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To cite this version:

Stéphane Portanguen, Pascal Tournayre, Jason Sicard, Thierry Astruc, Pierre-Sylvain Mirade. Toward the design of functional foods and biobased products by 3D printing: A review. Trends in Food Science and Technology, Elsevier, 2019, 86, pp.188-198. 10.1016/j.tifs.2019.02.023 . hal-02048852

HAL Id: hal-02048852
https://hal.archives-ouvertes.fr/hal-02048852

Submitted on 26 May 2020

Accepted Manuscript

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PII: S0924-2244(18)30308-X
DOI: https://doi.org/10.1016/j.tifs.2019.02.023
Reference: TIFS 2429

To appear in: *Trends in Food Science & Technology*

Received Date: 4 May 2018
Revised Date: 6 August 2018
Accepted Date: 6 February 2019

Please cite this article as: Portanguen, S., Tournayre, P., Sicard, J., Astruc, T., Mirade, P.-S., Toward the design of functional foods and biobased products by 3D printing: A review, *Trends in Food Science & Technology*, https://doi.org/10.1016/j.tifs.2019.02.023.

Toward the design of functional foods and biobased products by 3D printing: A review

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Declarations of interest: none

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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Abstract

Background:

3D printing or additive manufacturing (AM) now provides enormous freedom to design, manufacture and innovate in various domains, even in foodstuffs development. Given the immense potential applications related to AM, many authors are even talking about a new industrial revolution.

Scope and approach:

In this article, we review the state of the science in applied AM methods for developing biobased products in the medical and food sectors, with these two sectors having similar points. We were therefore interested in the technological locks encountered in the various studies carried out on the subject. Consideration has also been given to the possibility of using alternative sources of protein, such as animal by-products, to address resource management and sustainable development issues. One of the strengths of 3D printing is personalization, so we chose to evaluate the impact of this technology on target populations and evaluate the possible evolutions.

Key findings and conclusions:

In order to design food in optimal conditions, the development of new 3D printers is fundamental 1) to ensure the sanitary quality (both microbiological and chemical) of these products, and 2) to control the structure and texture of these 3D-printed foods. From there, it will be possible to propose personalized foods, adapted to different categories of population (e.g. seniors or young people...). The major challenge in the next years will be to develop, using 3D printing, meat products or products blending alternative protein sources that remain perfectly structured without having to use additives. The final step will be to garner consumer acceptance for these 3D-printed foods.

Keywords: Additive manufacturing; by-products; protein; personalization; sustainable development; consumer acceptability.

Highlights:

We reviewed the state of the science on the 3D printing of biobased products;

Some 3D printing applications developed in the medical and food sectors were analysed;

We looked at 3D-printed functional foods targeting various sectors of the population;

The consumer acceptability of 3D-printed food products was also deeply discussed;

Some development prospects for 3D printed biobased products were also investigated.

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I) Introduction

Additive manufacturing (AM), popularly dubbed "3D printing", has emerged, expanded and matured to a stage where it provides enormous freedom to design, manufacture and innovate in spheres from mechanical engineering (Chen et al., 2017) and aeronautics (Ford, Mortara & Minshall, 2016) to design science (Lanaro et al., 2017; Areir, Xu, Harrison & Fyson, 2017; Takezawa & Kobashi, 2017), biomedical engineering (Singh & Ramakrishna, 2017), the pharmaceutical industry (Icten et al., 2017; Goole & Amighi, 2016), biotechnology (Krujatz et al., 2017), and even food (Pinna et al., 2017). The literature on 3D printing technologies is booming, and with the immense promise and potential applications unlocked by AM, a number of authors are even starting to talk about a new industrial revolution (Campbell, Williams, Ivanova & Garett, 2011; Gross, Erkal, Lockwood, Chen & Spence, 2014; Attaran, 2017). There are niche markets (jewellery, luxury cars, and others) where AM is already used to produce certain objects which are then marketed (Ford et al., 2016). Research in 3D printing is expanding, as the technology is ideally geared to the rapid prototyping phases (Berman, 2012; Attaran, 2017) that require feasibility without mass production and rapid manufacturing. AM is a digitally-controlled robotic construction process, which can build up complex solid forms layer by layer and apply phase transitions or chemical reactions to bind the layers together (Sun, Peng, Yan, Fuh & Hong, 2015a). To do this, several reference techniques exist, using different materials. We can cite: binder jetting (Meteyer, Xu, Perry & Zhao, 2014), directed energy deposition (Heigel, Michaleris & Reutzel, 2015), material jetting (Krujatz et al., 2017), powder bed fusion/binding (Huang, Liu, Mokasdar, & Hou, 2012), sheet lamination (Shimizu et al., 2014), vat photopolymerization (Singh, Ramakrishna & Singh, 2017) and material extrusion (Huang et al., 2012). Versatility is another big reason to use AM, particularly for biobased products. Indeed, being able to work from the macroscopic scale (e.g. 3D-printing of foodstuffs) up to a microscopic scale (e.g. cell-by-cell deposition for the construction of organs or tissues) makes it possible thanks to the wide range of existing printing techniques. For 3D printing of biobased products or foods, the following techniques are well-suited: 1) extrusion-based printing, the most popular method in food printing (Sun, Zhou, Yan, Huang & Lin, 2017), 2) inkjet printing (Singh, Haverinen, Dhagat, Jabbour, 2010), and 3) laser-assisted printing (Guillotin et al., 2010). Figure 1 schematizes the operating principles of these methods.

Practically all commercial 3D printing machines outside heavy industry, chiefly extrusion machines, are customizable, and there are even some project device designs that are open-source, enabling custom-tailored manufacturing, which is an important feature for research and R&D labs as it enables them to adapt the devices to their applications. For example, Zeleny & Ruzicka (2017) managed to adapt a commercial printer model for printing foodstuffs which originally used for fused

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deposition modelling of thermoplastic. While metal feed 3D printers for industry can cost up to $500,000 (Severini, Derossi & Azzolini, 2016), there are mainstream 3D printers now available that offer perfectly acceptable performances for an affordable few hundred dollars (Prusa i3®, RepRap, France; Hephestos 2®, BQ®, Spain…). This means that cost of the hardware is no longer a barrier, and so a huge number of applications can now be developed, by anyone ready to make a few appropriate machine customizations: e.g. adding of syringe pump system, embedded cooking system, or cooling system ... In our opinion, personalization means a major modification and not simply to use various nozzles or needles. For instance, Bégin-Drolet et al. (2017) have developed a new printhead for making structures out of sugar, based on a system using a lead gear and a worm gear combined with an ultra-fine pitch screw to deliver a syrup contained in a syringe. To obtain a quickly solidification of the sugar, an air cooling system was added near the nozzle.

Attaran (2017) reported that worldwide revenues from AM are growing exponentially, from $3.07 billion in 2013, nearly doubling to $5 billion in 2016, and on a curve to exceed $21 billion in 2020. However, this expansion may get slowed by some key technology-related drawbacks, chiefly the size, time-to-manufacture, and cost of printed objects, and change in the regulatory landscape. That said, the many advantages over conventional 'hard' manufacturing—customizability, rapid prototyping, on-demand manufacture of spare parts, decentralized/distributed manufacturing, and more—can be expected to drive further expansion of AM in a whole number of sectors, and especially the automotive industry. Healthcare may be the sector where 3D printing holds the greatest transformative potential: the AM-driven healthcare economy, estimated at just $11 million in 2012, is projected to hit $1.9 billion by 2025 (Attaran, 2017). 3D-printed implants and tissue organs are currently the focus of intensive research (So, Mandas & Hlad, 2018; Almela et al., 2018). To our knowledge, regarding the food sector, no economic data exist, but several industrial projects are in progress, especially in Europe (e.g. with Barilla group).

Here, in response to this content, we set out to review the state of the science in applied AM methods for developing biobased products in the medical sector, and in the food sector. Indeed, there are many common points between these two sectors, especially in terms of printing methods of proteins-based hydrogels. The review analyses the applications developed on the back of these methods, targeting the impact these methods have on the design and production-line sustainability of the biobased products *per se* and on consumer acceptability of these 3D-printed products. We also look at 3D-printed functional foods targeting different sectors of the population, and the development prospects for 3D-printed biobased products in the coming decade.

II) Biobased product development by additive manufacturing

II.1) In the medical sector

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Bose, Ke, Sahasrabudhe, & Bandyopadhyay (2018) dichotomizes the two categories of 3D printing processes for biomaterials: acellular (ceramics, hydrogels, thermoplastics…) and cellular. Cellular-category biomaterials can serve as scaffolds to print living cells that will multiply and form tissue constructs. For Krujatz et al. (2017), biofabrication and bioprinting are two tightly-linked bioengineering fields that are both synonymous with processes for living-cell and biomaterials. Most commonly used methods are inkjet printing, extrusion-based printing and laser-assisted printing (fig.1). The main biomedical applications are for 3D printing body tissue (Chia & Wu, 2015), from bone and organs to blood vessels, nerves, and more. Almela et al. (2017) demonstrated that 3D printing could be used to fabricate a human bone-like calcium-scaffold microstructure, and their study opens promising perspectives for bone grafting. However, despite the opportunities these techniques bring to medicine for building or regenerating organ tissue *in situ*, there are a number of technical issues still to overcome, as highlighted by Gudapati, Dey & Ozbolat (2016), such as the droplet-based bioprinting technique that leads to narrow range of available bioink material, cell damages induced by bioprinting, restrictions on the size of constructs due to lack of vascularization and porosity… Over and above complex ethical or regulatory issues, there are also fundamental technical bottlenecks to contend with, like the narrow range of available biomaterials, the cellular lesions induced by the bioprinting process, or the mechanical and structural integrity of the tissue constructs that will affect the vascularization—and therefore the viability—of 3D-bioprinted tissue organs. Jakab et al. (2010) assert that it is crucial to design a fully-controllable cellular environment in order to provide a biomimetic paradigm that can place the right cells in the right place and with the right phenotype to make functional assemblies. The authors also underscore the core role of the scaffold in the tissue fabrication process, as it is the scaffold, designed from biodegradable material, that serve as the template providing the tissue with specific topological features at nano, micro and macro scale. However, the use of biodegradable scaffolds leads to the residual presence of polymer fragments, which may disrupt the normal organization of the vascular wall (Jakab et al., 2010; confirmed by Gudapati et al., 2016). Several studies (Melchels et al., 2012; Inzana et al., 2014; Munaz et al., 2016; Wlodarczyk-Biegun & Del Campo, 2017; Shanjani et al., 2017) deal with ways to implement the scaffolds, which are absolutely crucial architectures for fabricating tissue. Wlodarczyk-Biegun & Del Campo (2017) reviewed recent achievements in bioprinting major structural proteins like collagen, silk and fibrin that confirm how porous and networked scaffolds are readily 3D printable. Note that it is possible to use different cellular types or materials simultaneously or sequentially during the same tissue engineering process. Scaffolds or hydrogels which offer the advantage of being biocompatible (Melchels et al., 2012) and providing a suitable environment for the cells due to their high water content and low polymer content (Wlodarczyk-Biegun & Del Campo, 2017). There are still-unresolved technical challenges with using them (rheological properties, crosslinking density, and more), but natural compounds (like gelatin or hyaluronic acid) can be already combined with synthetic polymer network components like methacrylamide to promote crosslinking (Melchels et al., 2012).

Collagen gels in 3D bioprinting can serve in medical applications for targeted cell placement to generate a given form, and extend cellular viability. Dunn, Yarmush, Koebe & Tompkins (1989), cited by Melchels et al. (2012), showed that hepatocytes conserved their functions for several weeks when sandwiched between two layers of collagen gel, against just a few days with a single layer. After observing similar effects, Munaz et al. (2016) concluded that the longer cellular viability conferred by this collagen hydrogel was because it keeps the cells better hydrated and better aggregated for a long time, without settling. Smith et al. (2004) developed a script to construct an artery branch of a pig heart using bovine aortic endothelial cells suspended in type-1 collagen. This data, even if it comes from the medical sector, suggests that 3D-printed foods containing collagen may hold an excellent level of hydration, which in turn would have a positive influence on their texture or mouthfeel.

II.2) In the food sector

Godoi, Prakash & Bhandari (2016) claim that AM technology holds huge potential to fabricate foods with complex geometries, advanced textures and tailored nutritional contents, but Liu, Zhang, Bhandari & Wang (2017) noticed only few studies dealing in the degree of precision required to make structurally-controlled foods by AM. In reality, the major difficulties for 3D printing novel foods stem from a number of factors, including material properties, printing-process parameters and post-processing parameter (methods of cooking, conservation, and so on). Even if some authors find that uptake of AM in the specialty food industry has ultimately disappointed (Gausemeier, Echterhoff, Kokoschka & Wall, 2011, cited by Mawale, Kuthe & Dahake, 2016), there are nevertheless signs of an emerging trend for culinary applications tied to the ‘food design’ movement, with several recent papers addressing these applications (Pallottino et al., 2016). The European project PERFORMANCE—Personalised Food using Rapid Manufacturing for the Nutrition of Elderly Consumers (Lipton, Cutler, Nigl, Cohen & Lipson, 2015; Liu et al., 2017), had even set out to use 3D printing for the development or appealing new foods for seniors. 3D printing can thus be used to enhance certain foods and make them more attractive to consumer populations, or simply to create new forms or structures for commercial profit. The technological angle may be interesting—printer customization, open source, programming, and so on—and the societal angle may be important—food attractiveness to certain populations—but there are legitimate grounds to stop and question

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the real scientific impact value of studies focused exclusively on food design. For example, Zhao et al. (2018) investigated the potential reach of programming with the aim of fashioning a personalized food product that can be printed with a face from a photo.

One of leading products studied this context is chocolate (Liu et al., 2017; Zeleny & Ruzicka, 2017; Lanaro et al., 2017). A review by Godoi et al. (2016) showed that 3D printing can create complex structures made out of chocolate or sugar, provided the process can firmly control a certain number of key parameters, including feedstock vat and extrusion system temperature, nozzle geometry and height from the forming bed, rheological behaviour, among others. Adding magnesium stearate to the chocolate feedstock provide a better flowability during deposition, and thus lends the chocolate better 'printability' (Mantihal, Prakash, Godoi & Bhandari, 2017). There are also studies on confectionery sugar, and on plant- or meat-based purees. As a rule, product rheology has to be modified using food additives, typically xanthan gum or agar-agar for plant foods or transglutaminase or gelatin for meat products (Lipton et al., 2015). However, as today's consumers tend to prefer clean label products containing as few additives as possible, blending additives into otherwise additive-free foods just to fit food to process is surely not the right way forward. Effort should instead be directed towards reworking the process to fit the food to be printed. Lipton (2017) reached this same conclusion, explaining that research in AM for the food industry is overconcerned with aesthetics factors and unconcerned with consumer health factors—yet aesthetics should only really be addressed further into the longer term, whereas it is by using AM technologies to design nutrition-controlled and/or nutrition-adapted foods that the benefits for human health could be most important. Lipton (2017) goes on to say that it would be possible to define a person's dietary energy needs and directly custom-print a food that meets their requirements. However, there is not, to our knowledge, a single study that has purposively addressed the nutritional value of 3D-printed foods, other than research just published by Derossi, Caporizzi, Azzolini & Severini (2018) on the antioxidant activity of 3D-printed fruit-based snacks.

Lipton et al. (2015) address the topic of manufacturing whole muscle tissue for human food supply, where the idea would be to remove the need to farm livestock in order to produce meat muscle and fat cells, in which case the nutritional value of these products would supposedly be identical or near-identical to 'conventional' meat. This is one of the goals of American start-up Modern Meadow, which is working on 3D printing stem cells that, once developed, should be able to render a meat-like matrix. However, even if right now, these approaches are still in their early days, we can already see the kind of difficulties to come in the future: the economics, nutritional and organoleptic properties, industrial scale-up, nutrient inputs needed for cell culture, food safety, ethics issues, and the list goes on.

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III) Impact of additive manufacturing processes on food macromolecules

Le Tohic et al. (2018) explain an AM process as subjecting the product to two types of constraints: 1) thermal treatment as the product melts, and 2) shear strain as the product extrudes through the nozzle. Process used thus has one or more effects on macromolecules making up the food product which will modify its properties. A majority of studies on compounds of interest in food applications of AM have focused on the 'printability', where printability is the set of material properties that lend a product enough stability in space to support its own weight (Godoi et al., 2016).
Although it is relevant to study a food in whole, in the case of the design of a food with therapeutic aim, it can be necessary to have elements in connection with the main macromolecules of nutritional or structural interest. Moreover, within the scope of the 3D printing of a food intended to be consumed by people within the framework of a deficiency or of a pathology, it is perfectly conceivable to resort to a basic medium having the form of a hydrogel containing meat proteins, which could be enriched in vegetable proteins, lipids and carbohydrates. In this case, understanding the interactions between the printing process and all the compounds taken one by one is fundamental.

III.1) Impact on proteins

Relatively few animal protein-rich products have been studied for applicability in AM. Exceptions include various types of pureed meat (Lipton et al., 2015), collagen (Inzana et al., 2014) and gelatin (Farag & Yun, 2014). Nevertheless, certain studies are hugely instructive on the difficulties posed by this kind of food matrix: For Godoi et al. (2016), materials should be homogenous, have appropriate flow properties for extrusion and should support its structure during and after printing process. For Wang, Zhang, Bhandari & Yang (2018), as a mixture, each component (proteins, carbohydrates, lipids and water) can undergo changes that will influence the fusion and the plasticization of the food. For example, printability of fish surimi gels systems was the best with a sodium chloride (NaCl) concentration of 1.5 g/100 g surimi (Wang et al., 2018). Gracia-Julia, Hurtado-Pnol, Leung & Capellas (2015) (cited by Severini et al., 2016) observed a better printability of beef-based preparations when the myofibrillar proteins were solubilized, due to salt adding. Electron microscopy showed that the added NaCl had led to myofibrillar protein crosslinking, enabling free amino acids to bind to the proteins, shrinking the void spaces, and changing the structure of the gel into a fine-strand network (Wang et al, 2018). This effect is maximal, and holds constant, at 1.0 g NaCl/100 g surimi. Protein printing is thus governed by the properties of the proteins, and crucially protein aggregation, which is further governed by the isoelectric point (pI). Godoi et al. (2016) assert that AM technologies can

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create new textures by intercalating layers of food proteins with layers of polysaccharide materials like alginate, applying temperature or mechanical stresses, or incorporating acid or base compound ingredients in the AM process to promote aggregation. Finally, Liu et al. (2017) posited that precise and accurate 3D food-based structures cannot be successfully printed without adding texturizers like hydrocolloids or gelable proteins, which has since been confirmed by Yang, Zhang, Bhandari & Liu (2018) for 3D food printing with turkey meat.

The major structural proteins (collagen, elastin, and fibrin) have already been studied for fabrication of complex-architecture scaffolds as a step towards performing cell-by-cell deposition. The organization of these fibrous proteins, governed by alignment constraints, diameter constraints and pore structure constraints, varies according to type of tissue and has a huge influence on its mechanical properties. Fibrin is a protein produced naturally by the body where it is used to repair injury, but it can also be 3D-printed in gel form (Melchels et al., 2012; Chia & Wu, 2015). Fibrin is used in AM for fabricating scaffolds to repair bone, neurons or heart valves (Munaz et al., 2016). Collagen, which is the most abundant protein in mammals, can be bioprinted as a gel, after extraction and enzymatic digestion. According to Wlodarczyk-Biegun & Del Campo (2017), printable collagen-based solutions vary in concentration between studies, from 0.2 mg/mL up to 20 mg/mL in an ionic strength adjustment solution. Choice of concentration will depend on the mechanical properties targeted, such as maintaining tissue integrity, or the viability characteristics of the seeded cells. For example, a 1 mg/mL gel can generate cohesive and reproducible structures, provided that pH is kept under control, as a high pH can clog the printhead nozzles. Pure collagen lacks the stability needed to form a 3D structure, so it has to be combined with other polymers. Furthermore, without inducing added crosslinking, collagen will form mechanically inferior hydrogels. Crosslinking is inducible by chemical reaction using formaldehyde or glutaraldehyde or by enzymatic reaction using transglutaminase (Wlodarczyk-Biegun & Del Campo, 2017). Inkjet, extrusion and laser-assisted bioprinting processes have all been mobilized for difficult-to-print collagen solutions (Inzana et al., 2014; Jakab et al., 2010; Wlodarczyk-Biegun & Del Campo, 2017). Extrusion processes can already work with multi-printhead and/or crosslinking system-coupled 3D printers (Smith, Christian, Warren & Williams, 2007; Hinton et al., 2015). However, according to Murphy, Skardal & Atala (2013), and Wlodarczyk-Biegun & Del Campo, (2017), the main difficulties with using collagen as an extrusion-process bioink are the gel time, which is long, and swelling, which was also flagged up by Munaz et al. (2016) who concluded that despite being easily constructed for 3D structures, collagen biomaterial molecules will eventually lose shape due to swelling or dissolution, which are the main limits to further use.

As gelatin is derived from collagen, the literature often pairs the two, even if each has its own set of properties. Gelatin has nevertheless been used in many applications. Munaz et al. (2016) showed

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that a collagen/gelatin hydrogel synergized the properties of each, making it possible to build a hydrogel scaffold and to use the gelatin to create fluidic channels which, once the gelatin has dissolved, would leave a vascular network architecture. The thermal properties of gelatin and collagen differ: indeed, gelatin (at 10%) is solid at room temperature and liquid at 37 °C (reversible phenomenon) while the collagen must be kept in ice until printing. Moreover, gelatin is more viscous at 37 °C than collagen, which imposes to increase the pressure for the 3D printing of the collagen (Lee et al., 2014). Gelatin has been used to study bacterial cell-to-cell communication by creating crosslinked microstructures (Connell, Ritschdorff, Whiteley & Shear, 2013), and to create scaffolds by AM for bone tissue regeneration, notably to improve the properties of ceramic scaffolds (Farag & Yun, 2014). Godoi et al. (2016) claim gelatin makes a good candidate for use as an ingredient of AM bio-inks. Gelatin gels possess a unique characteristic texture that provides appreciable mouthfeel together with good flavour perception. As stated earlier, pI has a major effect on protein structure. In the case of gelatin, at the pI, its contraction is maximal, and therefore its viscosity is minimal. This viscosity is a parameter that increases when pH changes. However, if the pH change is too sharp, the molecule will depict its maximum extension, in which case the gelatin will adopt a non-Newtonian behaviour—gelatin normally exhibits Newtonian flow in dilute solution, except when extended by charged groups. Shear also has a major effect on viscosity, and extreme shear can trigger an irreversible loss of viscosity (Godoi et al., 2016).

Both Lipton et al. (2015) and Godoi et al. (2016) talk up the use of transglutaminase to build complex geometries out of meat. Transglutaminase is an enzyme that can catalyse new protein matrices by forming covalent bonds between lysine and glutamine residues, in a calcium-dependent reaction. This process thus manages to enzymatically crosslink proteins present in meat purees, giving rise to self-supporting hydrogels. However, the use of additives like transglutaminase, even if has potentially valuable effects in terms of the resulting mechanical properties, runs counter to the current market trend of getting back to more 'natural' foods. This means that any product developed via this kind of process is likely to meet with consumer resistance, let alone regulatory hurdles in certain countries.

The biggest challenge for printing food, then, remains getting the right kind of texture to deliver an appreciable mouthfeel. Proteins, as key structural macromolecules, are no exception to the rule. The next step forward is to engineer printing strategies that can deliver fully-controlled structures—and, if possible, without using texture-stabilizing additives (fig. 2).

III.2) Impact on lipids

Even though 3D printing studies have tackled high-fat-content foods like chocolate, very few have investigated the effect of 3D printing on lipids and, *vice versa*, the effect of lipids on printability. To

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the best of our knowledge, only Le Tohic et al. (2018) and Lille, Nurmela, Nordlund, Metsä-Kortelainen & Sozer (2018) have tackled the issue. Le Tohic et al. (2018), working with an untreated (i.e. non-extruded) cheese matrix, showed that the fat globules were round and homogeneously distributed in a continuous protein phase. A comparable structure was observed in cheese melting at 75°C, although with bulkier fat globules due to heat ramp-induced coalescence. Cheese extrusion-printed at 4 mL/min and 75°C showed heavily altered microstructure: the protein phase had become discontinuous and the fat globules had changed morphology—losing sphericity and gaining volume—with the appearance of interstitial fat. However, the print parameters also have a visibly major effect, since fat globule size and distribution were more homogeneous after printing at 12 mL/min (75°C), likely due to a higher shear rate in this condition. Protein–lipid interactions are though to explain the rheological changes observed to occur in 3D-printed cheeses, i.e. a softer texture that is not as sticky due to the greater amount of surface fat released during the shear processes.

Lille et al. (2018) examined the role of lipids during food printing processes by working on milk powder as a source of both proteins and fat. They tested two formulations presenting equivalent protein contents (21% and 22%, respectively) in solutions of water with skimmed (0.4% fat) and semi-skimmed (9% fat) milk powder. They showed that the skimmed-milk formulation gave a highly-viscous and difficult-to-print paste that was too sticky to evenly deposit, and when the milk powder concentration was upped from 50% to 60%, printing became simply impossible, whatever the nozzle diameter used, whereas with the semi-skimmed formulation, even at 60% concentration, printability proved to excellent, both in terms of precision and of holding printed shape. Lille et al. (2018) explained that fat had acted as a lubricant in the extrusion system and that the biomaterial was more fluid. Note that carbohydrate content differed substantially between the two formulations (32% and 23%, respectively), which may also have influenced fluid flowrate.

Godoi et al. (2016) are optimistic about the use of lipids in AM, given that their triglyceride composition and different melting points influence meat texture and, crucially, tenderness and flavour. 3D printing methods (especially extrusion) thus have the potential for fabricating custom-textured foods. Using different-chain-length fatty acids with different degrees of unsaturation should make it possible lock down melting points, which would improve layer-on-layer adhesion, enabling the constructs to better hold their shape, in pre- and post-processing.

III.3) Impact on carbohydrates

Several studies have investigated the printability of sugar polymers. Holland, Foster, MacNaughtan & Tuck (2018) demonstrated that cellulose (powder) is printable layer-by-layer, provided the process can firmly control the rheological properties, surface tension and density of the build material. Kim,

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Bae & Park (2018), using methyl cellulose as reference biomaterial to simulate the printability of various food-inks, showed that 9%, 11% and 13% hydrocolloid concentrations were able to scaffold 28 mm-diameter cylindrical constructs with heights of 20 mm, 40 mm and 80 mm, respectively, without collapse. Working on printable pectin-based formulation, Vancauwenberghe et al. (2017) tested the effect, at otherwise-constant print parameters, of different formulations involving different stirring speeds and different concentrations of pectin, calcium chloride, bovine serum albumin (BSA) and sugar syrup. A coherent and lasting 3D structure was only achievable by adding $CaCl_2$ to partially crosslink the pectin. This study showed that pectin and sugar syrup concentrations directly influenced viscosity of the mixture, and that BSA stabilized and aerated the mixture. Vancauwenberghe et al. (2017) thus demonstrated the feasibility of 3D printing textured variable-microstructure foods.

Starch, a commonplace food additive, has also been investigated. Liu, Zhang, Bhandari & Yang (2018) led research on 3D printing low-starch to high-starch potato purees and found that a puree had to contain at least 2% starch to be printable. In this condition, the material showed an increase in elastic limit, and better extrudability. However, at 4% starch content, despite the material comfortably holding its 3D shape and structure, it had poor extrudability due to over-high viscosity. Yang et al. (2018) also confirmed that complex sugars like potato starch are 3D printable. Their study, which paired lemon juice and starch (at 15 g/100 g), managed to determine the optimal print-process parameters—nozzle diameter, printhead speed and extrusion rate—that fabricating smooth-surfaced constructs with zero deformation. Research by Lille et al. (2018) demonstrated, much like for lipids (see section III.2), that a 15% starch solution had better printability when the formulation contained semi-skimmed milk powder instead of skimmed-milk powder. However, feedrate through the extrusion system was dependent on the particle size of the food components, as for plant-based foods containing protein, starch and fibre, the viscous aspect of the starch, which comes from the presence of particles, quickly clogs up the system.

The papers published to date point to two big problems for 3D food printing: 1) particle size of the food components used (Lille et al., 2018), and 2) the material–material bonding mechanisms. Some upstream control over the process steps should suffice to address the first problem. On the second, authors like Liu et al. (2017) advise using additives, such as fats or blood plasma proteins, to improve solidification on cooling or crosslinking. Considering only ‘natural’ additives as candidates, it is easy to imagine using highly unsaturated lipids, which would also bring health benefit to consumers.

IV) Effect of additive manufacturing process on the preservation of 3D-printed food

IV.1) Solutions for safe fabrication

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If uptake of food engineering/manufacture by AM finally takes off, then the heath–safety issue is going to come up during the process, but also during the food preservation stage, both in terms of microbiological safety (pathogenic and spoilage bacteria, fungus) and food chemistry (oxidation, newly-formed compounds). Most current 3D printers for food products were originally developed in laboratories, where easy-to-clean and/or easy-to-decontaminate design is not generally a concern. 3D printers tomorrow will need to be made in stainless steel and meet strict industry standards (Lipton et al., 2015) to prevent cross-contaminations between foods while minimizing the amount of time the 3D-printed food product is exposed to open air (presence of oxygen, high temperatures, and so on). This is confirmed by Severini, Derossi, Ricci, Caporizzi & Fiore (2018a). They 3D-printed a fruit-and-vegetable-based smoothie and monitored its microbiological profile over 8 days when the product was stored at 5 °C in air (20% O_2 and 80% N_2) or under modified atmosphere (5% O_2 and 95% N_2). Microbial concentrations (mesophilic flora, psychrophilic microorganisms and yeasts) in the samples started high, at between 4 and 5 log CFU·g^{-1}, on Day 0, remained stable between Day 0 and Day 6 whatever the food preservation conditions, then showed a decrease at Day 8. The authors explained this initially high microbial contamination as introduced by the printer itself, via its pistons, its tubes or the extruder, as they had carefully washed the ingredients beforehand.

According to King et al. (2017), global population is expected to reach at least 9 billion by the year 2050, requiring 70% more food and requiring fully-sustainable food production systems. Meeting this food security challenge needs to be part and parcel of tackling equally big strategic issues for food research, such as the ageing demographics with a growing population of immunocompromised persons, and ring consumer demand for clean-label foods. The authors thus raised the hypothesis of 'extra-safe' food fabrication processes to make irradiated, sterilized, or pasteurized foods that are targeted to higher-risk populations. On 3D food printing, King et al. (2017) raised a number of concerns, chiefly the fact it could make everyone a food manufacturer without having any real control over the water activities and pH of their self-created food, which will necessarily bring food safety risks. Personalized diets, which we touched on earlier, are also a concern for King et al. (2017). As consumers put more focus on the nutritional aspects than on food safety, there is a risk that modifying, for example, the microbial flora of foods could create unintended food safety issues by changing their gut microflora. Clearly, the 3D food printing, where industrially or at home, needs to be tightly regulated to compensate for the evident lack of lookback experience on this technology and eliminate all risks to health.

The microbiological quality of the 3D-printed food deserves to be taken into consideration from the design of the printing process. In fact, should the raw 3D-printed food be cooked directly after the printing phase? Or, should it be conditioned as it is? These two pathways will not have the same repercussions in terms of food safety. Let us imagine a random food product, 3D-printed raw under

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controlled aseptic conditions. With the technology available today, we could easily directly print up its packaging, which means the packaging step could be integrated directly into the process. From there, imagine too that this packaging is edible, and so does not need to be removed to cook or eat the product. The packaging could even be made to have bacteriostatic or bactericidal action, using natural compounds (Moghimi, Aliahmadi & Rafati, 2017; Saberi, Chockchaisawasdee, Golding, Scarlett & Stathopoulos, 2017), in which case, as there is no further need for human intervention downstream of printing, the risk of microbiological contamination will be dramatically reduced.
The other key utility of carefully thinking out the process design is to facilitate storage of the packed–packaged product. A seamlessly controlled process, combining printing and packaging, could enable room-temperature no-refrigeration-needed storage, which could substantially reduce energy demand and prove enormously useful, especially in hot-climate countries.

IV.2) The post-processing issue

Post-processing operations like drying, cooking and frying, but also pre-treatments like ultrasound and radiofrequency processing, affect the rheology of food materials, especially gel formation. For more substance-dense foods like lean beef paste, transglutaminase has to be added 0.5% by weight to maintain shape fidelity after cooking (Liu et al., 2017). Lille et al. (2018), among others, think that post-processing treatments could have a positive impact on 3D-printed foods. An example would be drying, which could increase their stiffness. Lille et al. (2018) showed that freeze-drying preserved 3D shapes much better than oven-drying, which tended to cause shrinkage. Water content of the product is an equally important parameter, as more water to remove means more risk of losing shape.
The data gap on post-processing steps in the 3D printing literature is manifest—a number of articles underline that further studies are needed to determine the most suitable pre- and post-processing (Liu et al., 2017), and that firm control of the physical-chemical, rheological and mechanical properties of the printed foods is essential (Godoi et al., 2016). Furthermore, the health–hygiene dimension has gone completely ignored. However, it is assuredly conceivable to design very precise post-processing processes, e.g. systems using a laser beam or hot air jet, which are directly coupled to the 3D printing system and which would, at the same time, ensure cooking and microbial decontamination of the food.

V) Eco-design and sustainability of additive manufacturing

V.1) Energy consumption and use of raw materials

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A number of studies essentially dealing with the fabrication non-food objects, and not foods, have focused on the environmental effects of AM, or at least attempted to investigate the potential effects ahead of widespread industrial-scale uptake (Burkhart & Aurich, 2015; Jackson et al., 2016). This effort translates into energy (electricity) consumption assessments or into raw material savings estimates (Huang et al., 2012). Although the scholarship appears unanimous that there is raw material gain inherent to geometric adjustment (Jin, Du & He, 2017), there is much less consensus on the electricity consumption issue. According to Kellens, Mertens, Paraskevas, Dewulf & Duflou (2017), the specific energy consumption for AM unit processes is one to two-fold higher than conventional machining and injection moulding processes, and according to Yoon et al. (2014), even up to a hundred times higher. However, this higher environmental impact could be minimized by optimizing the parts manufactured and making lighter parts, especially transport-sector applications for road, rail and flight industries. According to Huang et al. (2012) and Peng (2016), 3D printing processes generally outperform traditional manufacturing processes on environmental impacts. However, as full industry uptake of AM methods has not yet taken off, quantifying its effects in mass production remains a difficult exercise. Nevertheless, Mognol, Lepicart & Perry (2006) have shown that optimized machine build parameters can save 40% to 60% energy on certain machines. Although they reached similar conclusions, Griffiths, Howarth, De Almeida-Rowbotham, Rees & Kerton (2016) toned down the prospects for transposing machine build parameter optimization to other processes, and highlighted the importance of developing design-specific models for AM. Implementing a more global approach based on lifecycle analysis, Le Bourhis, Kerbrat, Dembinski, Hascoet & Mognol (2014) showed that it was entirely possible to develop environmental impact analysis tools assessing AM-specific electricity, material and fluids flows. They also highlighted that materials consumption actually had a bigger environmental impact that electricity consumption in AM processes. Watson & Taminger (2018) very recently developed a model for comparing additive *vs* subtractive manufacturing based on energy consumption. Their model accounts for the entire end-to-end fabrication-process lifecycle, from production, transport and recycling of process materials through to post-production waste processing and the energy used by the equipment on standby. Their conclusions, which were fairly disappointing on balance, underline how certain data is difficult to get, especially energy values for producing certain materials, and crucially, that the model results output cannot be readily extrapolated for studying different AM process scripts and scenarios.

Peng (2016) gave five benefits of AM for reducing carbon footprint: 1) reducing the amount of raw material in the supply chain, and thus the mining/processing of ores, 2) reducing the need to use energy-intensive processes like casting and wasteful/harmful input materials like cutting fluid for CNC machining, 3) flexibility for efficient process component design by optimizing operational

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performance, 4) reducing the mass weight of process components to reduce the carbon footprint in land and air transport service (which Huang et al., 2012 also mentioned), and 5) limiting logistics-factor effects by bring manufacture close to point-of-use. This last point was also flagged up by Huang et al. (2012) and Kietzmann, Pitt & Berthon (2015) who added that this production modality would cut down on inventory by only fabricating objects on-demand. It would also eliminate the need to make spares that may never get used, particularly in the aeronautics industry. The recyclability of 3D-printed materials is another non-negligible advantage of AM that should be seen as an asset (Kietzmann et al., 2015).

The environmental impact of AM technologies has not yet been defined in any real depth, and the latest literature gives a fairly good picture of the kind of questions and contradictions raised for large-scale use. However, there are still a number of as-yet unexplored avenues for research to explore that could weed out certain approximations, primarily in energy consumption assessments, in lifecycle analyses, or in the effects of 3D printing technologies on human health, typically volatile organic compound emissions. The paper by Rejeski, Zhao & Huang (2018) spelled out all of these factors. If we take the example of 3D extrusion printing, a process using plastics is forced to work at high temperatures, which necessarily increases energy demand, whereas food applications will work at lower temperatures, especially if the food products are 3D-printed raw, so it is perfectly conceivable that this type of product would be far more energy-efficient.

V.2) Upcycling animal by-products by additive manufacturing

To the best of our knowledge, only Lupton & Turner (2016) and Lupton (2017) touch on the fact that 3D-printed foods could be environment-positive, by reducing waste, reducing the footprint of transport via local-locale fabrication, reusing foodstuff material categorized as human-inedible, using substitute foods, or developing edible packaging.

According to FAO figures (FAO, 2012), 33% of all food produced for human consumption globally—whether plant-based or animal-origin—gets lost or wasted, which amounts to about 1.3 billion tons per year: 30% of cereals, 20% of meat and dairy, and 45% of fruit and vegetables. In developing countries, 40% of food losses occur upstream of the supply chain, at harvest, post-harvest and processing, whereas in industrialized countries, more than 40% of food waste occur downstream of the supply chain, at retail and consumer level. Food losses and food waste can have many causes, and yet are sometimes based solely on product appearance standards (FAO, 2012). These food loss and food waste figures also feature certain human-edible protein-rich animal by-products like offal, along with human-inedible parts of a carcass like the bones, tendons and feathers. ADEME [the French environment and energy management agency] defines a by-product as material output

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inevitably yet intentionally created at the same time through the same manufacturing process as the main product. Main finished product and by-product both have to meet specific characteristics, and each is fit for direct use in its own specific purpose. There is thriving research community looking at ways to up value certain animal by-products for non-food purposes using AM. A good example is Singh et al. (2017) who are working on designing biomaterials made out of poultry-industry feathers. The rationale is that feathers have such a high protein content that they can serve as base material for fabricating biocompatible tailor-made scaffolds. Given the huge pool of untapped resources, especially very-good-quality proteins, locked in animal products that are already very expensive to produce, it is perfectly logical to ask whether there are ways to squeeze every ounce of added value out of these by-products by using AM to engineer innovative functional foods.

Consumption patterns for butchered beef have changed dramatically in the past few years. More and more beef cuts are no longer being used in traditional French slow-cooked recipes like *pot-au-feu* and beef *bourguignon*. This is explained by a shift in consumer lifestyle trends, where certain recipes are now seen as taking far too long to prepare, and that is before we count the fact that consumers today only want the most tender cuts, and the big background burger trend. The upshot is that consumers today, right from their earliest age, are being taught to eat tender or even very soft food.

There are two different technology pathways to re-value-stream meat, especially beef which is currently either processed as ground beef patties or undervalued as its initial tenderness is mediocre at best: 1) work on mechanical tenderization of chunked meat, by optimizing the tumbling processes (Daudin, Sharedeh, Favier, Portanguen, Auberger, & Kondjoyan, 2016); 2) design innovative foods by AM. In both cases, the goal is to fashion meat products presenting a fully process-controlled texture.

Muscle is not the only carcass component that AM can upvalue. As discussed earlier, the collagen is also used, especially in the medical sector as a scaffold material (Inzana et al., 2014; Shanjani et al., 2017). This structural protein, which is considered a by-product as it comes from the skin, bones and tendons of animals, also finds an array of food-industry applications (gelatin) and could well find great usability in fabricating functional foods engineered by AM (fig. 2). Mobilizing the structural potential of collagen via AM could be a way to develop foods based on undervalued meat or offal that have a texture suitable for young or senior citizens. Indeed, the only studies available to date on AM-engineered meat-based foods (Gracia-Julia et al., 2015; Godoi et al., 2016), used purees or ground beef, except those reporting whole-tissue fabrication by culturing stem cells (Lipton et al., 2015). Research led by Shanjani et al. (2017) to spur orthopaedic applications could well inspire new avenues for research in the food sector. Collagen-based architectures (scaffolds) with purpose-defined motif and pore structure could serve as the build platform for fabricating texture-controlled meat-based foods.

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VI) Towards personalizable functional foods

Spurred by the rapid development of 3D technologies for food, authors like Wegrzyn, Golding & Archer (2012), Sun et al. (2015a), Derossi et al. (2018), Liu et al. (2017), Severini et al. (2018a) and Kousani et al. (2017) all believe that personalization holds bright prospects for the sector, which could really take off if 'home' 3D food printers become mainstream kitchen appliances—something that companies like Natural Machines, with their Foodini system, and Print2Taste, with their Bocusini system, are already offering. The paper by Liu et al. (2017) gives insight into the various applications of personalized food—for populations with medical conditions, for soldiers, for astronauts, and so on—and the inherent difficulties involved—shape fidelity for delicate objects with architectural complexities, printing speed, and so on. Among these target populations, the most widely cited in the literature is elderly people with sarcopenia or dysphagia. Thompson (2007) explains that sarcopenia is a loss of skeletal muscle mass resulting in a reduction of physical strength that can lead to loss of independence, pain, and prolongation of hospitalizations. It is projected that the global population of people aged 60 years and over will reach 1.4 billion by 2030 and 2.1 billion by 2050 (including 202 million people aged 80 years and over by 2030 and 434 million by 2050), yet there are no effective therapeutic interventions against this age-related disease. One therapeutic strategy is diet interventions to supply essential specific nutrients for this population (Luo, Lin, Li & Liu, 2017). This is where food-sector AM can prove helpful by proposing new controlled-composition foods with adapted flavours. Dysphagia or swallowing troubles affects 15%–25% of seniors (Sun, Peng, Yan, Fuh, & Hong, 2015b), and the incidence is high in patients who have had stroke, paralysis, Parkinson's disease, the list goes on. In response, as the swallowing reflex is impaired, the food given has to be made texture-appropriate, i.e. purees and thickened fluids (Kousani et al., 2017). Food texture is thus a central concern for these ageing-related syndromes. Food design by 3D printing could make it easier for these populations to intake animal protein-packed foods that do not have to be mashed into a puree.

Derossi et al. (2018) underlined how people struggle to meet the nutritional guidelines on getting 5 fruits and vegetables per day, with only 10% of the Italian population following these recommendations. The upshot is that there are many children and teenagers with vitamin and mineral deficiencies, especially for iron and calcium, which is partly due to parents struggling to get their children to eat certain foods. Personalization by 3D printing could serve to develop foods or food supplements that are nutritionally targeted to this population by playing on tastes and texture. Derossi et al. (2018) 3D-printed a snack devised to provide the recommended nutritional requirements, and composed of the following ingredients: banana (for palatability), dried mushrooms, white beans, skimmed milk powder, lemon juice, ascorbic acid (an antioxidant), and

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pectin (11% to get consistency and avoid phase separation). All these ingredients were blended then 3D-printed to a set geometry while controlling for print speed and flow level. The results showed that flow level had a big effect on microstructure: low flow resulted in irregular structures and filament breakup, whereas higher flow led to better filament fusion but worse porosity (enlarged total volume). Despite running into technical problems, chiefly rheological issues, this study has proven that it was entirely possible to 3D print functional foods targeting a specific population. However, it would have been useful to capture the target population's experience of the food, especially in terms of organoleptics and acceptability.

The population segments cited above (seniors and children/teenagers) are not the only populations concerned by food customization, which also directly concerns a large number of 'subpopulations' that, together, represents a substantial mass of people: athletes, pregnant women, people with allergies, or young adults who lack either the time or the desire for cooking. However, where these new technologies really could bring transformative benefit to the masses would be to improve global food security and fight famine. There are a number of countries in the world affected by famine, and the people exposed have specific needs. AM could help these populations by maximizing the nutritional composition of foods available and pulling together different sources of nourishment, from meats to algae, lupine seed, insects, and more (Lupton, 2017).

Lipton (2017), who is primarily focused on western populations, asserts that there are two main reasons to use AM for the food industry: one is health, the other is consumer preferences. Lipton (2017) takes the example of the US population, where 4% of people have food allergies, where a substantial fraction of the population has digestive disorders (like lactose intolerance), where 60 to 70 million Americans are on dietary adjustments due to diseases (like Crohn's disease or irritable bowel syndrome), and where 69% of the population is overweight or obese—and all this without counting all the people that have difficulty chewing and/or swallowing. Lipton (2017) believes that automated (i.e. computer-controlled) mass customization of food would not only help make life easier for certain people with special food needs but also make food contamination by allergens far less likely, or even completely eliminate an ingredient.

This dimension of personalized food has been investigated in a handful of studies in continents worldwide. Examples would include, again, the European PERFORMANCE project, and research by Kousani et al. (2017) who endeavoured to find solutions for people with swallowing difficulties by developing a 3D printer that can fuse visually appetizing foods from pureed tuna, pureed pumpkin and pureed beetroot. They underline that there has been little effort made to use 3D food printing to improve the lives of people with special mealtime needs. They go on to state that 3D food printing could be used to automate the production of pureed foods and thickened liquids, improve the consistency and repeatability of foods produced in terms of texture and moisture, enhance the taste-

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sensory experiences in texture-modified meals, and manufacture visually attractive pureed foods and thickened liquids for people with dysphagia.

VII) Consumer acceptability of an innovative process

The big consumer demand trend is towards less-processed additive-free foods. That said, how would perceptions change in the case of diagnosis-confirmed and severe malnutrition-related conditions when AM can design a supplemented food, say a protein-supplemented food, offering optimal mechanical and nutritional properties? It would then be possible to define two separate spaces for 3D food printing applications: additive-free foods for masses, and foods for therapeutic intervention that entail a higher level of food processing. However, would they still be perceived as ‘foods’? And, if so, how could these foods be integrated into daily diet?

Earlier we touched on muscle tissue fabrication by culturing stem cells as potential application for 3D food printing. The studies by Siegrist & Sutterlin (2017) and Carocho, Morales & Ferreira (2015) showed that consumers were looking for foods that were as natural as possible and had better perceptions of traditionally-farmed meat than *in vitro* meat, even if *in vitro* (cultured) meat is more environment- and animal welfare-conscious. However, these same studies also underline how consumers will evaluate a food based on symbolic but high-impact information signals. An in-depth survey on consumer attitudes to a new technology and the release of short, sharp, and straightforward information would provide consumers relevant insight on the value and utility of a new process or a new way to eat. Brunner, Dellez & Denkel (2017) tackled this objective by polling 2047 people, and learned that consumers had a poor understanding of 3D food printing. However, they were able to test the positive effect of consumer-targeted information by explaining that the new technology could help them prepare healthy, personalized meals, all while injecting a dose of fun. This is confirmed by Lupton (2017) who argued that for a new technology or a new food to win acceptance, it must first convince the consumers of its potential and its value, while at the same time offering them reassurances. As we have seen throughout this paper, 3D food printing cannot currently do without additives (Hamilton, Alici & In Het Panhuis, 2018), chiefly texture stabilizers, especially when printing meat products. Evans, de Challemaison & Cox (2010) revealed that in terms of prompting consumer deviation from ‘natural’, chemical changes were more potent than physical changes. AM today, though, aggregates both types of processing, which is precisely why 3D food printing research needs to press ahead, to attempt to minimize the use of additive inputs while further improving process output. Lupton & Turner (2016) state that 3D food printing technologies will only expand if they manage to keep the food ‘natural’. This vision would enable consumers to hold onto their affective ties with food and turn a blind eye to the transgressive side of the

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technology. Their study also addressed what looks like the biggest segment opportunity for 3D food printing: personalization/customization. If perceptions of 3D-printed food can be oriented towards nutrition/health dimensions or towards combating malnutrition, then the technology could become an asset rather than a barrier to eating 3D-printed food. Niche markets, natural resource stewardship, food security and culinary creativity are all factors expected to drive uptake of this new type of food process.

3D food printing could well find a place as a new process in the collective consciousness, and become no more revolutionary than the microwave oven back in its day. Even if, as Brunner et al. (2017) concluded, simply drawing comparisons between an old and a new technology is not enough to break down reticence and resistance to the new one, food neophobia will always crystallize, or even galvanize, in some people. Generation Z today (the demographic cohort born after the year 2000), in France alone, will represent 75% of the working population tomorrow. This new generation is set to turn today’s food patterns upside down, using digital devices that will become ubiquitous. Round-the-clock home delivery, the influence of social networks on the way we eat, and diet tracking via dedicated apps will emerge new ways to feed our bodies—ways where AM is expected to flourish. Note that several surveys are already reporting that one in two 18–24-year-olds is ready to use a 3D food printer sometime in the future (The NPD Group, 2017; Kantar TNS, 2017). According to analysis by The Nielsen Company (2015), four different categories of Millennials (the demographic cohort born between 1980 and 2000, also labelled Generation Y) are set to coexist: Consumers who are environmentally conscious and concerned about the environmental impact of food-related processes will stand next to people drawn by high-tech, people concerned about their purchasing power, or people who embrace innovation yet hold onto certain more ‘traditional’ values. Researchers and engineers need to compose with all of these audiences in order to develop the uptake of 3D printing. Another category of people—a multigenerational demographic this time—could also shape the way we eat, particularly meat: they are the flexitarians. Flexitarianism is a diet–lifestyle movement in which meat consumption is kept moderate, reduced or even minimized, but not entirely excluded. While around 1.7% of the French population are vegetarian and another 0.5% vegan, 34% of households are flexitarians, and 19% of flexitarians are under-35s (Kantar Worldpanel, 2016). This population, which is convinced climate change is a very real problem, could be receptive to the arguments for 3D food printing based on upcycling animal by-products and minimizing food waste. Flexitarians could also be a first-line target audience for the design of new foods built with different protein sources, as discussed earlier in this paper. The study by Noort, Van Bommel & Renzetti (2017) offers a good foundation for avenues to progress on these challenges. On top of building a pilot-scale 3D food-printing facility that can print 60 full meals per hour and using a multi-scale approach to deliver a personalized food texture, they also ran fortified composition tests. Working on plant-based

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products, they kept at least 80% of the main ingredient, with the other 20% allowing for fortification with proteins, fats, micronutrients, and gelling agents. The same strategy was followed by Severini, Azzolini, Albenzio & Derossi (2018b) with using edible insects as a new protein source. These efforts demonstrate that it is possible to 3D print foods composed of different sources of protein or other macromolecules. It is therefore perfectly conceivable to use a similar approach for meat-based products, by lending them added nutritional value and adapting a sustainable development approach in which meat products, fats and plant-crop proteins or proteins from algae, mushroom or insect sources could be co-incorporated.

CONCLUSION

3D printing is unquestionably a technology with a bright future in a whole number of sector spaces. The food chain industry can also use these innovative processes to tackle today's issues for tomorrow's generations. Providing custom-tailored turnkey nutritional solutions to populations that have thus far been excluded from certain markets due to their health conditions, deprived of regular access to food resources, or simply too short of buying power, represents a series of issues that, although complex and challenging, are not impossible to overcome. Resolving these issues will undoubtedly revolve around some degree of mass customization of new additive manufacturing processes, or by new product value-streaming processes. This review arrives at the conclusion that 3D food printing is on a trajectory to further progress and development. A number of products are, or soon will be, ready to go to market. Nevertheless, the meat-based foods problem, where the main technological hurdle remains texturizing the printed foods, has yet to be resolved. The major challenge for the coming years will be to work on using 3D printing to develop meat products or products blending alternative protein sources that remain perfectly structured without having to use additives. A substantive work remains to be done at this level by seeking to increase the cohesion between the layers of the product by optimizing the 3D-printing parameters, but also by adapting the physical and / or chemical properties of the printed product with no adding of chemical substances. Once this step is completed, research will be essential to enable the manufacture of healthy foods, both from a microbiological and chemical point of view. To achieve this, tomorrow's 3D printers for foodstuffs have to be think from now so that their design accounts for easy cleaning and integration of a post-processing system (cooking, drying ...), and why not, a system of packaging, in order to limit the handling of product and thus the risks of external contamination. From a chemical point of view, the printing times being, for the moment, relatively long, it is therefore necessary to pay careful attention to the immediate environment of the food being printed in order to preserve its various constituents from the oxidation phenomena (printing under nitrogen atmosphere…). If all these various challenges are raised, the manufacture by 3D-printing of microbiologically and chemically stable foodstuffs that could be then conserved at room temperature will then be a reality, thus leading to a real sustainable development approach. The final step will then be to garner consumer acceptance for these 3D-printed foods. If consumers are properly briefed on the methods employed and the benefits offered, then we see no real barriers to wider acceptability, especially among the future generations coming of age, many of whom will likely embrace both flexitarianism and hyperconnectedness. Today, the signs and signals suggest additive manufacturing is about to usher in the next new industrial revolution. So why not in food manufacturing? Time will tell.

Acknowledgments

The authors thank ATT (an ISO 9001:2008-certified technical and scientific translation services company) for proofreading the manuscript.

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Figure captions

Figure 1: Schematic representation of the operating principles of the main 3D printing methods used in the food sector: A) extrusion-based printing in the form of pneumatic, piston-driven or screw-driven robotic dispensing systems, in which a continuous stream of hydrogel is dispensed; B) thermal inkjet printers which are configured with a heater creating air-pressure pulses to generate droplets at the printhead. In piezoelectric inkjet printing, an actuator produces a mechanical pulse to force the bio-ink to flow from the nozzle as droplets. C) laser-assisted printing system which consists of a laser-absorbing layer - called the ribbon - a feeding layer of cell-laden hydrogel beneath, and a receiving substrate.

Figure 2: Evolution under consideration for the 3D printing of new proteinaceous-based foods in the next years.

Balck and white print is required for the figures.

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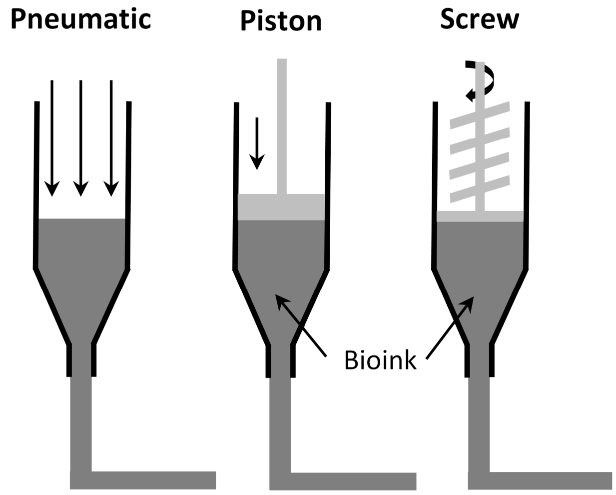
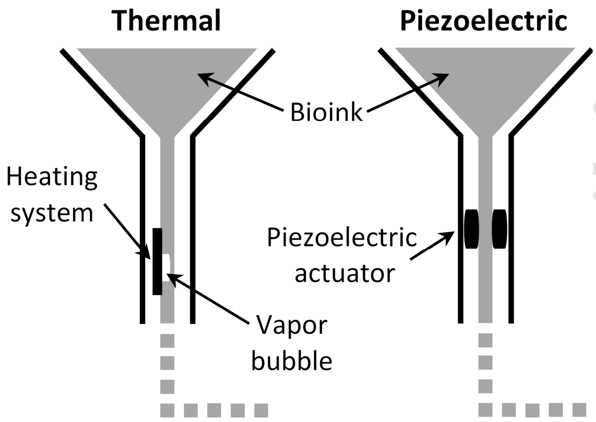
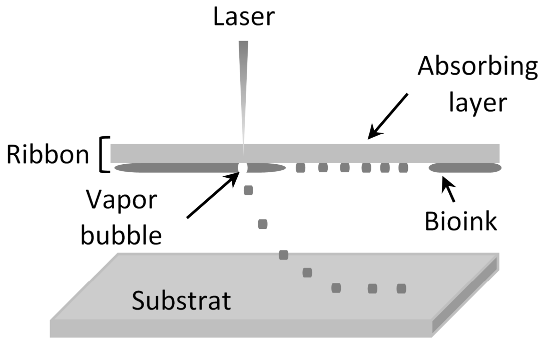


A - Extrusion-based printing



B - Inkjet printing



C - Laser-assisted printing

Figure 1

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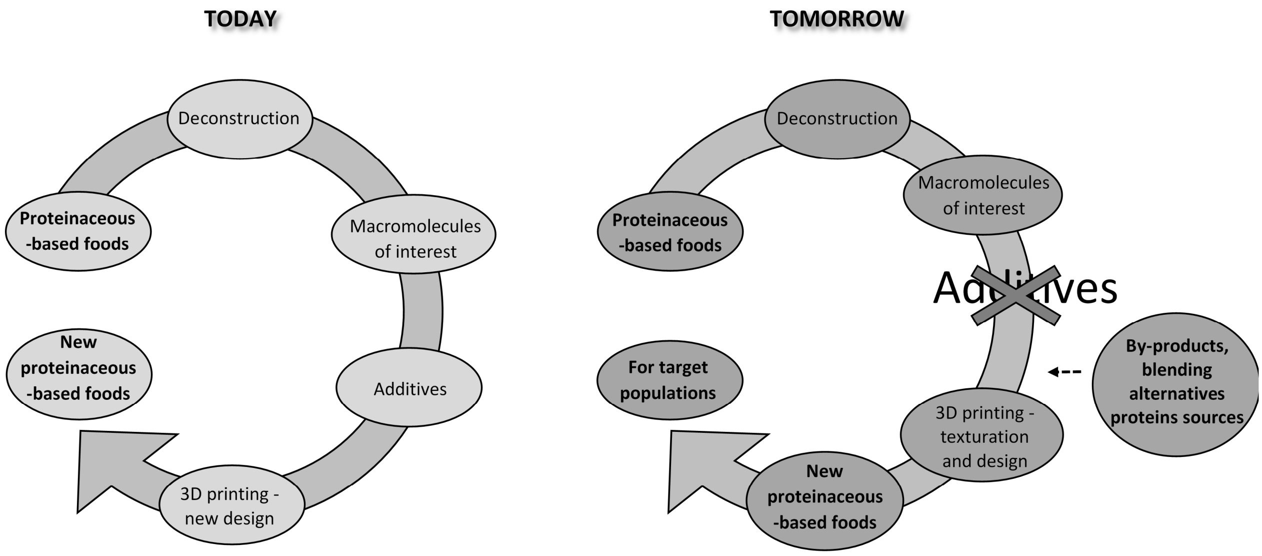

Figure 2

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Highlights

We reviewed the state of the science on the 3D printing of biobased products;

Some 3D printing applications developed in the medical and food sectors were analysed;

We looked at 3D-printed functional foods targeting various sectors of the population;

The consumer acceptability of 3D-printed food products was also deeply discussed;

Some development prospects for 3D printed biobased products were also investigated.

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