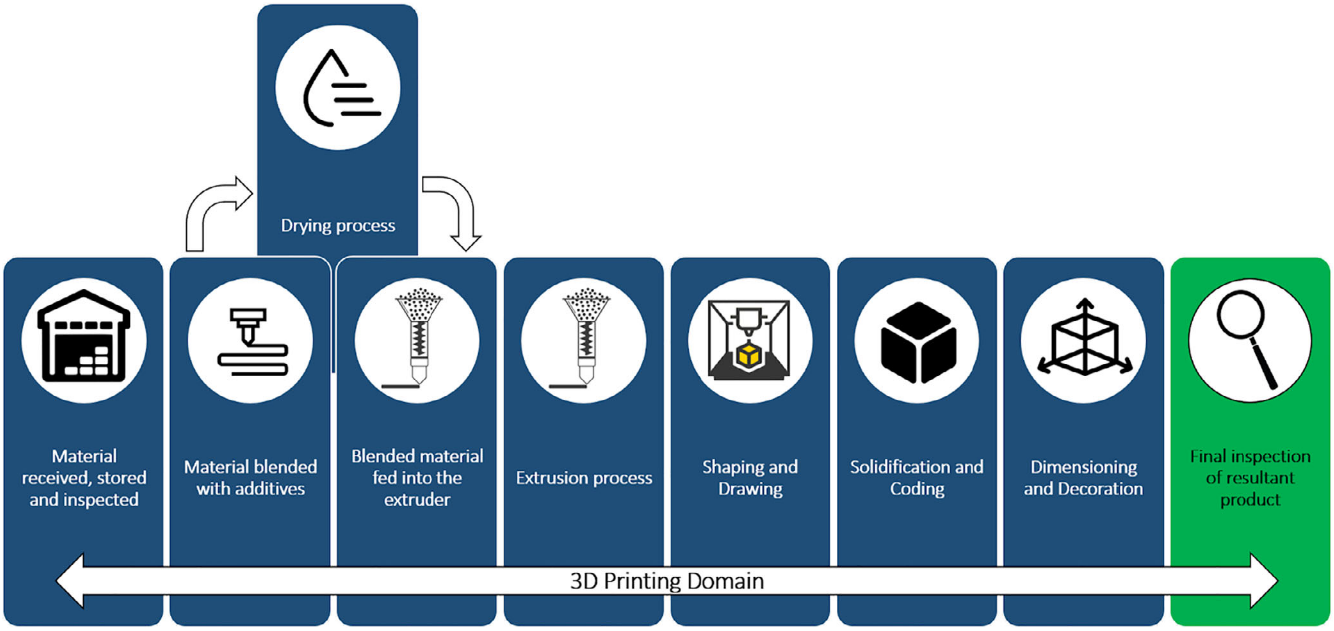

FIGURE 2 A schematic representation of typical extrusion process of a given food material, and how it locates easily itself within the 3D printing domain (modified from Giles et al., 2005)

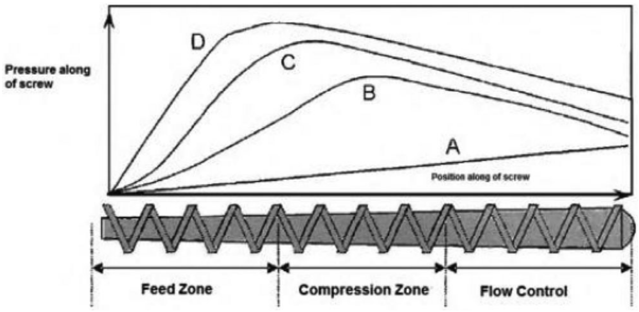

FIGURE 3 The processing zones to a single screw (reproduced from Neto et al., 2014, with permission for use from Taylor and Francis)

screw torque, as well as compressive, shear, tensile, and yield strength (Neto et al., 2014).

4.2 | A typical 3D printer

A standard food printer chiefly comprises three components: a computer, which allows the interaction between the user and the printer through software; the software, which allows the computer to communicate with the motor control box; and the food printer motors, which is controlled by the control box (Baiano, 2020; Millen, 2012). In turn, the food printer platform consists of an *XYZ* three-axis motorized stage, one or more dispensing/sintering units, and a user interface. As a result, the food is produced in a real-time way by deposition or sintering, point by point and layer by layer, according to computerized design modeling and path planning. The functions proposed are metering, mixing, dispensing, and heating/cooling (Baiano, 2020; Zoran & Coelho, 2011).

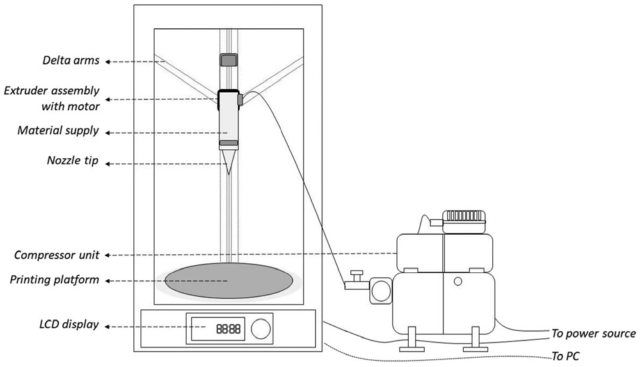

FIGURE 4 A schematic diagram of a typical extrusion type 3D food printer (reproduced from Nachal et al., 2019 with permission from Springer Nature)

For emphasis, a schematic diagram of a typical extrusion type 3D food printer is displayed in Figure 4. A typical 3D printer consists of (a) control circuit for integrating the computer and the printer; (b) motor, filament, and drive system for guiding the motors; (c) mixing chamber into the store and mix the material supply; (d) feed rollers; (e) flow sensors; (f) pressure regulators; (g) nozzles; and (h) a printing platform over which the food is printed. The printing platform consists of a three-axis stage (Cartesian coordinate), a dispensing/sintering unit, and a user interface. With the digital control over the material feeding system, one can manipulate the fabrication process to meet customer expectations (Nachal et al., 2019). For 3D printing technology to thrive, the materials and printers have to be suitable for a wide range of specific purposes. According to Yang et al. (2015), 3D printers have categories for the fabrication of shape, namely: rectangle-cassette-structure, rectangle-pole-structure, triangle-structure, and triangle-claw-structure printers. Triangle-structure printers, mainly DIY-assembled ones, possess major merits like their convenience of maintenance despite having lower accuracy. Moreover, the rectangle-cassette-structure printers as primarily commercially available, possessing high accuracy although the high maintenance cost makes its demerit (Yang et al., 2015).

4.3 | Typical 3D printing activity and its enhancement

The 3D food printing is performed through three steps: 3D model building, objects printing, and post-treatment (Baiano, 2020). A pictorial flow of extrusion-based 3D food printing process is shown in Figure 5. Indeed, the extrusion-based food printing would commence with the design phase, which would employ a virtual 3D model. The slicing software translates this 3D model into the actual individual layer patterns, which then would finally generate the machine codes for the printing to take place. It should be noted that, after the uploading process of the codes into a given 3D food printer, and choosing a preferred food recipe, the actual food printing activity would commence (Sun, Peng, et al., 2015; Sun et al., 2018). According to the layer patterns generated from the 3D model, the extruded material is dispensed either by moving the nozzle above a motorized stage or by moving the stage underneath the nozzle to form a layer. Each layer welds to the previous layer on the stage and forms a layer-based 3D structure. The printed foods may go through a post-deposition cooking process such as baking (Sun, Peng, et al., 2015; Sun et al., 2018). Furthermore, the foundation that the CAD has laid for the 3D printing activity has been underpinned by, among others, the model building strategy. Other workers like Guo et al. (2019) understood that the (model) building strategy employs the 3D model that gets changed into an STL file, wherein the slicing activity enables the model to build the layers, and also helps to actualize each of the section's outline. Moreover, building the 3D model encompasses not only the CAD-based model, but also, the scanning-based model, and others. Besides 3D models being customized to specific food printing, the model slicing requires the G-code, together with parameters like layer height, nozzle speed, extrusion rate, as well as infill. Guo et al. (2019) further understood that the numerical techniques for 3D printing can engage simulation activities either for 3D models/printed objects analysis, as well as extrusion analyzing.

In order to enhance a given 3D printing process, Dankar et al. (2018a) and Dankar, Pujolà, el Omar, Sepulcre, and Haddarah (2018) understood that the parameters of a 3D printer and the food itself have to be considered. On one hand, the parameters of a 3D printer (also known as process parameters)include: (a) the print/extrusion speed of the 3D printer; (b) pressure and speed flow level of product on quality of printed materials; (c) deposition rate; (d) nozzle size for printing; (e) distance between the nozzle and printing bed (nozzle height; (f) infill layer, and layer height; as well as (g) temperature of extruder or printing bed (found in some 3D printers). On the other hand, the parameters of the food itself can include food physio-structural and rheological properties, food mechanical properties, ingredient optimization within the foods, as well as sensory properties. Dankar et al. (2018a) relayed that these parameters of 3D printer and the food itself interact/interrelate, as depicted in Figure 6, where different properties and conditions have to be controlled while 3D printing, and such, it would resemble the best 3D printing process, as well as realize a quality product that fits between both parameters. Besides printing temperature associated with the viscosity of the food material, the 3D food structures should have the capacity to resist post-processing (baking, cooking, frying, etc) (Liu et al., 2017). Nonetheless, Zhang et al. (2021) discussed factors that can influence 3D printing to include the external experimental design, parameters designed around the food constituents, as well as critical food properties, which the latter can comprise the concentration of ingredients, the composition of food ink, rheology together with other textural attributes. Specifically, these workers drew the distinction between rheology and texture. From the rheology

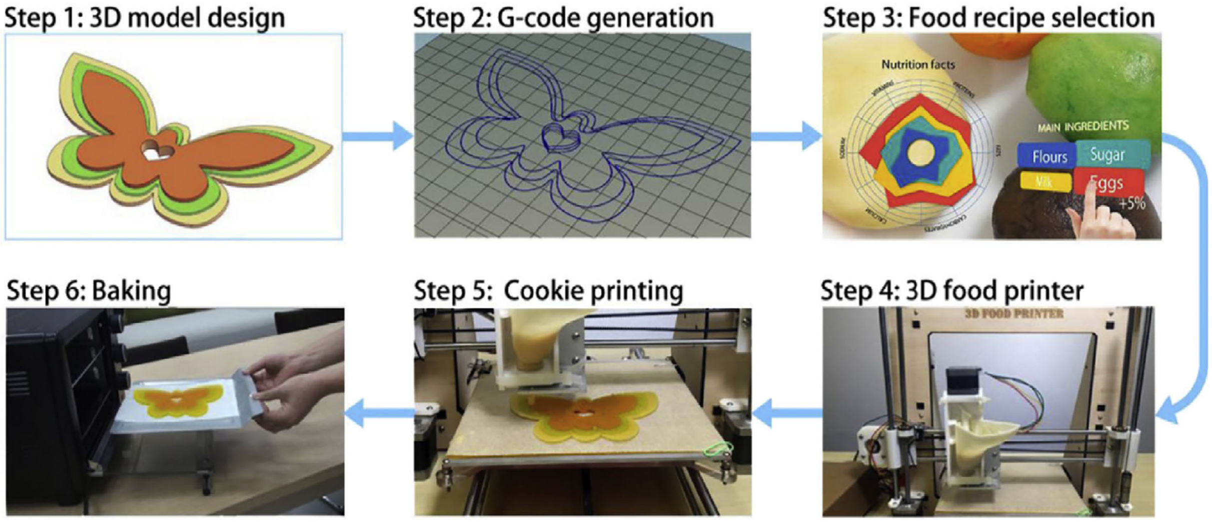

FIGURE 5 A pictorial flow of extrusion-based 3D food printing process (reproduced from Sun et al., 2018 with permission from Elsevier B.V.)

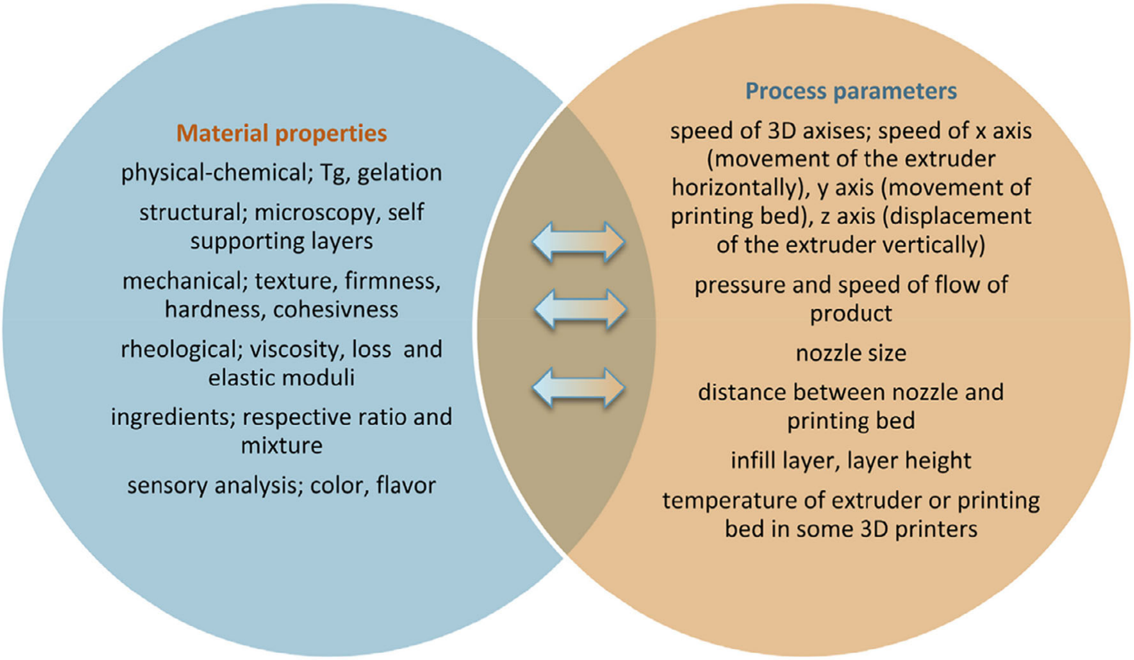

FIGURE 6 Different properties and conditions require control during 3D printing, and how to achieve the best process/product given the fit between both parameters (reproduced from Dankar et al., 2018a, with permission from Elsevier B.V.)

standpoint, food types take both pseudo-plastic and viscoelastic groups, where both (food types) can behave in Newtonian (viscosity independent of shear rate) and non-Newtonian (viscosity dependent on shear rate) manners. Rheology tests usually require the rheometer (most common include TA instruments and Anton Paar) largely equipped with parallel plates of different diameters and gaps that help to provide the rheological readings. From the texture standpoint, the physical property of the food type(s) is determined in relation to sensorial and structural elements. The analysis and quantification of texture largely utilize the instrument called Texture Analyzer, Stable Microsystems being among the well-known manufacturers. This instrument provides a texture profile analysis from which various (texture) parameters are collected. Other external influences, also discussed by Zhang et al. (2021) included printing parameters, print design, processing techniques as well as the 3D printing equipment itself.

5 | 3D PRINTING IN EXTRUSION FOOD SYSTEMS: FOOD/PRINTER EXAMPLES, RESEARCH LABS/GROUPS, AND OPEN-SOURCE PROVISION

5.1 | Food printer examples

3D printing can reduce the many challenges in terms of skills and resources that currently confront tech enthusiasts, innovators, and inventors from bringing ideas to reality. Thus, it will allow creativity that introduces new independent creators and a new system of custom-made products (Porter, Phipps, Szepkouski, & Abidi, 2015). Concerning this, food printers are becoming available commercially, although at a fairly expensive cost. They can be set up to achieve their intended use, according to personal and technical specifications. For emphasis, Figure 7 shows food examples printed by an extrusion-based 3D food printer (specifically the Foodini Printer), as displayed by Natural Machines (2020). For emphasis also, Figure 8 shows three examples of commercial 3D food printers, which include: (a) Choc Creator by Choc Edge (Choc Edge, 2018; Godoi et al., 2016) (b) Foodini by Natural Machines (2020) (c) Fab@Home by Creative Machines (Creative Machines Lab, 2020; Lipton et al., 2010, 2015). For example, Foodini Printer by Natural Machines (2020) already was specifically built to be used as a kitchen appliance for professional/home kitchen users. Chocolate printers also was built not only for personal use but also in confection and other professional food applications. Similarly, there are multi-material open-source printers capable of printing food ingredients (Van der Linden, 2015). Choc Edge launched the first commercial 3D chocolate printer officially in 2012 (Choc Edge, 2018; Godoi et al., 2016). But before then, the Fab@Home Printer became available and was used for exploring the printing of a wide variety of edible food materials (Lipton et al., 2010, 2015).

5.2 | 3D printing in food systems—research groups/labs

The 3D Printing in Food Systems—Research Groups/Labs are summarized in Table 2. It can be seen that raw materials, products, printer/features, and technology can differ across the research groups/labs.

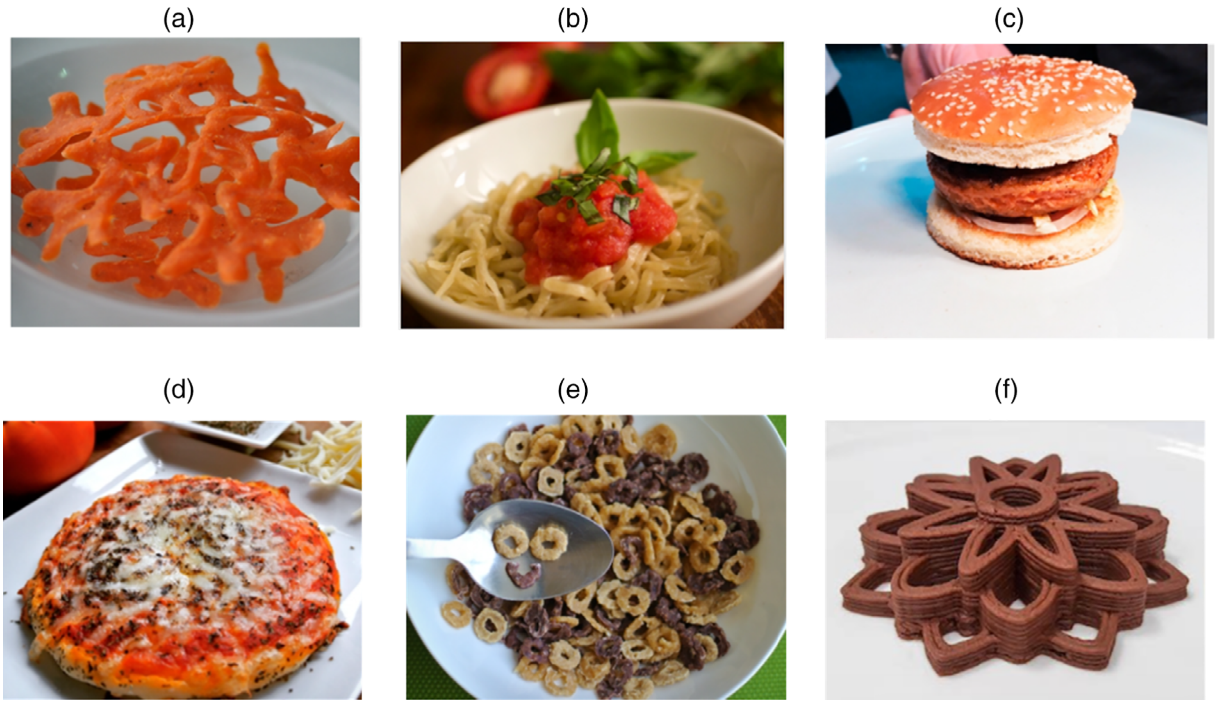

FIGURE 7 Food samples printed by Foodini Printer as displayed on the Natural Machines website (Natural Machines, 2020) (a) thin crackers (b) pasta (c) bread rolls (d) pizza (e) oat cereal (f) chocolate

FIGURE 8 Commercial 3D food printers (a) Choc Creator by ChocEdge (Choc Edge, 2018; Godoi et al., 2016) (b) Foodini by Natural Machines (Natural Machines, 2020) (c) Fab@Home by Creative Machines (Creative Machines, 2020; Lipton et al., 2010, 2015)

TABLE 2 3D food printing systems—research groups/labs with respect to raw materials, products, printer/features, and technology

Research groups/labs	Raw materials	Products	Printer/features	Technology	References
TNO	Liquid chocolate, dough, Nesquik powders, wheat flour, gels	Chocolate dessert, pasta, curry cubes, cake, 3D-printed carrot and broccoli	TNO 3D printer (polar configuration); barilla pasta printer (multiple print head, pneumatic based system)	Extrusion printing, SLS, powder bed printing	Dankar et al. (2018a)
Creative Machines Lab (Columbia University)	Paste, batter, dough, jelly, chocolate	Cheese, pasta, pizza, cake frosting, tortilla, chocolate, jam, meat	Fab@home model 1, 2, and 3 (syringe based; multiple syringes; multiple printhead/ pneumatic based system); Sanna printer (SCARA configuration)	Extrusion printing	Lipton et al. (2010, 2015)
Choc Edge ltd. (University of Exeter)	Tempered chocolate	Complex geometries of chocolate dessert	Choc creator V1; V2	Extrusion printing	Choc Edge (2018)
RIG	Dough and purees	Cream cheese, cake, pasta, ice cream	FoodForm 3D printer	Extrusion printing	RIG (2018)
University of the West of England Centre for fine print research (edible printing)	Sugars, starch powders, alcohol, mashed potato, cream cheese, and chocolate	Sugar teeth, snacks		Powder bed printing; extrusion printing	Walters et al. (2011)

The extrusion printing appears the most widely used technology, as shown in Table 2. The raw material/food products that seem to appear increasingly is chocolate, and across some research groups/ labs. The TNO Research Group/Labs, for instance, besides employing 3D printing technologies like Extrusion printing, SLS, Powder bed printing, used specific printers/features like TNO 3D Printer (Polar Configuration), Barilla Pasta Printer (Multiple print head, Pneumatic based System), in order to help realize such products as Chocolate dessert, Pasta, Curry cubes, Cake, 3D-printed carrot and broccoli (Dankar et al., 2018a). Whereas authors like Walters et al. (2011) showed both Powder bed Printing and Extrusion printing could be applied to raw materials like Sugars, Starch powders, Alcohol, Mashed potato, Cream cheese, and Chocolate, groups like Choc Edge (2018) applied Extrusion printing to Tempered chocolate.

The 3D food printing systems–companies with respect to raw materials, products, printer/features, and technology are summarized in Table 3. The 3D Ventures (Edutechwiki, 2018) used Extrusion printing in the form of Candy3D Printer on Sugar and Confections to make Candy and Confectioneries. Whereas Michiel Cornelissen Ontwerp (2021) used Extrusion printing in the form of XOCO Chocolate printer (Polar Configuration) on Chocolate, and Natural Machines (2020) did so in the form of Foodini Printer (Cartesian, Pneumatic System; Multi print heads) on Natural food ingredients, mostly paste or puree in the making of Pasta, Burgers, Pizza, cookies, crackers, brownies, chocolate, etc., XYZ Printing (Van der Linden, 2015) did so in the form of XYZ 3D Food Printer (Touch Screen; Multiple nozzles) on Dough/Paste/Puree in the making of Pasta, Tomato sauce, Cheese. BeeHex Inc. (BeeHex, 2018) did so in the form of Chef3D Pizza Printer (Pneumatic System; Multiple printheads) on Dough, Purees in the making of Pizza, cheese, sauce, Chocolate Desserts. We can see from Table 3 that companies like Mmuse, Createbot, and ByFlow used Extrusion printing with three, respectively, different printer features Mmuse Touchscreen 3D chocolate printer, 3D Delta Pancake Printer, Createbot Food Printer, and Focus 3D Food Printer (Syringe-based mechanism), all of which could still be applied in the making of chocolate products.

5.3 | 3D printing in food systems provided by Open-Source

Table 4 summarizes the 3D printing in food systems provided by Open-Source, which also applies the extrusion approach. Creative Machines Lab (Creative Machines, 2020; Lipton et al., 2010, 2015) did so using Fab@Home Model 1 -Multiple-Syringe-based mechanism on Multi-material ingredients and Hydrocolloids in the making of Cheese, Pasta, Cake Frosting, Peanut butter, Chocolate, Cookies, etc. Open Electronics (Landoni, 2015) did so using 3D Drag Choco; 3D Drag Big Dual Chocolate Printer (Syringe-based Mechanism) on Chocolate in the making of Chocolate dessert. Another is Itis3D (Itis3d, 2016) that did so using Focus multi-material 3D Printer Two interchangeable heads (one for polymers, the other for food pastes) on Polymers, Ceramic, and Food Pastes in the making of Buttercream, and Chocolate. This differed from Tytan 3D (Krassenstein, 2014) where multi-material Delta printer had been applied to flour and salt mixture, paper pulp, chocolate adhesives, and other self-hardening materials. Elsewhere, Lanaro et al. (2017) investigated the

TABLE 3 3D food printing systems—companies with respect to raw materials, products, printer/features, and technology

Companies	Raw materials	Products	Printer/features	Technology	References
FoodJet	Purees and liquids	Chocolate, fondants, and other decorations	FoodJet printer	Inkjet printing	FoodJet (2021)
3D ventures	Sugar and confections	Candy and confectioneries	Candy3D printer	Extrusion printing	Edutechwiki (2018)
Candyfab Machines	Sugar and sugar-rich powders	Sugar and fondant sculptures	CandyFab printer	Selective heat sintering	CandyFab (2006)
Dovetailed	Fruit juices	Spherical fruits	Nufood 3D fruit printer	Hydrogel forming extrusion	Dovetailed (2018)
Michiel Cornelissen Ontwerp	Chocolate	Chocolate	XOCO chocolate printer (polar configuration)	Extrusion printing	Ontwerp (2021)
Natural Machines	Natural food ingredients, mostly paste or puree	Pasta, burgers, pizza, cookies, crackers, brownies, chocolate, etc.	Foodini Printer (Cartesian, pneumatic system; multi print heads)	Extrusion printing	Natural Machines (2020)
3D systems	Sugar/sugar-rich powders and chocolate	Fondant, candy, and chocolate	ChefJet/ChefJet pro; CocoJet printer	Powder bed printing; extrusion printing	3D Systems (2018)
XYZ printing	Dough/paste/puree	Pasta, tomato sauce, cheese	XYZ 3D food printer (touch screen; multiple nozzles)	Extrusion printing	Van der Linden (2015)
Procusini	Flowable/liquid food materials	Pasta, chocolate, fondant, potato puree octopus, desserts	Procusini 3.0 and 3.0 dual	Extrusion printing	Procusini (2018)
BeeHex Inc.	Dough, purees	Pizza, cheese, sauce, chocolate desserts	Chef3D pizza printer (pneumatic system; multiple printheads)	Extrusion printing	BeeHex (2018)
Mmuse	Chocolate powder, pancake/tomato/salad puree	Chocolate dessert, pancake, sauce	Mmuse touchscreen 3D chocolate printer, 3D delta pancake printer	Extrusion printing	Mmuse (2018)
Createbot	Mashed potatoes, beans, black sesame, etc.	Biscuits, chocolates, and snacks	Createbot food printer	Extrusion printing	Createbot (2018)
ByFlow	Pastes and purees	Chocolate, Nutella, noodles, pancakes	Focus 3D food printer (syringe-based mechanism)	Extrusion printing	Byflow (2018)

platform design, optimization, and evaluation of 3D printing complex chocolate objects. These workers presented the construction of 3D printer melt extrusion that employed readily available open-source parts. These workers found chocolate spanning distance was unaffected despite movement speed range between 300 and 700 mm/min, with optimal extrusion rate 10–20% leaner. Additionally, there was an improvement in the spanning distance as the air was directed across the printing part, to lower (the air) temperature roughly by 3.5°C.

6 | 3D PRINTING SOFTWARE/ALGORITHM AND KEY FOOD RHEOLOGICAL PROPERTIES

6.1 | 3D printing software platform and algorithm improvement

The term curved layer printing and its variants mainly refer to slicing a model using curved layers instead of the traditional planar layer slicing or a combination of planar and curved. A very complete review of planar and non-planar slicing methods and path planning for AM is presented by Zhao and Guo (2020). Different approaches are also found in the literature related to conformal printing on non-planar surfaces that are not commonly associated with the curved slicing model, but which are included here due to their importance in this study. The term curved layer fused deposition modeling (CLFDM) was first introduced by Chakraborty, Reddy, and Choudhury (2008) who formulated a theoretical method, mainly based on CNC traditional concepts, for the manufacturing of thin curved shells to improve the mechanical properties and reduce the stair-step effect. Their work was based on employing longer length tool paths, focused on the proper orientation of the filament and appropriate bonding between adjacent filaments. Their formulation used a parametric surface, calculated the partial derivative of it to obtain the normal vector and then generated an offset surface. The concept of CLFDM was experimentally reported by a number of researchers (Diegel, Singamneni, Chowdhury, Gibson, & Huang, 2010; Diegel, Singamneni, Huang, & Gibson, 2011; Huang,

TABLE 4 3D food printing systems—open source with respect to raw materials, products, printer/features, and technology

Companies	Raw materials	Products	Printer/features	Technology	References
Creative Machines Lab	Multi-material ingredients and hydrocolloids	Cheese, pasta, cake frosting, Peanut butter, chocolate, cookies, etc.	Fab@home model 1; multiple-syringe-based mechanism;	Extrusion printing	Lipton et al. (2010, 2015); Creative Machines Lab (2020)
Open electronics	Chocolate	Chocolate dessert	3D drag Choco; 3D drag big dual chocolate printer (syringe-based mechanism)	Extrusion printing	Landoni (2015)
3D digital cooks	Pastes and purees	Chocolate, yogurt, cream cheese, snacks	Pinya 3 delta 3D printer	Extrusion printing	3DigitalCooks (2018)
Itis3D	Polymers, ceramic and food pastes	Buttercream and chocolate	Focus multi-material 3D printer; two interchangeable heads (one for polymers, the other for food pastes)	Extrusion printing	Itis3d (2016)
Tytan 3D	Flour and salt mixture, paper pulp, chocolate adhesives and other self-hardening materials		Tytan 3D multi-material Delta printer	Extrusion printing	Krassenstein (2014)

Singamneni, & Diegel, 2008). These workers generated the path planning (flat layers) to produce a mandril as a support structure where the curved layers were later deposited, following the contour of the part.

Singamneni, Roychoudhury, Diegel, and Huang (2012) improved the algorithm of the cross product of four vectors by considering a vertical plane, which was passed through three consecutive surface points. Although their contributions laid the foundations of experimental CLFDM, they studied the generation/selection of data points to produce the offset curved layer directly from the G-code or M-code generated by a CAM software, and as a result, the printing trajectory was limited to those points. The curved layer slicing by modeling and fitting the surface using B-spline was further developed by Jin, Du, He, and Fu (2017), who fitted an STL mesh surface with a B-spline surface with two independent parameters (*u* and *v*). They modified the original tessellated surface to reduce the number of triangles of the STL file and then fitted the surface. The first printing path (the author recommends it to be along one of the edges of the design) defines the next paths, which are generated by a certain offset (equidistant). They reported some limitations in the processing of the part surface due to the CAD and CAM software used. Patel, Kshattriya, Singamneni, and Choudhury (2015) optimized the number of curved layers needed for printing by preserving the critical features. They modeled a B-spline surface using selected critical points and generated curved offset layers optimized by the application of genetic algorithms and surface-surface intersection. Their results included simulations but a non-physical implementation. Allen and Trask (2015) used a delta configuration system and generated the printing path of a surface or skin, which was defined mathematically, with a core component (infill pattern) having a contrasting but yet distinct structural or physical functions. This was also demonstrated by Llewellyn-Jones, Allen, and Trask (2016) via producing models with esthetic and structural properties. The algorithm consisted of converting the analytical surface in a grid *XY* following the points in order and calculating *z* for dynamic movements.

McCaw and Cuan-Urquizo (2018) discussed a procedure to fabricate non-planar lattice-shells on non-planar equation-defined surfaces (parametric Bèzier surfaces of arbitrary order), whereas Cuan-Urquizo et al. (2019) generated and fabricated a lattice using rectangular equations and studied the mechanical behavior when force is applied. McCaw and Cuan-Urquizo (2020) presented a mathematical approach to parametrize lattices onto Bèzier surfaces to fabricate non-planar chirality lattices and studied them under cyclic loading. Conformal printing has emerged as a process to deposit silver inks on curvilinear surfaces to create conductive paths (Adams et al., 2011). However, some recent studies have shown the path planning for conformal 3D printing. For instance, Shembekar, Yoon, Kanyuck, and Gupta (2019) proposed an algorithm for conformal printing using non-planar layers and evaluated the differences in roughness between a surface finish when printed using planar layer slicing and the proposed algorithm. The algorithm aims at collision-free trajectory planning using a projection method: (a) a grid is created on the *XY* plane (0.5 mm spacing); (b) vertices of each triangle are projected to the *XY* plane; (c) specific points of the grid belong to a particular triangle; (d) the equation of the plane of the triangle is calculated from three vertices; and then

(e) the *z* value for these points inside the triangle is calculated and mapped back to the non-planar surface. A zigzag pattern at two different angles is used to improve the finishing of the surface.

Alkadi, Lee, Bashiri, and Choi (2020) proposed an algorithm to locate conformally one tessellated structure onto a second tesselapplated surface (substrate). The algorithm achieves the following: (a) it generates a curved slicing surface by offsetting the top of the substrate; (b) it obtains the boundaries of the pattern to be printed by the intersection of the structure and the slicing surface; and (c) 2D printing patterns are projected to create 3D patterns. To achieve conformal trajectories, this algorithm has the restriction that the bottom of the 3D structure must fit the freeform substrate, and in the case of a mismatch, the free spaces are filled to connect both structures. The algorithm outputs the G-code for 3D printing. A different approach for printing quality improvement was proposed by Ahlers, Wasserfall, Hendrich, and Zhang (2019a, 2019b), who developed an algorithm for planar and non-planar slicing. Their main contribution is the detection of the parts suitable to be printed using non-planar slicing assuring collision-free toolpaths, using a simplified printhead model defined by the maximum non-planar angle and the maximum non-planar height. The printing trajectories presented are focused to achieve smooth surfaces (zigzag pattern). Feng et al. (2021) implemented a five-axis machine (a delta printer plus a platform rotating) and proposed an algorithm for curved layer material extrusion. Their main contribution is the reduction of the material used for the mandril to achieve conformal curved printing; hence, the printing time is also reduced. They generated a conformal surface offset and a toolpath using the geodesic distance as the shortest zigzag along the facet edges of the STL file. The path planning consisted in equidistantly offsetting the starting curves.

6.2 | 3D printing: Food rheology properties applicable to extrusion process

In order to maintain its shape upon deposition, the extrusion process in 3D printing requires food materials of consistency and viscosity that produces smooth flow via the nozzle. The characterization of food materials can be seen through the lenses of structural properties via microscopic techniques (self-supporting layers), as well as mechanical properties via texture analysis (firmness, hardness), rheological analysis (viscosity, loss, and elastic moduli), and material ingredient formulation (respective ratio and moisture). To estimate and improve printing performance particularly in extrusion-based printing, the understanding of material properties (especially rheological properties) of food materials is, therefore, important (Jiang et al., 2019). Food materials for extrusion printing should be pseudoplastic fluids with suitable shear-thinning behavior, be easily extruded from the printer nozzle under an appropriate shear force, and can undergo rapid structural recovery solidification following extrusion (Liu, Liu, Wei, Ma, et al., 2018). Texture, being among the quality framework of 3D-printed food products, can be modified via the manipulation of the target design's internal structure. The design requires adequate construct/holding so as to support the structure sufficiently. This action is possible because 3D software is able to control the infill pattern/percentage (Mantihal et al., 2020).

For the extrusion-based 3D printing process, the rheological properties of materials, directly linked to composition, help determine their printability. Rheological properties of potato puree have been shown to be influenced by starch content (Liu, Liu, Wei, Ma, et al., 2018; Martínez-Monzó, Cárdenas, & García-Segovia, 2019; Yang, Zhang, Prakash, & Liu, 2018). During the extrusion process, the rheological properties of materials provide proper extrudability, binding different layers together, and supporting the deposited layers by weight (Liu et al., 2017). To evaluate the printing behavior/performance of food material (Jiang et al., 2019), examples of rheological properties like viscosity, yield stress (σ^0), storage modulus (G'), loss modulus (G''), and tan(δ), serve as critical indicators of the material's self-supporting abilities, storage characteristics, extrudability, and printability. Some of these properties will be discussed briefly below.

6.2.1 | Viscosity

An apparent viscosity, which has to be at the required level, is among vital parameters for extrusion-based 3D printing (Godoi et al., 2016). 3D printing food materials should possess sufficient mechanical strength that supports the weight of subsequently deposited layers (Wang, Zhang, Bhandari, & Yang, 2018); and should also have appropriate viscosity to go through the nozzle and adhere layer by layer (Liu, Liu, Wei, Ma, et al., 2018). In other words, the viscosity of the material needs to be low enough at high shear rates, to allow flow through a small nozzle. At the same time, however, the material has to quickly regain a high viscosity at rest to support the structure after deposition (Liu et al., 2017). The viscosity of printable food materials to decrease at increased shear rates would be indicative of a non-Newtonian pseudoplastic behavior with shear-thinning properties (Huang, Zhang, & Bhandari, 2019). Remember, pseudoplastic (food) materials are understood to typically behave in a non-Newtonian manner. This is a reflection of their (pseudoplastic [food] materials) capacity to possess a shear thinning behavior (Zhang et al., 2021).

For emphasis, the viscosity of a Newtonian fluid would not noticeably vary with the rate of deformation. In the ideal scenario, the zero viscosity, that is a situation where there is no resistance to shear stress, would appear at low temperatures, given that the second law of thermodynamics mandates that all fluids obtain positive viscosity (Landau & Lifshitz, 1987). However, both power law and exponential type models can help establish the relationship between concentration and apparent viscosity. Besides, as viscosity increases with concentration and water content, that of the paste would decrease (Chen, Zhang, Devahastin, & Yu, 2021; Liu, Zhang, & Ye, 2020). Viscosity profiles of potato puree in another study by (Martínez-Monzó et al., 2019) with different quantities of potato formulation at varying temperatures (10–30°C) revealed decreases in viscosity with increased temperatures. Therein, lower temperatures were found to help the food actualize a consistent structure. Liu et al. (2020) reported rice flour varieties would display varying viscosity behaviors, with some more viscous than others, attributed to their amylose content and network.

6.2.2 | Storage and loss modulus

The elastic and viscous modulus (G' and G'', respectively) of printable food materials showed frequency-dependent behavior. When the material experiences mechanical deformation, its elastic and viscous responses are represented by its storage (G') and loss modulus (G''), respectively. G' represents the amount of energy stored during shearing and can serve as an indicator of the material's stiffness or mechanical strength (Liu, Liu, Wei, Ma, et al., 2018; Steffe, 1996). In contrast, G'' represents the amount of energy dissipated due to the flow of the material. Thus, a suitable material for 3D printing should possess high G' to provide shape retention. Enough mechanical strength is necessary for the material to support the 3D-printed structure. Stiffer material can build more geometrically complex structures with overhangs and bridges without collapse. Furthermore, a suitable material should possess low G'' to prevent spreading but if it's too low the material may fracture instead of flows during the extrusion process. Thus, G' well above G'' suggests a gel-like structure dominated by elastic behavior, which would favor the shape and retention ability of a printed object (Huang et al., 2019). The materials with higher G' have stronger shape retention for the extruded objects (Chen et al., 2019; Liu, Liu, Wei, Ma, et al., 2018; Liu et al., 2017). The G' is also strongly dependent on concentration. An increase in potato starch concentration led to an increase in G'' and G' (Liu et al., 2017). Shear stress increased with decrease in G' would portray breakdown of the internal structure of the material. However, increased moisture content would significantly decrease both G' and G'', as did happen in mashed potatoes (Liu, Tang, et al., 2020).

6.2.3 | Dynamic mechanical loss tangents (tan $\delta = G''/G'$)

The degree of viscoelasticity of the material, also obtained from the loss tangent (tan δ), refers to the ratio of G'' to G'. Loss tangent value smaller than 1 depicts a predominantly elastic behavior, and greater than 1 depicts a predominantly viscous behavior (Liu et al., 2017). A high tan δ value indicates that the material as with a more fluid-like behavior, and a low tan δ value indicates a more solid-like behavior, but with poor fluidity (Liu et al., 2017; Yang, Zhang, Prakash, & Liu, 2018). A recent study on extrusion-based 3D printing indicates that inks with tan $\delta < 0.1$ may be harder to extrude and produce broken lines due to poor fluidity (Liu et al., 2017; Wang et al., 2018).

6.2.4 | Yield stress (σ^0)

The yield stress is defined as the point where the internal structure of the material starts to break down that is, the material goes from behaving like an elastic solid to flowing like a fluid. (Steffe, 1996). It can be used to assess the suitability of food materials for extrusion-based 3D printing where the yield stress should be low enough so that the material can be extruded but not too low that once extruded, the material will spread under its weight. The yield stress is related to the ability of the material to keep its shape under gravity and the stresses generated by material layers deposited on top of it (Lille, Nurmela, Nordlund, Metsä-Kortelainen, & Sozer, 2018). Higher yield stress value, which reflects the mechanical strength of materials is crucial for supporting the subsequently deposited layers and maintaining printed shapes during the deposition process. Higher concentrations could contribute to higher σ^0 values, which would lead to better resistance to deformation. Thus, there would be more stacked layers without printing defects and high resolutions of the printed structures (Chen, Xie, Chen, & Zheng, 2018; Lille et al., 2018). G' and σ^0 can be used together to predict the mechanical strength of a material. Materials with suitable G' and σ^0 would exhibit a better shape retention capability and high resolutions of printed samples (Chen et al., 2018). Both parameters have been found to increase with increased starch concentration (Liu et al., 2017). High structural strength at rest (G') may not suffice to ensure good printability of material, but that a certain degree of resistance to external stresses (yield stress) would be required as well. The rate of structure recovery after cessation of shear also plays a role in shape-stability after printing and (Lille et al., 2018) concluded that high yield stress was required to achieve good shape stability after printing.

Furthermore, rheological models established to explore the relationship between the rheological properties abound, especially the material composition using the flow behavior index (n) and flow consistency coefficient (K) (Sun et al., 2018). Flow behavior or flowability is among the key requirements of any food material to achieve smooth extrusion during 3D printing (Krishnaraj, Anukiruthika, Choudhary, Moses, & Anandharamakrishnan, 2019). Shear-thinning characteristics are closely linked with the flowability of the material through the nozzle (Anukiruthika, Moses, & Anandharamakrishnan, 2020). Rheological models (e.g., Hershel–Bulkey, Williamson, Power Law, Bingham, Casson models, etc.) have been applied to explain the ideal flow behavior for printable food materials.

Álvarez-Castillo et al. (2021) fitted the flow data obtained from the viscosity profiles of plasma protein doughs to the model developed by Williamson for shear-thinning materials (Equation 1);

$$\eta = \frac{\eta_0}{1+(K.\gamma)^m}, \quad (1)$$

where η_0 is the zero-shear rate-limiting viscosity, at low shear rates; K is the consistency coefficient, and m is a dimensionless shear-thinning index.

Equation (1) was further modeled to describe the flow behavior of the printable doughs by introducing a time-concentration factor a_c in Equation (2).

$$\frac{\eta}{\eta_0}=\frac{1}{1+[K\cdot(a_c\cdot\gamma)]^m}. \tag{2}$$

The author concluded that all the samples displayed a very shear-thinning behavior, with *m* values generally close to the unity, which is the theoretical maximum value allowed for stable flow. Also, other studies (Liu et al., 2017; Martínez-Monzó et al., 2019; Yang, Zhang, Bhandari, & Liu, 2018) fitted the flow curves to the Herschel–Bulkley model in Equation (3) as follows.

$$\tau=\tau_0+K\gamma^n, \tag{3}$$

where τ means shear stress (Pa), τ_0 yield stress (Pa), *K* is the consistency index (Pa.s^n) and *n is* the flow behavior index. Regression analysis was also conducted to calculate the τ_0 and *n* of individual potato-based samples.

Similarly, the Herschel–Bulkley equation is a widely used model for pseudoplastic materials. For a pseudo-plastic material, $n < 1$ is ideal (Chen et al., 2019). Liu et al. (2017) indicated that *n* values for all potato mixtures in his study were less than 1, meaning non-Newtonian flow behavior. Martínez-Monzó et al. (2019) also calculated the apparent viscosity at a constant shear rate of 50 s^{-1} using Equation (4);

$$\eta_{ap}=\left({}^{\tau_0}\!/_{\gamma}\right)+K\gamma^{n-1}, \tag{4}$$

where η_{ap} is the apparent viscosity.

The power-law model (Equation 5) is also widely used for shear-thinning food materials (Chen et al., 2021; Krishnaraj et al., 2019; Liu, Bhandari, Prakash, Mantihal, & Zhang, 2019; Liu, Liang, Saeed, Lan, & Qin, 2019; Liu, Tang, et al., 2020).

$$\tau=K\gamma^n, \tag{5}$$

where *k* is the flow consistency index (Pa.s^n), γ is the shear-rate (s^{-1}), and *n* is the flow behavior index (dimensionless). All the printable samples showed shear thinning behavior with $n < 1$.

However, Dankar et al. (2018a), Dankar, Haddarah, el Omar, Sepulcre, and Pujolà (2018b), and Dankar, Pujolà, et al. (2018) tried to fit the experimental data to actualize their best mathematical equation or model (Hershel–Bulkey, Casson Model, Power Law, Bingham). These authors described Bingham model as the best model to fit the flow characteristics of the studied potato puree samples, and at the same time, evaluating the effect of additives such as agar-agar, soybean lecithin, sodium alginate, and glycerol. The Bingham model is described by the following equation;

$$\tau=\tau_0+\eta_p\gamma, \tag{6}$$

where τ is the shear stress (Pa), σ^0 is the yield stress (Pa), η_p is the viscosity (Pa.s) and γ is the shear rate (s^{-1}).

The authors further applied the Cox–Merz rule to these potato-additive complexes. The empirical Cox–Merz rule (Cox & Merz, 1958) states that values of the complex viscosity (η^*) and the steady shear viscosity (η) must have equal magnitudes at equal values of frequency (ω) and shear rate (γ) as described in Equation (6).

$$\eta(\gamma)=\eta^*(\omega)|_{\gamma=w}. \tag{7}$$

The relationship between dynamic complex viscosity (η^*) and the shear viscosity data (η) in the frequency range 0.1 to 10 s^{-1} was studied for all the potato puree samples. Parallel dependencies of $\eta^*(\omega)$ and $\eta(\gamma)$ were obtained for all the samples. As detected in most food systems, the complex viscosity was greater than the apparent viscosity, indicating that these purees did not obey the Cox–Merz rule.

Therefore, a multiplicative horizontal shift factor (α) was introduced into the original equation as shown in Equation (7).

$$\eta(\gamma)=\eta^*(\alpha.\omega)|_{\gamma=w}. \tag{8}$$

The shift factor α was observed to increase with an increase in all the additive concentrations in the potato puree samples, which implied the combined effect exerted by the additives on modifying the internal structure of the potato puree at their respective higher concentrations. The author concluded that the modified Cox–Merz rule obtained in their study has potential importance for the determination of the rheological properties of food materials combined with different additives as well as for direct predictions of textural characteristics.

Another engineering principle was found in the study carried out by Liu, Bhandari, et al. (2019) and Liu, Liang, et al. (2019). The yield stress (flow stress) was described to be closely related to the minimum force required to initiate a flow of material. This relationship can be described in Equation (8) below;

$$P_{\text{min}}=\left(\frac{4L}{D}\right)\tau_{\text{yield}}, \tag{9}$$

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

During extrusion-based food printing processes, the low yield stress is highly desirable as the extrusion is not continuous but starts and stops frequently during printing. Aside from the yield stress, the required pressure to maintain a continuous flow would depend on the viscosity and shear-thinning behavior of food materials. Therefore, in conjunction with the power-law model, the coefficients *K* and *n* could give a better understanding of the material's flow behavior according to the following Equation (9)

$$Q=\frac{\pi R^3}{\frac{1}{n}+3}\left(\frac{\Delta P}{L}\frac{R}{2K}\right)^{1/n}, \tag{10}$$

where *Q* means the flow rate, *R* means the radius tube, ΔP means the pressure drop, and *L* means the length of tube length. A low *K* and *n* are necessary to control the moderately low or adequate pressure for a continuous flow (Liu, Zhang, Bhandari, & Yang, 2018).

Generally, the shear-thinning behavior of mixtures is an ideal property during 3D printing. A low *n* indicates strong shear-thinning behavior and materials with this behavior could be easily extruded out due to low viscosity with the application of shear stress (Yang, Zhang, Prakash, & Liu, 2018). Higher coefficient index '*K*' reflects the viscosity of mixtures and *K* values have been found to decrease when the moisture content and temperature increase while mashed potato samples became easier to keep a continuous flow when moisture content increased (Liu, Zhang, & Ye, 2020). Materials with low viscosity and *K* values could easily be extruded, but when combined with low yield stress and G' values, the extruded parts could not attain proper mechanical strength to support the following deposited layers thus resulting in the compressed deformation and poor resolution, while materials with suitable G' and τ_0 showed better shape stability (Liu et al., 2017). The materials with very high viscosity and *K* values also could not be easily extruded out thus resulting in broken extrusion thread and poor structure. The highly desirable materials for extrusion during 3D printing therefore should not only possess suitable τ_0 and G' to be capable of maintaining printed shapes but also have relatively low *K* and *n* be easily extruded out from nozzle tip in an extrusion-based type printer.

Furthermore, the qualitative correlation between the rheological properties of food materials especially starch dough or pastes, and its printability for rice flour has been reported (Liu, Tang, et al., 2020; Theagarajan, Moses, & Anandharamakrishnan, 2020). The printability of the rice starch/flour would depend on the amount of water, the swelling pattern, the viscoelasticity of the material supply, and the interactions between the molecules. Understanding the rheology of starch materials can explain how its properties change upon interaction with water, also providing insights on its state of dispersions, emulsions, and gels. The associated viscoelastic properties can be affected by many factors, such as cultivar types, composition, water content, and the capacity of hydrogen cross-linking amylose.

7 | EXTRUSION MECHANISM IN 3D PRINTING: SOME ESSENTIALS INVOLVING MATERIAL FLOW AND CONFIGURATION

7.1 | Some 3D extrusion essentials for material flow

In extrusion-based printing, the rheological properties of food materials are essential, particularly for 3D printing performance. Specifically, extrusion-based printing requires food materials to be pseudoplastic fluid-like with suitable shear-thinning behavior. This is so that under an appropriate shear force, it could be easily extruded from the printer nozzle, and be capable of rapid structural recovery solidification. It might be a challenge to predict the effect of extrusion through the nozzle. That is why the knowledge of such rheological properties as flaw behavior index (*K*), flow characteristic index (*n*), loss modulus (G''), storage modulus (G'), and yield stress (σ^0), is very useful. It is crucial to mention that the ability of the matrix to self-support rests on yield stress (σ^0) and G' whereas the important role in extrudability and printability rests on *K* and *n* parameters. The shape and strength of the printed food material/object, together with adherence to (previously) deposited layers must be well balanced (Jiang et al., 2019; Liu, Zhang, Bhandari, & Yang, 2018).

Texture component remains crucial in the quality framework of 3D-printed food products, and can be modified via the manipulation of the target design's internal structure. The design requires construction as well as holding some intricacy in order to hold the support structure sufficiently. This action is possible because 3D software is able to control the infill pattern/percentage (Mantihal et al., 2020). For emphasis, there are a number of factors influencing 3D food printing specific to accuracy and precision, according to Liu et al. (2017), which include extrusion-based, SLS based, binder jetting, and Inkjet types. Specific to extrusion-based types, three mechanisms can apply in 3D food printing, namely: air pressure, screw- and syringe-based methods. Godoi et al. (2016) showed that food properties like moisture, rheological, and thermal properties, as well as specific cross-linking mechanisms enhance the success of 3D printing. Liu et al. (2017) further reiterated that for the extrusion-based type printer to progress 3D printing, the highly desirable materials should have a suitable elastic modulus (G0) and yield stress (σ^0) capable of maintaining printed shapes, as well as relative low flow behavior index (*n*) and consistency index (*K*) to enhance the extruding process out from its nozzle. Critical to the quality of printed constructs, Liu et al. (2017) also noted processing parameters like nozzle diameter, height, extrusion rate, and nozzle moving speed.

It is important to throw more light on the extrusion mechanism, especially as it associates with the control of the material flow. In particular, this extrusion mechanism would involve the extruder component within the 3D printer. Essentially, it provides some clue about how the flow of materials would differ as well as the ease at which either the paste, puree, or dough materials would get deposited. The popular extrusion mechanisms include syringe, pneumatic, and screw-based (Dankar et al., 2018b). For the syringe-based mechanism, a stepper motor drives the extrusion process, while the food materials are put in a syringe. The plunger is directly controlled by the stepper motor to push the food material out of the nozzle. It is suitable for most paste and semi-solid materials, as it allows for greater control of material flow, although time lag experienced at the beginning and toward the final phase of the printing process is one of the limitations of this mechanism (Dankar et al., 2018b).

Compared to the extrusion mechanism, the pneumatic mechanism is much different. This is because the pneumatic mechanism is typically driven by the air pressure, which is facilitated by a (pneumatic) pump that supplies sufficient force to control the cartridge and subsequently, through the nozzle in order to deposit the food material. Importantly, the pneumatic mechanism has been considered to work efficiently with mostly liquid materials at a low viscosity (Sun et al., 2018). But, it is also capable of controlling multiple print heads. Response delays are also believed to be minimal when compared to the syringe mechanism (Huang, 2018). Conversely, the screw-based mechanism is different from the other two, as it allows for the continuous sustenance of the feed materials, whereas the earlier two mechanisms (that is, syringe and pneumatic systems) only permit the batch-like feeding of the materials for the reason that the syringes/cartridges are rather mostly of a small volume, ranging from 30 mL to 130 ml, which is a major limitation during their repetitive printing process(es) (Pusch, Hinton, & Feinberg, 2018). However, for the screw type, a feed hopper directly releases food materials into the cartridge, before they are conveyed to the nozzle by the screw for continuous printing. This can be described as an abridged version of the food extrusion process and 3D printing, because of the similarity in structure. However, the food materials directly come in contact with the printer components, and as such safety precaution, in terms of the type of materials, used for the machine components such as the feed hopper, screw and nozzles should be ensured (Sun et al., 2018). This type can also handle solid materials, although, it would be most inappropriate for delicate soft food materials (Huang, 2018).

7.2 | Some 3D extrusion essentials for configuration

The extrusion-based 3D food printing configuration is depicted in Figure 9, which reflects the categories of extrusion-based food printers, namely: (a) Cartesian; (b) Delta; (c) Polar; and (d) SCARA configurations (Figure 9a–d) (Creative Machines, 2020; Dankar et al., 2018a). The Cartesian configuration is easier to design, maintain and calibrate, and it is commonly used by most printers (refer to Table 4). It consists of *X*, *Y*, and *Z* axes for the left to right movement of the build platform; nozzle movement from front to back as well as its up and down motion (Sun et al., 2018). Open-source software is often available for this type of configuration. Relative movements of three bearings support often control the delta configuration, while the print platform may be fixed. Reduced maintenance and cost are major advantages because it consists of less number of components. It is also faster, but more difficult to control than the Cartesian type (Huang, 2018). The delta printer configuration is such that the printer nozzle is mounted on the base intersecting three carriages. In this, the controlled movement is positioned by the three carriages relative to each other, and as such, carries little weight on the base, making its movement faster than that of Cartesian configuration (Horvath, 2014). The delta configuration could be reversible, able to switch from free moving tool for printing, to the fixed tool for extruding paste (Anzalone, Wijnen, & Pearce, 2015). Generally, this printer type appears more complicated for calibration and modification compared to the Cartesian printers (Huang, 2018).

Technically, the polar coordinate system involves the location of a point, which corresponds to an angle and distance in a circular plane. 3D printers using this configuration type are very few and are still under development. It usually takes a smaller space compared to the cartesian and delta types, plus it has a spinning platform, while its

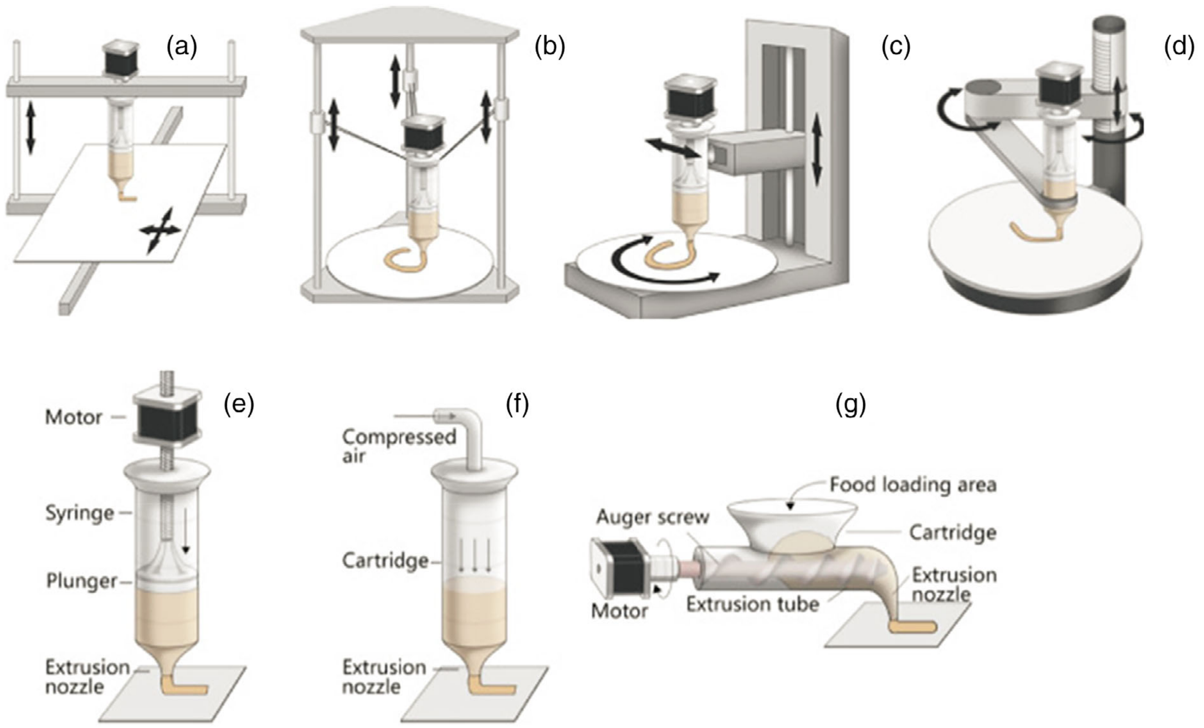

FIGURE 9 Extrusion-based 3D food printing configuration (a–d) (a) cartesian (b) delta (c) polar (d) SCARA; & Mechanism (e–g) (e) syringe (f) pneumatic (g) screw (reproduced from Sun et al., 2018 with permission from Elsevier B.V.)

nozzle movement goes up and down to cover the *Z*-axis, and left to right to cover *X* and *Y* tangentially. Its performance is believed to be of higher speed with minor mechanical errors and minimum calibration. Examples of 3D Food Printers with this configuration include; XOCO 3D printer (Ontwerp, 2021) and the TNO food printer (Van der Linden, 2015). The SCARA (Selective Compliant Assembly Robot Arm) configuration, although more compact and expensive than the others, is relatively a new type, easy to build and modified for 3D printing. It consists of a robot arm moving along the *X*-*Y* plane and an additional actuator to move along the *Z*-axis. An example is the Sanna food printer, a concept by Creative Machines Lab (Creative Machines, 2020; Huang, 2018; Sun et al., 2018).

Additionally, both material flow and configuration are essential in achieving optimization in 3D food printing processes. Indeed, several conditions that need to be optimized in 3D food printing, include, but are not limited to mechanical force generated by extrusion mechanisms, material formulation, temperature, etc. (Martinez-Monzo et al., 2019). Different food material mixtures require different mechanical forces (Dankar et al., 2018a). Also, the temperature may be related to the material flow rate through the nozzle. The temperature, in this case, can be categorized into two parts; the temperature of the food material (either for gel, paste, puree, or dough), as well as the printing temperature of the extruder. Chocolate is mostly printed at temperatures above (for solid chocolate) or room temperature (for liquid chocolate), while food materials like dough, cheese, and meat, etc. are mostly printed at room temperature. Some food printers also have temperature control features to accommodate a wide variety of food ingredients apart from chocolate, such as the Wiiboox Sweetin food printer.

8 | EXTRUSION-BASED 3D FOOD PRINTING: UNIQUENESS, SUITABILITY, AND PRINTABILITY OF FOOD MATERIALS

What makes the extrusion-based printing unique has largely been the system by which it operates with, that is, through a syringe nozzle, pneumatic or screw-based system (Sun et al., 2018). It is a generally used technique due to its ability to process many foods, such as mashed potatoes (Southerland, Walters, & Huson, 2011), chocolates (Hao et al., 2010), cookie dough (Lipton et al., 2010), soft cheeses (Le Tohic, O'Sullivan et al., 2018), hydrogels and fibers (Lille et al., 2018; Wang et al., 2017), and blends of fruits and vegetables (Severini, Derossi, Ricci, Caporizzi, & Fiore, 2018). If employed with more than one nozzle, this technique has the capacity to provide numerous combinations and decrease any emerging processing constraints for food production (Liu, Zhang, & Bhandari, 2018; Liu, Zhang, Bhandari, & Yang, 2018). Technically, the uniqueness of extrusion-based printing can also be underpinned by, for instance, maintaining the compatibility between specific printing parameters and its corresponding printed substance. Besides effectively modulating the essential process parameters, as well as monitoring the properties and composition of the food material itself (Dankar et al., 2018a; Liu et al., 2017), the extrusion-based printing process parameters should be controlled and modified by the food (printing) operator, so as to ensure a successful printing process and good object quality. Nonetheless, the critical process parameters that can influence the final resolution of the (emergent) food product can include the print speed, nozzle height, and size (Derossi et al., 2018; Hao et al., 2010). To make the 3D printing process better particularly entails the use of parameters such as extrusion temperature (°C), printing speed (mm/s), layer height (mm), fill pattern or density (%), nozzle size (mm), shell thickness (mm) have to be considered to enhance the success of extrusion-based food printing (Lille et al., 2017). Additionally, monitoring food material composition/properties like rheology, density, texture, and microstructure are imperative. This is because it aids in predicting the printability behavior of particular food material during 3D printing for reference purposes, and also helps in assembling a complex shape with many layers that are stable enough to maintain its profile for a long time after deposition (Dankar, Pujolà, et al., 2018; Dankar et al., 2018a; Lipton et al., 2010, 2015; Yang, Zhang, Prakash, & Liu, 2018). As a result, more researches are being undertaken to improve the suitability of extrusion-based printing techniques for food materials (Liu et al., 2017; Sun et al., 2018). TNO in conjunction with Barilla Pasta Company successfully printed pasta using wheat semolina and water (Van der Linden, 2015).

Largely, the 3D printing of food material appears dependent on the rheological properties, as well as liquid–solid transition response to compositional/environmental changes (Zhang et al., 2021; Zhu, Stieger, van der Goot, & Schutyser, 2019). Rheological properties would involve the plastic-nature of the material, whereas the liquid–solid transition response would be underpinned by various transition phenomena like fat crystallization and gelling of hydrocolloids, which might be induced by cold, cross-linking agents or heat (Zhang et al., 2021). Hao et al. (2010) characterized the material property of chocolate and investigated the relationship between process parameters and the resultant property of the final product. Lille et al. (2017) also designed healthy novel food products which are high in fiber, protein, and low in fat or sugar. Liu et al. (2017) investigated the rheological properties of the mashed potatoes with the addition of potato starch and their 3D printing behavior. There are other workers (Dankar, Pujolà, et al., 2018; Martínez-Monzó et al., 2019; Yang et al., 2017) who have demonstrated the rheological properties of food materials would be influenced by their composition. Given that food materials remain complex/diverse, a good understanding of both the process parameters and material properties is important, if successful (3D food) printing were to be achieved. Process parameters such as temperature, shear force, pressure, extrusion rate, nozzle diameter, nozzle height, nozzle movement speed, printing speed, etc., are all critical to the quality of food constructs (Hamilton, Alici, & Panhuis, 2018).

Printability in the context of 3D printing simply refers to when a selected printer successfully prints a material and at the same time maintaining the object's shape and structural integrity (Zhang et al., 2021). Printability also refers to the ability of a 3D food printer to deposit food materials sequentially in layers, and successfully create a print object, according to the design model (Lipton et al., 2015;

TABLE 5 Printability of food materials in relation to extrusion conditions, mechanisms, configuration, and print object quality tests

Extrusion conditions	Extrusion mechanism	Printer configuration	Food materials investigated	Print object quality tests	References
Hot-melt extrusion	Screw	Cartesian	Chocolate	Line measurement for deposition uniformity;	Hao et al. (2010)
Hydro-gel forming extrusion	Syringe	Cartesian	Hydrocolloids such as cellulose, xanthan gum, gellan gum, gelatin, locust bean gum. Foods such as ketchup, Greek yogurt, cheese, mashed potato, chocolate, jam, ground ham, peanut butter, bean paste, cookie dough, sugar paste	Cylinder geometry (deformation rate using an optical 3D scanner: Degree of deformation as a function of the height of deposition)	Kim, Bae, and Park (2017)
Room temperature extrusion	Pneumatic	Cartesian	Starch, milk powder, cellulose nanofiber, rye bran, oat, and faba bean	Qualitative observation/visual inspection of printing process and object (precision, shape stability, and clogged nozzles); lattice design	Lille et al. (2017)
Room temperature extrusion	Screw	Cartesian	Potato, tetrahalose and potato starch, purple sweet potato powder (1%)	Visual inspection (precision and shape stability)	Liu, Liu, Wei, Ma, et al. (2018)
Room temperature extrusion	Syringe	Delta	Wheat dough	Cylinder geometry	Severini, Derossi, and Azzollini (2016)
Room temperature extrusion; HFE	Syringe	Delta	Xanthan gum, modified starch, carrot puree	Line (optimal settings of volumetric extrusion rate, nozzle speed, and layer height) and cylinder (rheology and infill levels)	Huang (2018)
Room temperature extrusion	Syringe	Cartesian (open-source printer)	Cheese	Cylindrical geometry	Le Tohic et al. (2017)
Room temperature extrusion	Screw	Cartesian	Surimi fish and NaCl	Line test	Wang et al. (2018)
Room temperature extrusion	Syringe	Delta	Fruit-based formula: Fresh bananas, dried mushrooms, canned white beans, dried non-fat milk, lemon juice, pectin powder ascorbic acid	Weight and height measurements of the extrudate	Derossi et al. (2017)
Room temperature extrusion	Pneumatic	Polar (biobot 1 extrusion printer)	Vegemite and mermite		Hamilton et al. (2017)
Room temperature	Screw	Cartesian	Lemon juice and potato starch	Line (extrusion speed) and cylinder (print parameters) tests	Yang et al. (2017)

Martínez-Monzó et al., 2019). The printability of food materials in relation to extrusion conditions, mechanisms, configuration, and print object quality test has been summarized in Table 5. Clearly, we demonstrate that whereas the extrusion conditions can involve hot-melt, hydro-gel as well as room temperature forms, the major extrusion mechanisms of screw, syringe, and pneumatic would vary with printing configurations across different food materials (Derossi, Caporizzi, Azzollini, & Severini, 2018; Hamilton, Alici, & Panhuis, 2018; Hao et al., 2010; Huang, 2018; Kim et al., 2017; Le Tohic et al., 2018; Lille et al., 2018; Liu, Zhang, & Bhandari, 2018; Severini et al., 2016; Wang et al., 2018; Yang, Zhang, Bhandari, & Liu, 2018). Furthermore, the print object quality test range between line (Hao et al., 2010; Huang, 2018; Wang et al., 2018; Yang, Zhang, Bhandari, & Liu, 2018), cylinder geometry (Kim et al., 2017; Le Tohic et al., 2018; Severini et al., 2016), qualitative observation/visual inspection (Lille et al., 2018; Liu, Zhang, & Bhandari, 2018), as well as exudate weight/height measurements (Derossi et al., 2018). Evidently from Table 5 and particularly from the extrusion standpoint, the research looking into the printability of various food materials research is on the increase. For printability to be effective and realistic, more attention should be given to extrusion conditions/mechanisms, printer configuration, food materials investigated, and print object quality test(s).

Severini et al. (2016) studied the printability of a cereal-based food product (that is, dough), and the quality of cooked samples. The two variables of interest were infill percentage and layer height. Layer height increases with the height of samples, but decreases the diameter. The infill level was found more important for changes in solid fraction, and at the same time, strongly related with the breaking strength. Kim et al. (2017) studied the printability of food gels for 3D food printing applications through various assessment techniques such as dimensional analysis, textural assessment, and rheology test using edible hydrocolloid as control materials. Moreover, such (food) material properties like rheology, viscosity, together with other physicochemical/mechanical properties contribute in determining the printability of a food material (Lipton et al., 2015; Martínez-Monzó et al., 2019). For emphasis, rheology and viscosity must be clearly differentiated. Practically and dependent on predicted (mechanical behavior) based on micro/nano-structure detail on one hand, the rheology (of food material) principally concerns an extension of continuum mechanics wherein material flow demonstrates cumulation of elastics, plastic, and viscous behavior, typically combining elasticity and (Newtonian) fluid mechanism (Morrison, 2001). On the other hand, it is believed that the viscosity largely depends on the fluid state of the (food) material, such its pressure, rate of deformation, and temperature (Landau & Lifshitz, 1987). Other workers like Dankar et al. (2018b) investigated the effects of food additives on the mechanical and microstructural properties of potato puree for extrusion-based 3D printing. Apparently, researches in extrusion-based 3D printing tends to reveal more the importance of getting the best out of the printing process parameters to suit the rheological characteristics of food material to be printed, which contributes to the eventual quality outcome of the final product. Thus, the rheological properties of food materials would have a direct link to the composition, and this would be very crucial to establish the printability. Elsewhere, the printability of cheese (Le Tohic et al., 2017), surimi fish gel (Wang et al., 2017), and fruit-based snack (Derossi et al., 2017) has been investigated.

9 | FOOD MATERIAL TYPES ASSOCIATED WITH EXTRUSION-BASED 3D PRINTING: SOME KEYS

Food materials are mostly liquid, solid, or semi-solid. However, they are prepared as pastes, purees, or dough for extrusion-based 3D printing. They have been classified into printable, non-printable materials as well as alternative ingredients based on their printability (Sun, Peng, et al., 2015). Sugar-rich powders and flours, which are used to produce confectionaries such as cake, chocolate, candy, ice-cream, etc. have been successfully printed, as their raw materials in form of paste or dough exhibit less difficulty during printing, and also possess enough shape stability after deposition, and may or may not require further post-processing after printing. They are mostly consumed as snacks, and not as main foods (Liu et al., 2017; Sun, Zhou, et al., 2015). Traditional foods such as cereals such as rice, legumes such as beans, animal protein such as meat and fish, as well as fruits and vegetables, which are daily consumed by people. Although they were termed unprintable (Godoi et al., 2016; Liu, Liu, Wei, Ma, et al., 2018), researches are ongoing to achieve perfect prints, by optimizing the material compositions. Printing of these materials is mostly limited to their puree form or achieved through the addition of starch or hydrocolloids to facilitate easier extrusion, and hold their shape post-deposition. Also, they require cooking, as they cannot be consumed in their raw form.

Generally, food materials fit for printing are required to exhibit high shear thinning and pseudo-plastic non-Newtonian behavior (Dankar, Pujolà, et al., 2018; Dankar et al., 2018a; Liu et al., 2017). This is critical for a good print object quality. Food printing often requires multiple ingredients of a wide range, including processed components such as cheese, sauce, spices, or dough to fundamental compositions in terms of ingredients such as sugars, proteins, and carbohydrates. As a result, for each food material, printing process, and post-processing method, the relationship between inputs and outputs data must be monitored by determining the key parameters such as viscosity, texture, printing speed and time, etc. (Sun, Peng, et al., 2015). The cooking properties of printed materials, their biochemical, microbiological, and biological variation should also be considered (Lille et al., 2017).

For 3D food printing to be effective, the (food) materials that are to be used, according to Jiang et al. (2021), have to be extrudable and supportable. Smooth extrusion of food materials especially from the nozzle typifies good extrudability. The avoidance of any form or shape of collapse/deformation specific to each layer typifies good supposition. Additionally, the food materials are largely dependent on such factors as applicability, printability, as well as post-processing, which lays the foundation for any form of optimization of food materials in 3D printing (Godoi et al., 2016; Jiang et al., 2021). Another aspect of printability that is worth mentioning is the incorporation of starch or gums, which can also be seen to play the role of rheology/texture modifier to the material composition. Indeed, such (that is, starch/gum) incorporation is believed to enhance the 3D facility to achieve a good print object quality. For instance, Liu et al. (2017) studied the rheological properties of the mashed potatoes with the addition of potato starch and their 3D printing behavior, and good printability was obtained at 2% potato starch. Furthermore, Yang et al. (2017) studied the printability of lemon juice gel with the addition of potato starch, and 10% potato starch was the optimal concentration. Additionally, Dankar, Pujolà, et al. (2018) studied the effects of agar, lecithin, glycerol, and alginate on the mechanical and microstructural properties of potato puree, and good product resolution was achieved at 0.5–1.5% alginate and 0.5–1% agar.

10 | MAJOR FOOD MATERIAL CONSTITUENTS AND THEIR IMPACT IN EXTRUSION-BASED 3D FOOD PRINTING

For a given food material to be printed, the flowability during the extrusion process especially from the nozzle of the printer needs to be adequate, and at same time, able to hold its structure (during extrusion and after deposition) (Jiang et al., 2019). Besides rheological properties (storage modulus, yield stress, consistency index, and flow behavior index) associated with 3D food printer parameters (nozzle speed and the layer height and thickness) being key for effective food printability, the food composition/matrix specific to macronutrient constituents can, to a great extent, have some impact on the (food) printing performance (Péreza, Nykvista, Brøggera, Larsena, & Falkeborga, 2019). In mind that food is a complex system with largely varied physical and chemical properties (Ofoedu et al., 2021), approaches to capitalize on the complex nature of food with different nutrients have been of interest, so as to broaden the application range of 3D printing to various novel food products with personalized nutrition (Liu, Bhandari, et al., 2019; Liu, Liang, et al., 2019). Elsewhere, dough (with or without additives) was found among successful food materials for 3D printing due to its rheology, consistency, and solidifying property after printing (Jiang et al., 2019). The variation in the macronutrient composition of the dough probably influenced this desirable characteristic. Therefore, in an attempt to shed more light to how the varying constituents in food materials are influenced by 3D printing, we will focus below only on the impact of carbohydrates, proteins, and lipids on the printing performance of extrusion-based 3D-printed food.

10.1 | Carbohydrates

Relevant information regards the impact of carbohydrate composition on 3D food printing is on the increase. During food processing, different hydrocolloids and other additives are commonly used to achieve the desired properties in the final food product (Péreza et al., 2019). In a study conducted by Dankar et al. (2018b), the rheological properties and 3D printing performance of mashed potato containing additives such as glycerol, lecithin, and alginate were studied by determining their viscosity data. Results showed an exponential decrease in shear viscosity when mashed potato is combined with the different additive at 0.5 and 1.0% concentration, which indicates a non-Newtonian shear-thinning behavior. On the other hand, an increase in alginate concentration caused a corresponding increase in mashed potato viscosity while a decrease in viscosity of mashed potato was observed when glycerol concentration was increased. Furthermore, pectin, as a carbohydrate whose gelling properties depend on temperature, pH, pectin source, etc. (Sharma, Naresh, Dhuldhoya, Merchant, & Merchant, 2006) has been studied for its gelling ability in 3D-food printing (Derossi et al., 2017; Vancauwenberghe et al., 2017). Gels containing pectin concentration of 15 gL^{-1} generated elastic gels while gels containing pectin concentration of 35–55 gL^{-1} generated less viscous or elastic gels (Péreza et al., 2019).

Potato starch is another potential raw material employed in 3D-food printing as a gelling agent given its capacity to retain water, according to Liu, Liu, Wei, Ma, et al. (2018). These workers showed that the inclusion of 2% potato starch to mashed potato produced a printed object with excellent extrudability, printability, which supported its structure after deposition, unlike the samples with no potato starch, which could not retain its shape after printing. Moreover, increasing the concentration of potato starch to about 4% presented good shape retention but with poor extrudability due to printing difficulties. Jeon, Yu, Kim, and Park (2021) investigated the production of customized food using 3D printing. These workers showed the addition of 3% xanthan gum to a formulated nano emulsion-filled gel systematically increased the storage modulus (G') and loss modulus (G''), indicating a dimensional stability of the printed material (nano emulsion-filled gel matrix). However, the decrease in G' and G'' was detected when incorporating xanthan gum of more than 5%, and as a result, the printing performance of the food was negatively affecting.

Other carbohydrates used as hydrocolloids (methylcellulose, guar gum, gellan gum, hydroxypropyl methylcellulose, and locust bean gum) for 3D-food printing have been reported (Kim et al., 2018). Moreover, there are some factors that influence the texture/viscosity analysis, which would significantly affect the printing performance. Such factors range from moisture content of the reference material, varying composition of ingredient-mix, additives, to rheological properties of the food material, (extrudability, printability, and structure retention after deposition) during the 3D printing (Lipton et al., 2010). For instance, Martınez, Oliete, and Gómez (2013) found that the inclusion of an expanded wheat flour on dough preparation decreased its extensibility with increased plasticity, indicating good characteristics when forming sharp geometric-printed structures. Liu, Liang, et al. (2019) investigated the properties of 3D printed dough formulated from a mixture of wheat flour, olive oil, frozen dried mango powder, and water, and showed that changes in the ratio of ingredient concentrations significantly influenced the printing performance. Thus, the printability of the food material, in that given context, depends greatly on the dough performance for the reason that these workers showed some printed objects were observed to have no basic form, blurred lines, disorderly lines, messy and discontinuous lines; leaving only a few with good molding properties. Given that 3D printing technology is an emerging food processing method, it is imperative that more compatible 3D food materials be developed in their right proportions for enhanced printability with good attributes.

10.2 | Proteins

Besides carbohydrate, proteins have been demonstrated to influence the printing performance of 3D-printed foods. According to Ofoedu et al. (2021), proteins are macromolecules consisting of one or more units of amino acids linked together in chains. Generally, most proteins (except for gelatin) cannot be used directly as a raw material for 3D-food printing unless they are denatured by a compound (for instance, strong base or acid) of through external stress (temperature and mechanical strength) (Jiang et al., 2018). Gels made of fish surimi (a high source of protein) were prepared by Wang et al. (2017) to study the printing performance of these gels using 3D printing technology. Results showed that adding 1.5% NaCl gave the most suitable 3D printing material that exhibited a non-Newtonian pseudoplastic behavior with shear-thinning properties. Furthermore, in a study by Chuanxing, Qi, Hui, Quancheng, and Wang (2018), peas protein was used as an additive to a potato starch-base to improve the structure of the printed food. The data obtained indicated that the incorporation of 1% pea protein resulted in a high precision printed structure while on increase in protein content of more than 2% negatively affected the final printed structure owed to decreased cross-linking.

In the preparation of a dough snack with different concentrations of yellow mealworm powder for an extrusion-based 3D printing operation, Severini, Azzollini, Albenzio, and Derossi (2018) showed that increasing the concentration of mealworm powder negatively affected the printing performance of the food material due to reduced dough performance (softer dough). Additionally, in a study on extrusion-based 3D printing with cellulose fiber, starch, and protein (faba bean protein concentrate, oat protein, concentrate, and milk powder) as raw materials, the most suitable structure stability and printing precision were achieved with a semi-skimmed milk powder (SMP) which was blended with cellulose nanofiber and starch. Also, transglutaminase enzyme, a potential additive for 3D printing of meat products has been studied. Printed pastes of scallops and turkey with the incorporation of transglutaminase were achieved but a section of the scallop-based print deformed while the turkey-based print contracted (shrinked) inwards after deep frying and cooking, respectively (Lipton et al., 2010). All these abovementioned debate show the impact of proteins would have on the printing performance for 3D structures and its potential is enhanced via cross-linking (chemical or ionotropic) and complex coacervate formation to create self-supporting hydrogels. This has been discussed in detail in other published literature (Jiang et al., 2018; Péreza et al., 2019).

10.3 | Lipids

In addition to the carbohydrate and protein, the lipids are among important macronutrients affecting the printing performance of 3D foods. Typically, the lipids are triglycerides formed by the esterification of three fatty acids with a glycerol molecule (Jiang et al., 2018). The quality of lipid (fat or oil) composition in the ingredient-mix formulation for 3D-food printing affects the functionality of the printed food material especially its melting point range, gloss, solid fat index, taste, shape retention, and crystal structure (Godoi et al., 2016). However, it is believed the degree of fat saturation and chain length would influence the 3D-rinted food material and its characteristics. For instance, saturated fats have more desirable physical properties, melts at desirable temperature of 30–40°C, and are stable during storage. This can be found in chocolate, a good material for extrusion-based 3D printing, containing cocoa butter that melts easily to provide desirable self-supporting properties to the deposited layers upon cooling. Notably, the fat crystallization of cocoa butter offers excellent mechanical properties in chocolates that are responsible for its stable and complex structure formation (Jiang et al., 2018; Péreza et al., 2019).

Lille et al. (2018) evaluated the printability of milk powders by analyzing SMP and semi-skimmed milk powder (SSMP) of equal total solid content of 60%. The results showed that the SSMP with a lipid content of 9% displayed excellent printability compared to SMP that resulted in a paste that was impossible to print due to its lipid content of 0.4%. This research suggests that lipids can act as lubricants for enhancing the flowability (flow behavior) of the material formulation for extrusion-based 3D printing. This corroborates the findings of Liu, Bhandari, et al. (2019) and Liu, Liang, et al. (2019) especially on how lipid influences the material characteristics of dough. Incorporation of olive oil in the dough for 3D printing caused a significant reduction in dough hardness by shielding or reducing the starch and gluten network from forming complexes, thus yielding a softer dough (Kapusniak & Tomasik, 2006; Sudha, Srivastava, Vetrimani, & Leelavathi, 2007). Interestingly, the enhancement of dough performance upon lipid addition for 3D printing could be due to both lubrication behavior and plasticity property within the ingredient-mix formulation. Thus, the fluidity of the food material would improve to achieve a desirable texture surface of the printed food (Liu, Bhandari, et al., 2019; Liu, Liang, et al., 2019; Pareyt & Delcour, 2008). Also, in evaluating the impact of different concentration (0, 3, 6, and 9%) of butter on the printability of dough, Yang, Zhang, Prakash, and Liu (2018) observed that the inclusion of butter up to 6% gave the best flawless shape, followed by 9 and 3%, while the exclusion of butter from the formulation produced the most irregular shape.

11 | SOME BOTTLENECKS/CONCERNS STILL APPLICABLE TO EXTRUSION-BASED 3D FOOD PRINTING

There are still some concerns regarding 3D food printing, largely because its acceptance as new food technology (or product) is dependent upon the conviction that potential consumers have about its acceptability and worth (Lupton, 2017). To increase consumer awareness of 3D food printing technology, therefore, would require addressing some of the bottlenecks/concerns still applicable to extrusion-based 3D food printing, from sensory qualities of the final product, shelf-stability of printed foods, safety and cleaning of 3D food printers, post-processing of 3D food printing, cost of 3D food printers, and its technical capabilities, and each of these will be discussed briefly.

11.1 | Sensory quality of printed foods

A consumer study regarding 3D-printed food reported seven images of different types of 3D-printed food products displayed for participants (Lupton & Turner, 2016). These workers included confections made from sugar; carrots made from carrot puree; snack made from ground insects; a food product made from gelled chicken puree; a food product made from gelled vegetable purees and sauce; pizza; as well as pasta and chocolates. The content of the food, which was described the extent to which its ingredients would be either tasty, healthy, or natural, and the sensory qualities of the food, (in terms of natural food-like appearance) directly linked to sensorial perceptions such as taste and texture (Lupton & Turner, 2016). This demonstrated the ambiguity of consumer responses to novel foods. Most were based on old customs, beliefs, values, and lifestyles around food, particularly about ideas of natural food, the physical appearance and supposed texture of food, the edibleness, and the processing involved.

Mantihal, Prakash, and Bhandari (2019) investigated the textural modification of 3D-printed dark chocolate by varying internal infill structure, and the extrusion type was used, at a temperature of 32°C, and printing speed of 70 mm/s. Their sensory evaluation and consumer perception study showed the 3D-printed dark chocolate had improved texture, and consumers preferred how samples appeared, particularly those with 25% and 50% infill percentages compared to those with 100%. These results demonstrated how sensory evaluation and consumer perception are among key commercial factors of 3D-printed dark chocolate and its application. Wang et al. (2021) opined that processing technologies should not be employed to the detriment of sensory quality of food materials but should aim to minimize the nutritional losses and sensory changes, and at the same time, improve the printing performance.

11.2 | Shelf-stability of printed foods

Researches on the shelf-stability of 3D-printed food product are gradually gaining attention. It is believed that most printed foods have a limited shelf life. This is attributed to other food processing technologies, in which raw materials and unprocessed ingredients usually have a longer shelf life than the final food products (Dankar et al., 2018a). Also, a study conducted reported that purees or doughs prepared for 3D printing, for example, would often experience a breakdown in their structural rheology after hours of production. The 3D-printed material would, therefore, be undesirable after long hours (Lipton et al., 2015). However, this does not validate whether printed foods are shelf-stable or not. Even though 3D food printing has been restricted to “based on demand” conditions, such that food items are created only hours before sale or consumption.

Severini, Derossi, et al. (2018), in the process of printing fruit and vegetable smoothie, as the 3D samples were more appreciated compared to the non-printed ones, detected a bacterial load of 4.28 Log CFU/g after printing. This study showed that printed fruit and vegetable smoothie can carry a reasonable microbial load, which would contribute to reduce its shelf-life. Besides, some other researchers reported 3D printing technology involving edible gel materials as gaining interest given its shelf life extension, which they (researchers) linked to the touch-free fabrication process (Rahman et al., 2020). Nonetheless, Wang et al. (2021) understood that a major challenge has been how to ensure both longevity and safety 3D-printed foods. Largely, almost all 3D-printed foods tend to possess a limited shelf life. Therefore, 3D printing processes must adhere to robust hygiene and quality regulations prior to it being applied in either factories or restaurants.

11.3 | Cleaning/safety, and post-processing activities involved in 3D food printers/printing

Most 3D food printers are difficult to clean, due to the type of available nozzle structure, even when equipped with a removable feed tube. The food material mostly gets in contact with the nozzle, during printing. Based on food safety, and the microbiological implications, adequate cleaning, therefore, becomes necessary. Also, the use of nozzles made with food-grade materials is of utmost importance. Severini, Derossi, et al. (2018), in the process of printing fruit and vegetable smoothie, suggested that 3D food printing would need to consider the sanitization of each part that has had contact with the food prior to its application, whether it be in the restaurants or even at the industrial scale. Sugar-rich foods such as frosting, cheese, candy, and chocolate are among the food components employed in 3D printing that do not require any post-processing. Some food materials like pizza or cookie dough, however, do require further processing, for example, cooking (baking, boiling, frying) or freeze-drying prior to consumption. This processing may alter the textural properties that might be unfavorable to the consumer (Sun et al., 2018). A 3D-printed pizza made by the BeeHex printer, due to its ultra-thin crust texture, produced different mouthfeel, swallowing, and chewing experiences after baking. Immediately after baking, the taste was found to liken to that of normal pizza, but turned out to be crusty-like crackers after few minutes (BeeHex, 2018). Howbeit, a challenge for 3D Food Printers currently is that there are believed not to have cooking capabilities.

11.4 | Cost of 3D food printer

3D Food Printers are generally considered pretty expensive and not so affordable, especially to the small-scale food industry. Its manufacture appears to focus on professional confectioners, cake artists, and decorators who want to produce creative, beautiful, and intricate designs in chocolate and sugar fondants (Godoi et al., 2016). About that, the cost-effectiveness of 3D printing technology is only advantageous because the cost of complex designs only depends on the amount of material used, unlike when the cost of highly intrinsic molds will need to be added to the production cost of a food product, to get the desired geometry and design (Pallottino et al., 2016; Porter et al., 2015). However, out of the several domestic food printers currently being developed, only a small number are available to consumers, still very expensive when compared with typical domestic kitchen appliances. The expectation is that, as 3D printers within the affordability range of consumers and small businesses become available, it will provide avenues for new researches and increase the diversity/range of food materials, which would bring about new categories of products. This would be beside those that already known, such as chocolates, candies, decorations made of sugar, and items made from puréed food.

11.5 | Technical capabilities/challenges of currently available food printers

For consumers, it might be inconsequential to use a printer to make food products of different shapes when some (food products) can be quickly and easily made by hand, which appears to restrict the current food printers and the length of time needed to print some types of food. The potential advantages of food printing, therefore, become more enhanced as printing technology improves and the speed of printing increases. For instance, the current feed tubes or cartridges are only able to hold a small amount of food material, such that during continuous or repeated printing, the printing process has to be put on hold, for refueling. This challenge would be minimized if a continuous feeding system were to be employed. In addition, the technical capabilities of the currently available food printers would align well with 3D extrusion-based printing approach.

Furthermore, to tackle the current limitations confronting extrusion-type of 3D printing, more efforts are needed especially in integrating the desirable cooking capabilities with the current designs of the food printer, from the likes of infrared heating beds, to the cooking elements in the nozzle (Creative Machines, 2020; Wegrzyn, Golding, & Archer, 2012). An example is the research conducted by the Creative Machines Lab that integrated an infrared cooking element with their recent design of food printer “Sanna” (Creative Machines, 2020; Sun et al., 2017). Considering that technical challenges are major drawbacks of this above-mentioned infrared cooking element integration, this specialist area needs more ample research particularly to generate ample data, especially with respect to cost considerations. Additionally, there are a number of other technical challenges/difficulties that need to be resolved, some of which would include: (a) the preparation of food materials for printing; (b) ensuring food safety standards; (c) establishing supply chains for food tubes/cartridges; (d) the speed of the printing process, and (e) the technology's cost and reliability, etc. Additionally, these technical challenges/difficulties have to tackled adequately prior to having this technology adopted across a broader range of uses (Dankar et al., 2018a; Liu et al., 2017; Pallottino et al., 2016)

12 | CONCLUDING REMARKS AND FUTURE HOPES

This perspective review has successfully scoped the potentials of 3D extrusion-based printing in resolving food processing challenges. This was performed by considering a number of areas, from

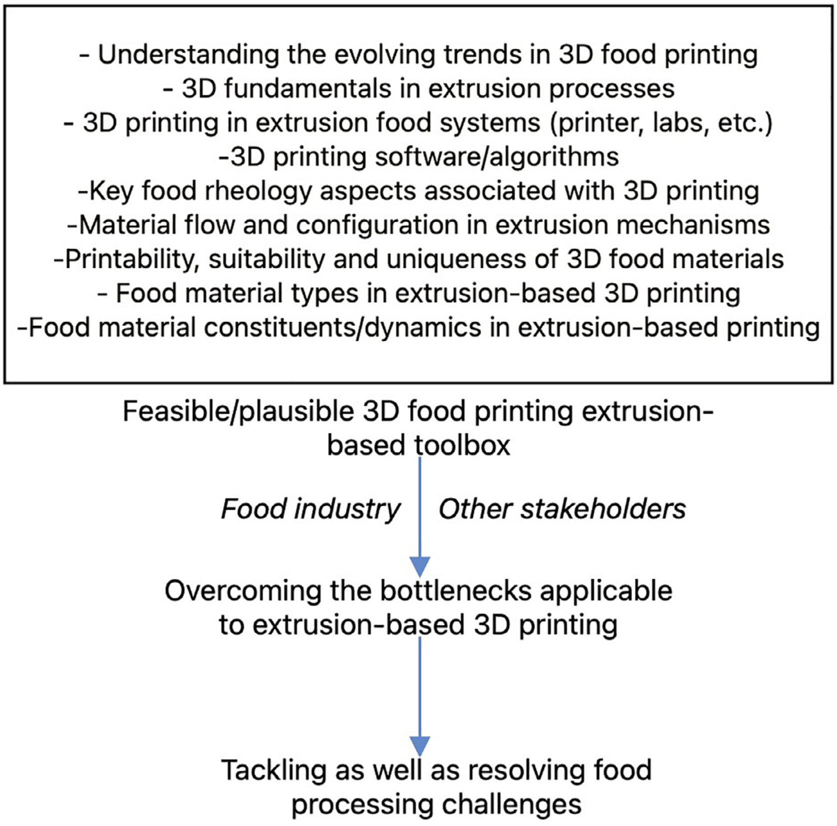

FIGURE 10 Feasible/plausible 3D food printing extrusion-based toolbox, which can serve as means for food industry and other stakeholders, not only to overcome the existing bottlenecks/concerns that would be associated with this technology, but also, to help resolve/tackle the emerging food processing challenges especially for the short- and long- term. This 3D-food printing extrusion-based toolbox should be considered relevant for debate by other researchers in this subject area

understanding the evolving trends, 3D printing fundamentals (in extrusion processes), to the food material constituents/dynamics that occupy the extrusion-based 3D printing domain. The authors herein believe that this current review has provided, what can be considered a feasible/plausible 3D-food printing extrusion-based toolbox, which would be relevant for the food industry and other stakeholders. Prior to embracing extrusion-based 3D printing, the food industry needs to fully understand the potentials this technology would provide in enhancing food material properties/types. By embracing as well as understanding the intricacies of the 3D extrusion-based printing, not only would it be plausible for the food industry and other stakeholders to overcome some of the bottlenecks/concerns above-enumerated in this current work, but also, it would be possible for them to resolve as well as tackle the emergent food processing challenges especially for the short and long term. To demonstrate this, Figure 10 depicts the feasible/plausible 3D-food printing extrusion-based toolbox, which the authors herein opine should be considered relevant for debate by other researchers in this subject area.

Thus far, it appears the extrusion-based method would provide the greater applicability, contributing to elevating as well as situating 3D food printing to be among innovative technologies with an upscale vision for (food) processing, and increasingly promising edge compared with the other 3D printing methods. Indeed, extrusion-based 3D printing provides a wide range of positives and support to the food industry sectors, from enhancing food product manufacturing, equipment calibration/prototyping, as well as packaging/production, to formulating/streamlining the complex geometries in food production, as well as new textures that emerge with enhanced nutritional value. Through specific formulation mixtures, new food products would emerge with exquisite shapes and designs. Remember, a 3D food printer typically creates and builds these intricate (3D) designs by depositing food materials in layers. Additionally, powdered, liquid, or paste food materials such as sugar-rich flours, liquid chocolate, and puréed food can serve as printing materials. Indeed, the food industry needs to fully understand the binding mechanisms and thermodynamic properties associated with the food materials, as well as the configuration mechanism surrounding this specific food printing technique in order to successfully utilize the extrusion-based 3D printing. The authors believe that the information provided herein about 3D extrusion-based food printing would contribute in convincing the agro-food product industry/sector especially about how promising this technology would be in resolving their (agro-food product) processing challenges.

Moreover, a lot of effort is still required into developing improved calibrating techniques for 3D printing materials, design improved methods that would help to better the integration of data, as well as establish improved algorithmic representations of printed foods. Besides, the printability, suitability and uniqueness of 3D extrusion-based food printing continues to be underpinned by, among others, the food material and its shape and structural integrity, the essential/specific printing as well as process parameters, etc. Given the rheological complexities associated with extrusion-based 3D food printing, there is the need for both the industry and researchers to come together to brainstorm on the (rheological) shifts that happen during the (extrusion) process, which tends to make the material unsuitable (for 3D printing). Additionally, there is still paucity of relevant information specific to how the agro-food industry perceives the 3D printing extrusion applications. Therefore, more awareness-focused campaign-based studies are required that will focus on providing more detailed enlightening of 3D printing process technicalities. And this kind of study has to be championed by the food industry themselves, as this would help them to better embrace as well as utilize this technology, more effectively, and efficiently. Moreover, the extrusion-based 3D printing still needs further investigations specific to the material formulation of food ingredients, the safety of the final food product, and cost/technical aspects of the food printer itself.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

AUTHOR CONTRIBUTIONS

AOA, LS, OJA, CEO, JSC, HTD, SHM and WAR were involved in conceptualization, data curation, investigation, and writing—original draft. CORO and MK were responsible for funding and resources. IS, CMO, CIO, CORO, MK, and RPFG were involved in software; coordination, and supervision; writing—review and editing.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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REFERENCES

3D Systems. (2018). *3D systems previews new chocolate 3D printer CocoJetTM at 2015 International CES*. Retrieved from http://www.3dsystems.com/de/node/7563

3DigitalCooks. (2018). *Pinya3: A 3D food printer platform [R/OL]*. http://www.instructables.com/id/Pinya3-a-3d-foodprinter

Adams, J. J., Duoss, E. B., Malkowski, T. F., Motala, M. J., Ahn, B. Y., Nuzzo, R. G., … Lewis, J. A. (2011). Conformal printing of electrically small antennas on three-dimensional surfaces. *Advanced Materials*, *23*, 1335–1340. https://doi.org/10.1002/adma.201003734

Ahlers, D., Wasserfall, F., Hendrich, N., & Zhang, J. (2019a). 3D printing of nonplanar layers for smooth surface generation. In *Proceedings of the 2019 IEEE 15th international conference on automation science and engineering (CASE), Vancouver, BC, Canada, 22–26 august 2019* (pp. 1737–1743).

Alkadi, F., Lee, K. C., Bashiri, A. H., & Choi, J. W. (2020). Conformal additive manufacturing using a direct-print process. *Additive Manufacturing*, *2020*(32), 100975. https://doi.org/10.1016/j.addma.2019.100975

Allen, R. J., & Trask, R. S. (2015). An experimental demonstration of effective curved layer fused filament fabrication utilising a parallel deposition robot. *Additive Manufacturing*, *8*, 78–87. https://doi.org/10.1016/j.addma.2015.09.001

Álvarez-Castillo, E., Oliveira, S., Bengoechea, C., Sousa, I., Raymundo, A., & Guerrero, A. (2021). A rheological approach to 3D printing of plasma protein based doughs. *Journal of Food Engineering*, *288*, 110255. https://doi.org/10.1016/j.jfoodeng.2020.110255

Anukiruthika, T., Moses, J. A., & Anandharamakrishnan, C. (2020). 3D printing of egg yolk and white with rice flour blends. *Journal of Food Engineering*, *265*, 109691. https://doi.org/10.1016/j.jfoodeng.2019.109691

Ahlers, D., Wasserfall, F., Hendrich, N., & Zhang, J. (2019b). Conformal additive manufacturing using a direct-print process. *Additive Manufacturing*, *32*, 100975. https://doi.org/10.1016/j.addma.2019.100975

Anzalone, G. C., Wijnen, B., & Pearce, J. M. (2015). Multi-material additive and subtractive prosumerdigital fabrication with a free and open-source convertible delta RepRap 3-D printer. *Rapid Prototyping Journal*, *21*, 506–519. https://doi.org/10.1108/RPJ-09-2014-0113

Baiano, A. (2020). 3D printed foods: A comprehensive review on technologies, nutritional value, safety, consumer attitude, regulatory framework, and economic and sustainability issues. *Food Reviews International*, 1–31. https://doi.org/10.1080/87559129.2020.1762091

BeeHex. (2018). *Beehex robots 3D print pizza*. http://beehex.com/

Byflow. (2018). *Focus 3D printer*. https://www.3dbyflow.com/home-en

CandyFab. (2006). *The CandyFab project*. https://candyfab.org/

Chakraborty, D., Reddy, B. A., & Choudhury, A. R. (2008). Extruder path generation for curved layer fused deposition modeling. *Computer-Aided Design*, *2008*(40), 235–243. https://doi.org/10.1016/j.cad.2007.10.014

Chen, H., Xie, F., Chen, L., & Zheng, B. (2018). Effect of rheological properties of potato, rice and corn starches on their hot-extrusion 3D printing behaviors. *Journal of Food Engineering.*, *244*, 150–158. https://doi.org/10.1016/j.jfoodeng.2018.09.011

Chen, J., Mu, T., Goffin, D., Blecker, C., Richard, G., Richel, A., & Haubruge, E. (2019). Application of soy protein isolate and hydrocolloids based mixtures as promising food material in 3D food printing. *Journal of Food Engineering*, *261*, 76–86. https://doi.org/10.1016/j.jfoodeng.2019.03.016

Chen, J., Zhang, M., Devahastin, S., & Yu, D. (2021). Novel alternative use of near-infrared spectroscopy to indirectly forecast 3D printability of purple sweet potato pastes. *Journal of Food Engineering*, *296*, 110464. https://doi.org/10.1016/j.jfoodeng.2020.110464

Choc Edge. (2018). *Choc creator from*. http://chocedge.com

Chuanxing, F., Qi, W., Hui, L., Quancheng, Z., & Wang, M. (2018). Effects of pea protein on the properties of potato starch-based 3D printing materials. *International Journal of Food Engineering*, *14*. https://doi.org/10.1515/ijfe-2017-0297

Chung, C. I. (2000). *Extrusion of polymers: Theory and practice*. Cincinnati, OH: Hanser.

Cox, W. P., & Merz, E. H. (1958). Correlation of dynamic and steady flow viscosities. *Journal of Polymer Science*, *28*(118), 619–622.

Createbot. (2018). *3D food printer*. https://www.3dprintersonlinestore.com/createbot-3d-food-printer

Creative Machines Lab. (2020). *Digital food*. http://www.creativemachineslab.com/digital-food.html

Cuan-Urquizo, E., Martínez-Magallanes, M., Crespo-Sánchez, S. E., Gómez-Espinosa, A., Olvera-Silva, O., & Roman-Flores, A. (2019). Additive manufacturing and mechanical properties of lattice-curved structures. *Rapid Prototyping Journal*, *2019*(25), 895–903. https://doi.org/10.1108/RPJ-11-2018-0286

Dankar, I., Haddarah, A., el Omar, F., Sepulcre, F., & Pujolà, M. (2018a). 3D printing technology: The new era for food customization and elaboration. *Trends in Food Science and Technology*, *75*, 231–242. https://doi.org/10.1016/j.tifs.2018.03.018

Dankar, I., Haddarah, A., el Omar, F., Sepulcre, F., & Pujolà, M. (2018b). Assessing the microstructural and rheological changes induced by food additives on potato puree. *Food Chemistry*, *240*, 304–313. https://doi.org/10.1016/j.foodchem.2017.07.121

Dankar, I., Pujolà, M., el Omar, F., Sepulcre, F., & Haddarah, A. (2018). Impact of mechanical and microstructural properties of potato puree-food additive complexes on extrusion-based 3D printing. *Food Bioprocess Technology*, *11*, 2021–2031. https://doi.org/10.1007/s11947-018-2159-5

Derossi, A., Caporizzi, R., Azzollini, D., & Severini, C. (2018). Application of 3D printing for customized food: A case on the development of a fruit-based snack for children. *Journal of Food Engineering*, *220*, 65–75. https://doi.org/10.1016/j.jfoodeng.2017.05.015

Diegel, O., Singamneni, S., Chowdhury, R., Gibson, I., & Huang, B. (2010). Curved-layer fused deposition modelling. *Journal for New Generation Sciences*, *8*, 95–107.

Diegel, O., Singamneni, S., Huang, B., & Gibson, I. (2011). Getting rid of the wires: Curved layer fused deposition modeling in conductive polymer additive manufacturing. *Key Engineering Materials*, *467*, 662–667. https://doi.org/10.4028/www.scientific.net/KEM.467-469.662

Dovetailed. (2018) *Dovetailed-webpage*. www.dovetailed.co

Edutechwiki. (2018). *3D food printing*. https://edutechwiki.unige.ch/en/3D_food_printing

Feng, C., Zhang, M., & Bhandari, B. (2019). Materials properties of printable edible inks and printing parameters optimization during 3D printing: A review. *Critical Reviews in Food Science and Nutrition*, *59*(19), 3074–3081.

Feng, X., Cui, B., Liu, Y., Li, L., Shi, X., & Zhang, X. (2021). Curved-layered material extrusion modeling for thin-walled parts by a 5-axis machine. *Rapid Prototyping Journal*, *27*, 1378–1387.

FoodJet. 2021. *FoodJet printing systems*. https://www.foodjet.com/article-on-3d-food-printing-using-a-foodjet-depositor

Formlabs. (2021a). *3D printing technology comparison: FDM vs. SLA vs. SLS*. https://formlabs.com/eu/blog/fdm-vs-sla-vs-sls-how-to-choose-the-right-3d-printing-technology/

Formlabs. (2021b). *Guide to selective laser sintering (SLS) 3D printing*. https://formlabs.com/eu/blog/what-is-selective-laser-sintering/

Giles, H. F., Jr., Wagner, J. R., Jr., & Mount, E. M., III. (2005). *Extrusion: The definitive processing guide and handbook*. Norwich, NY: William Andrew, Inc.

Godoi, F. C., Prakash, S., & Bhandari, B. (2016). 3D printing technologies applied for food design: Status and prospects. *Journal of Food Engineering*, *179*, 44–54. https://doi.org/10.1016/j.jfoodeng.2016

Guo, C., Zhang, M., & Bhandari, B. (2019). Model building and slicing in food 3D printing processes: A review. *Comprehensive Reviews in Food Science and Food Safety*, *18*(4), 1052–1069.

Hamilton, C. A., Alici, G., & Panhuis, M. (2018). 3D printing vegemite and marmite: Redefining "breadboards". *Journal of Food Engineering*, *220*, 83–88. https://doi.org/10.1016/j.jfoodeng.2017.01.008

Hao, L., Mellor, S., Seaman, O., Henderson, J., Sewell, N., & Sloan, M. (2010). Material characterization and process development for chocolate additive layer manufacturing. *Virtual and Physical Prototyping*, *5*(2), 57–64. https://doi.org/10.1080/17452751003753212

He, C., Zhang, M., & Fang, Z. (2020). 3D printing of food: Pretreatment and post-treatment of materials. *Critical Reviews in Food Science and Nutrition*, *60*(14), 2379–2392.

Horvath, J. (2014). The desktop 3D printer. In *Mastering 3D printing* (pp. 11–20). Berkeley, CA: Apress. https://doi.org/10.1007/978-1-4842-0025-4_2

Huang, B., Singamneni, S., & Diegel, O. (2008). Construction of a curved layer rapid prototyping system: Integrating mechanical, electronic and software engineering. In *Proceedings of the 2008 15th international conference on mechatronics and machine vision in practice, Auckland, New Zealand, 2–4 December 2008* (pp. 599–603).

Huang CY. (2018). *Extrusion-based 3D printing and characterization of edible materials* (Thesis in Chemical Engineering). University of Waterloo.

Huang, M., Zhang, M., & Bhandari, B. (2019). Assessing the 3D printing precision and texture properties of Brown Rice induced by infill levels and printing variables. *Food and Bioprocess Technology*, *12*(7), 1185–1196. https://doi.org/10.1007/s11947-019-02287-x

Hull, C. W. (1986). *Apparatus for production of three-dimensional objects by stereolithography*. US Patent 4,575,330:1–16.

Itis3d. (2016). *3D printer for multipurpose printing [N/OL]*. https://itis3d.com/3d-printer-multi-purpose-printing

Jeon, W. Y., Yu, J. Y., Kim, H. W., & Park, H. J. (2021). Production of customized food through the insertion of a formulated nanoemulsion using coaxial 3D food printing. *Journal of Food Engineering*, *311*, 110689.

Jiang, H., Zheng, L., Zou, Y., Tong, Z., Han, S., & Wang, S. (2019). 3D food printing: Main components selection by considering rheological properties. *Critical Reviews in Food Science and Nutrition*, *59*(14), 2335–2347.

Jiang, Q., Zhang, M., & Mujumdar, A. S. (2021). Novel evaluation technology for the demand characteristics of 3D food printing materials: A review. *Critical Reviews in Food Science and Nutrition*, 1–16. https://doi.org/10.1080/10408398.2021.1878099

Jin, Y., Du, J., He, Y., & Fu, G. (2017). Modeling and process planning for curved layer fused deposition. *International Journal of Advanced Manufacturing Technology*, *91*, 273–285.

Kapusniak, J., & Tomasik, P. (2006). Lipid microencapsulation in starch. *Journal of Microencapsulation*, *23*(3), 341–348.

Kewuyemi, Y. O., Kesa, H., & Adebo, O. A. (2021). Trends in functional food development with three-dimensional (3D) food printing technology: Prospects for value-added traditionally processed food products. *Critical Reviews in Food Science and Nutrition*, 1–38. https://doi.org/10.1080/10408398.2021.1920569

Kim, H. W., Bae, H. J., & Park, H. J. (2017). Classification of the printability of selected food for 3D printing: Development of an assessment method using hydrocolloids as reference material. *Journal of Food Engineering*, *215*, 23–32. https://doi.org/10.1016/j.jfoodeng.2017.07.017

Kim, H. W., Lee, J. H., Park, S. M., Lee, M. H., Lee, I. W., Doh, H. S., & 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

Krassenstein B. (2014). *Tytan 3D to launch a multi-material 3D printer which prints in salt, paper, food, adhesives and more [R/OL]*. https://3dprint.com/6893/tytan-3d-printer/

Krishnaraj, P., Anukiruthika, T., Choudhary, P., Moses, J. A., & Anandharamakrishnan, C. (2019). 3D extrusion printing and post-processing of fibre-rich snack from indigenous composite flour. *Food and Bioprocess Technology*, *12*(10), 1776–1786. https://doi.org/10.1007/s11947-019-02336-5

Lanaro, M., Forrestal, D. P., Scheurer, S., Slinger, D. J., SamLiao, S., Powell, S. K., & Woodruff, M. A. (2017). 3D printing complex chocolate objects: Platform design, optimization and evaluation. *Journal of Food Engineering*, *215*, 13–22.

Landau, L. D., & Lifshitz, E. M. (1987). *Fluid Mechanics (2nd Edition - Landau and Lifshitz: Course of Theoretical Physics)*, 2nd ed. (pp. 554), Oxford, UK: Elsevier Ltd.

Landoni B. (2015). *3Drag Choco [N/OL]*. https://www.open-electronics.org/3drag-is-now-printing-with-chocolate/

Le Tohic, C., O`Sullivan, J., Drapala, K. P., Chatrin, V., Chan, T., Morrison, A. P., … Kelly, A. L. (2018). Effect of 3D printing on the structure and textural properties of processed cheese. *Journal of Food Engineering*, *220*, 56–64. https://doi.org/10.1016/j.jfoodeng.2017.02.003

Li, S. (2016). Structure, processing and properties of 3D printable metallic materials. *Materials Technology*, *31*(2), 65. https://doi.org/10.1080/10667857.2016.1163019

Lille, M., Nurmela, A., Nordlund, E., Metsä-Kortelainen, S., & Sozer, N. (2018). Applicability of protein and fiber-rich food materials in extrusion-based 3D printing. *Journal of Food Engineering*, *220*, 20–27. https://doi.org/10.1016/j.jfoodeng.2017.04.034

Lipton JI, Arnold D, Nigl F, Cohen D., and Lipson, H. (2010). *Multi-material food printing with complex internal structure suitable for conventional post-processing*. In International solid freeform fabrication symposium. https://doi.org/10.26153/tsw/15245

Lipton, J. I., Cutler, M., Nigl, F., Cohen, D., & Lipson, H. (2015). Additive manufacturing for the food industry. *Trends in Food Science & Technology*, *43*(1), 114–123. https://doi.org/10.1016/j.tifs.2015.02.004

Liu, Y., Liang, X., Saeed, A., Lan, W., & Qin, W. (2019). Properties of 3D printed dough and optimization of printing parameters. *Innovative Food Science and Emerging Technologies*, *54*, 9–18. https://doi.org/10.1016/j.ifset.2019.03.008

Liu, Y., Liu, D., Wei, G., Ma, Y., Bhandari, B., & Zhou, P. (2018). 3D printed milk protein food simulant: Improving the printing performance of milk protein concentration by incorporating whey protein isolate. *Innovative Food Science and Emerging Technologies*, *49*, 116–126. https://doi.org/10.1016/j.ifset.2018.07.018

Liu, Y., Tang, T., Duan, S., Qin, Z., Zhao, H., Wang, M., & Li, C. (2020). Applicability of rice doughs as promising food materials in extrusion-based 3D printing. *Food and Bioprocess Technology*, *13*, 548–563. https://doi.org/10.1007/s11947-020-02415-y

Liu, Z., Bhandari, B., Prakash, S., Mantihal, S., & Zhang, M. (2019). Linking rheology and printability of a multicomponent gel system of carrageenan-xanthan-starch in extrusion based additive manufacturing. *Food Hydrocolloids*, *87*, 413–424. https://doi.org/10.1016/J.FOODHYD.2018.08.026

Liu, Z., Zhang, M., & Bhandari, B. (2017). 3D printing: Printing precision and application in food sector. *Trends in Food Science and Technology*, *69*, 83–94.

Liu, Z., Zhang, M., & Bhandari, B. (2018). Effect of gums on the rheological, microstructural, and extrusion printing characteristics of mashed potatoes. *International Journal of Biological Macromolecules*, *117*, 1179–1187. https://doi.org/10.1016/j.ijbiomac.2018.06.048

Liu, Z., Zhang, M., Bhandari, B., & Yang, C. (2018). Impact of rheological properties of mashed potatoes on 3D printing. *Journal of Food Engineering*, *220*, 76–82. https://doi.org/10.1016/j.jfoodeng.2017.04.017

Liu, Z., Zhang, M., & Ye, Y. (2020). Indirect prediction of 3D printability of mashed potatoes based on LF-NMR measurements. *Journal of Food Engineering*, *287*, 110137. https://doi.org/10.1016/j.jfoodeng.2020.110137

Llewellyn-Jones, T., Allen, R., & Trask, R. (2016). Curved layer fused filament fabrication using automated toolpath generation. 3D print. *Additive Manufacturing*, *3*, 236–243.

Lupton, D. (2017). 'Download to delicious': Promissory themes and sociotechnical imaginaries in coverage of 3D printed food in online news sources. *Futures*, *93*, 44–53.

Lupton, D., & Turner, B. (2016). I can't get past the fact that it is printed: consumer attitudes to 3D printed food. *An International Journal of Multidisciplinary Research*, *21*(3), 402–418. https://doi.org/10.1080/15528014.2018.1451044

Manrich, S. (2005). *Processamento de termoplastico*. São Paulo, Brazil, Artiliber Editora, São Paulo. Artliber Ed.

Mantihal, S., Kobun, R., & Lee, B.-B. (2020). 3D food printing of as the new way of preparing food: A review. *International Journal of Gastronomy and Food Science*, *22*, 100260. https://doi.org/10.1016/j.ijgfs.2020.100260

Mantihal, S., Prakash, S., & Bhandari, B. (2019). Textural modification of 3D printed dark chocolate by varying internal infill structure. *Food Research International*, *121*, 648–657. https://doi.org/10.1016/j.foodres.2018.12.034

Martınez, M., Oliete, B., & Gómez, M. (2013). Effect of the addition of extruded wheat flours on dough rheology and bread quality. *Journal of Cereal Science*, *57*, 424–429.

Martínez-Monzó, J., Cárdenas, J., & García-Segovia, P. (2019). Effect of temperature on 3D printing of commercial potato puree. *Food Biophysics*, *14*(3), 225–234. https://doi.org/10.1007/s11483-019-09576-0

McCaw, J. C., & Cuan-Urquizo, E. (2018). Curved-layered additive manufacturing of non-planar, parametric lattice structures. *Materials and Design*, *160*, 949–963.

McCaw, J. C., & Cuan-Urquizo, E. (2020). Mechanical characterization of 3D printed, non-planar lattice structures under quasi-static cyclicloading. *Rapid Prototyping Journal*, *2020*(26), 707–717.

Millen, C. I. (2012). *The development of a colour 3D food printing system* (Master thesis). https://mro.massey.ac.nz/handle/10179/4255

Mmuse. 2018. *Mmuse chocolate 3D printer*. https://www.3dprintersonlinestore.com/mmuse-touch-screen-chocolate-3d-printer

Morrison, F. A. (2001). *Understanding rheology*. Oxford, UK: Oxford University Press.

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

Natural Machines. (2020). *Foodini*. https://www.naturalmachines.com/press-kit/

Neto, I., Noritomi, P. Y., Silva, J. V. L., Freitas, M. S., & Silveria, Z. C. (2014). Development of an interchangeable head based on variable section screw applied to desktop 3-D printers. In P. J. da Silva Bartolo, A. C. de Lemos, A. M. Pereira, A. J. Mateus, C. Ramos, C. Dos Santos, et al. (Eds.), *High value manufacturing: Advanced research in virtual and rapid prototyping. Proceedings of the 6th international conference on advanced research in virtual and rapid prototyping, Leiria, Portugal, 1–5 October, 2013, UK* (pp. 19–23). CRC Press and Taylor & Francis.

Ofoedu, C. E., Iwouno, J. O., Ofoedu, E. O., Ogueke, C. C., Igwe, V. S., Agunwah, I. M., … Okpala, C. O. R. (2021). Revisiting food-sourced vitamins for consumer diet and health needs: A perspective review, from vitamin classification, metabolic functions, absorption, utilization, to balancing nutritional requirements. *PeerJ*, *9*, e11940. https://doi.org/10.7717/peerj.11940

Ontwerp M C. (2021). *XOCO chocolate printer*. www.michielcornelissen.com/

Palermo E. (2013) *Fused deposition modeling: Most common 3D printing method*. https://www.livescience.com/39810-fused-deposition-modeling.html/

Pallottino, F., Hakola, L., Costa, C., Antonucci, F., Figorilli, S., Seisto, A., & Menesatti, P. (2016). Printing on food or food printing: A review. *Food Bioprocess Technology*, *9*(5), 725–733.

Pareyt, B., & Delcour, J. A. (2008). The role of wheat flour constituents, sugar and fat in low moisture cereal-based products: A review on sugar-snap cookies. *Critical Reviews in Food Science & Nutrition*, *48*, 824–839.

Patel, Y., Kshattriya, A., Singamneni, S. B., & Choudhury, A. R. (2015). Application of curved layer manufacturing for preservation of randomly located minute critical surface features in rapid prototyping. *Rapid Prototyping Journal*, *21*, 725–734.

Péreza, B., Nykvista, H., Brøggera, A. F., Larsena, M. B., & Falkeborga, M. F. (2019). Impact of macronutrients printability and 3D-printer parameters on 3D-food printing: A review. *Food Chemistry*, *287*, 249–257. https://doi.org/10.1016/j.foodchem.2019.02.090

Porter, K., Phipps, J., Szepkouski, A., & Abidi, S. (2015). 3D opportunity serves it up - Additive manufacturing and food, In: *A Deloitte series on additive manufacturing*, London, UK: Deloitte University Press, pp. 1-20, https://www2.deloitte.com/content/dam/insights/us/articles/3d-printing-in-the-food-industry/DUP_1147-3D-opportunity-food_MASTER1.pdf

Procusini. (2018). *Procusini-webpage*. https://www.procusini.com/shop/

Pusch, K., Hinton, T. J., & Feinberg, A. W. (2018). Large volume syringe pump extruder for desktop 3D printers. *HardwareX*, *3*, 49–61.

Rahman, J. M. H., Shiblee, M. N. I., Ahmed, K., Khosla, A., Kawakami, M., & Furukawa, H. (2020). Rheological and mechanical properties of edible gel materials for 3D food printing technology. *Heliyon*, *6*(12), e05859.

RIG. 2018. *Robots in Gastronomy—Web page*. www.robotsingastronomy.com

Rodgers, S. (2016). Minimally processed functional foods: Technological and operational pathways. *Food Science*, *81*(10), 9–19. https://doi.org/10.1111/1750-3841.13422

Sanchez, L. C., Beatrice, C. A. G., Lotti, C., Marini, J., Bettini, S. H. P., & Costa, L. C. (2019). Rheological approach for an additive manufacturing printer based on material extrusion. *International Journal of Advanced Manufacturing Technology*, *105*, 2403–2414. https://doi.org/10.1007/s00170-019-04376-9

Severini, C., Azzollini, D., Albenzio, M., & Derossi, A. (2018). On printability, quality and nutritional properties of 3D printed cereal based snacks enriched with edible insects. *Food Research International*, *106*, 666–676.

Severini, C., Derossi, A., & Azzollini, D. (2016). Variables affecting the printability of foods: Preliminary tests on cereal-based products. *Innovative Food Science and Emerging Technologies*, *38*, 281–291.

Severini, C., Derossi, A., Ricci, I., Caporizzi, R., & Fiore, A. (2018). Printing a blend of fruit and vegetables. New advances on critical variables and shelf life of 3D edible objects. *Journal of Food Engineering*, *220*, 89–100. https://doi.org/10.1016/j.jfoodeng.2017.08.025

Sharma, B. R., Naresh, L., Dhuldhoya, N. C., Merchant, S. U., & Merchant, U. C. (2006). An overview on Pectins. *Times Food Processing Journal*, *51*, 44–51. https://doi.org/10.1016/j.steroids.2009.10.005

Shembekar, A. V., Yoon, Y. J., Kanyuck, A., & Gupta, S. K. (2019). Generating robot trajectories for conformal three-dimensional printing using nonplanar layers. *Journal of Computing and Information Science in Engineering*, *2019*(19), 031011.

Sher, D., & Tutó, X. (2015). Review of 3D food printing. *Temes de Disseny*, *31*, 104–117.

Singamneni, S., Roychoudhury, A., Diegel, O., & Huang, B. (2012). Modeling and evaluation of curved layer fused deposition. *Journal of Materials Processing Technology*, *212*, 27–35.

Southerland D, Walters P, Huson D. (2011). *Edible 3D printing [C]//Digital Fabrication Conference, NIP 27, 27th International Conference on Digital Printing Technologies* (pp. 819–822).

Steffe, J. F. (1996). *Rheological Methods in Food Process Engineering*. 2nd ed., East Lansing, MI: Freeman Press.

Sudha, M. L., Srivastava, A. K., Vetrimani, R., & Leelavathi, K. (2007). Fat replacement in soft dough biscuits: Its implications on dough rheology and biscuit quality. *Journal of Food Engineering*, *803*, 922–930.

Sun, J., Peng, Z., Yan, L. K., Fuh, J. Y. H., & Hong, G. S. (2015). 3D food printing—An innovative way of mass customization in food fabrication. *Bioprinting*, *1*(1), 27–38. https://doi.org/10.18063/IJB.2015.01.006

Sun, J., Zhou, W., Huang, D., Fuh, J. Y. H., & Hong, G. S. (2015). An overview of 3D printing technologies for food fabrication. *Food Bioprocess Technology*, *8*, 1605–1615. https://doi.org/10.1007/s11947-015-1528-6

Sun, J., Zhou, W., Yan, L., Huang, D., & Lin, L.-Y. (2018). Extrusion-based food printing for digitalized food design and nutrition control. *Journal of Food Engineering*, *220*, 1–11. https://doi.org/10.1016/j.jfoodeng.2017.02.028

Theagarajan, R., Moses, J. A., & Anandharamakrishnan, C. (2020). 3D extrusion printability of rice starch and optimization of process variables. *Food and Bioprocess Technology*, *13*(6), 1048–1062. https://doi.org/10.1007/s11947-020-02453-6

Tomašević, I., Putnik, P., Valjak, F., Pavlić, B., Šojić, B., Markovinović, A. B., & Kovačević, D. B. (2021). 3D printing as novel tool for fruit-based functional food production. *Current Opinion in Food Science*, *41*, 138–145.

Van der Linden, D. (2015). *3D food printing: Creating shapes and textures: Report of Organization for Applied Scientific Research*. The Hague, Netherlands: TNO.

Vancauwenberghe, V., Katalagarianakis, L., Wang, Z., Meerts, M., Hertog, M., Verboven, P., … Nicolaï, B. (2017). Pectin based food-ink formulations for 3-D printing of customizable porous food simulants. *Innovative Food Science & Emerging Technologies*, *42*, 138–150. https://doi.org/10.1016/j.ifset.2017.06.011

Voon, S. L., An, J., Wong, G., Zhang, Y., & Chua, C. K. (2019). 3D food printing: A categorised review of inks and their development. *Virtual and Physical Prototyping*, *14*(3), 203–218.

Walters P, Huson D, Southerland D (2011). *Edible 3D printing*. In Proceedings of 27th international conference on digital printing technologies.

Wang, L., Zhang, M., Bhandari, B., & 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

Wang, M., Li, D., Zang, Z., Sun, X., Tan, H., Si, X., … Liu, R. (2021). *3D food printing: Applications of plant-based materials in extrusion-based food printing*. Critical Reviews in Food Science and Nutrition. https://doi.org/10.1080/10408398.2021.1911929

Wegrzyn, T. F., Golding, M., & Archer, R. H. (2012). Food layered manufacture: A new process for constructing solid foods. *Trends in Food Science and Technology*, *27*(2), 66–72.

Yang, F., Zhang, M., & Bhandari, B. (2017). Recent development in 3D food printing. *Critical Reviews in Food Science and Nutrition*, *57*(14), 3145–3153.

Yang, F., Zhang, M., Bhandari, B., & Liu, Y. (2018). Investigation on lemon juice gel as food material for 3D printing and optimization of printing parameters. *LWT—Food Science and Technology*, *87*, 67–76. https://doi.org/10.1016/j.lwt.2017.08.054

Yang, F., Zhang, M., Prakash, S., & Liu, Y. (2018). Physical properties of 3D printed baking dough as affected by different compositions. *Innovative Food Science and Emerging Technologies*, *49*, 202–210.

Zhang, J. Y., Pandya, J. K., McClements, D. J., Lu, J., & Kinchla, A. J. (2021). Advancements in 3D food printing: A comprehensive overview of properties and opportunities. *Critical Reviews in Food Science and Nutrition*, 1–18. https://doi.org/10.1080/10408398.2021.1878103

Zhao, D., & Guo, W. (2020). Shape and performance controlled advanced design for additive manufacturing: A review of slicing and path planning. *Journal of Manufacturing Science and Engineering*, *142*, 010801.

Zhao, L., Zhang, M., Chitrakar, B., & Adhikari, B. (2021). Recent advances in functional 3D printing of foods: A review of functions of ingredients and internal. *Critical reviews in food science and nutrition*, *61*(21), 3489–3503.

Zhao, L., Zhang, M., Chitrakar, B., & Adhikari, B. (2020). Recent advances in functional 3D printing of foods: A review of functions of ingredients and internal structures. *Critical Reviews in Food Science and Nutrition*, *61*, 3489–3503. https://doi.org/10.1080/10408398.2020.1799327

Zhu, S., Stieger, M. A., van der Goot, A. J., & Schutyser, M. A. I. (2019). Extrusion-based 3D printing of food pastes: Correlating rheological properties with printing behaviour. *Innovative Food Science & Emerging Technologies*, *58*, 102214.

Zoran, A., & Coelho, M. (2011). Cornucopia: The concept of digital astronomy. *Leonardo*, *44*(5), 425–431. https://doi.org/10.1162/LEON_a_00243

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