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1 **Toward the design of functional foods and biobased products by 3D printing:**

2 **A review**

3

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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.

46 I) Introduction

47
48 Additive manufacturing (AM), popularly dubbed “3D printing”, has emerged, expanded and matured
49 to a stage where it provides enormous freedom to design, manufacture and innovate in spheres from
50 mechanical engineering (Chen et al., 2017) and aeronautics (Ford, Mortara & Minshall, 2016) to
51 design science (Lanaro et al., 2017; Areir, Xu, Harrison & Fyson, 2017; Takezawa & Kobashi, 2017),
52 biomedical engineering (Singh & Ramakrishna, 2017), the pharmaceutical industry (Icten et al., 2017;
53 Goole & Amighi, 2016), biotechnology (Krujatz et al., 2017), and even food (Pinna et al., 2017). The
54 literature on 3D printing technologies is booming, and with the immense promise and potential
55 applications unlocked by AM, a number of authors are even starting to talk about a new industrial
56 revolution (Campbell, Williams, Ivanova & Garrett, 2011; Gross, Erkal, Lockwood, Chen & Spence,
57 2014; Attaran, 2017). There are niche markets (jewellery, luxury cars, and others) where AM is
58 already used to produce certain objects which are then marketed (Ford et al., 2016). Research in 3D
59 printing is expanding, as the technology is ideally geared to the rapid prototyping phases (Berman,
60 2012; Attaran, 2017) that require feasibility without mass production and rapid manufacturing. AM is
61 a digitally-controlled robotic construction process, which can build up complex solid forms layer by
62 layer and apply phase transitions or chemical reactions to bind the layers together (Sun, Peng, Yan,
63 Fuh & Hong, 2015a). To do this, several reference techniques exist, using different materials. We can
64 cite: binder jetting (Meteyer, Xu, Perry & Zhao, 2014), directed energy deposition (Heigel, Michaleris
65 & Reutzler, 2015), material jetting (Krujatz et al., 2017), powder bed fusion/binding (Huang, Liu,
66 Mokasdar, & Hou, 2012), sheet lamination (Shimizu et al., 2014), vat photopolymerization (Singh,
67 Ramakrishna & Singh, 2017) and material extrusion (Huang et al., 2012). Versatility is another big
68 reason to use AM, particularly for biobased products. Indeed, being able to work from the
69 macroscopic scale (e.g. 3D-printing of foodstuffs) up to a microscopic scale (e.g. cell-by-cell
70 deposition for the construction of organs or tissues) makes it possible thanks to the wide range of
71 existing printing techniques. For 3D printing of biobased products or foods, the following techniques
72 are well-suited: 1) extrusion-based printing, the most popular method in food printing (Sun, Zhou,
73 Yan, Huang & Lin, 2017), 2) inkjet printing (Singh, Haverinen, Dhagat, Jabbour, 2010), and 3) laser-
74 assisted printing (Guillot et al., 2010). Figure 1 schematizes the operating principles of these
75 methods.

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

81 deposition modelling of thermoplastic. While metal feed 3D printers for industry can cost up to
82 \$500,000 (Severini, Derossi & Azzolini, 2016), there are mainstream 3D printers now available that
83 offer perfectly acceptable performances for an affordable few hundred dollars (Prusa i3[®], RepRap,
84 France; Hephestos 2[®], BQ[®], Spain...). This means that cost of the hardware is no longer a barrier, and
85 so a huge number of applications can now be developed, by anyone ready to make a few appropriate
86 machine customizations: e.g. adding of syringe pump system, embedded cooking system, or cooling
87 system ... In our opinion, personalization means a major modification and not simply to use various
88 nozzles or needles. For instance, Bégine-Drolet et al. (2017) have developed a new printhead for
89 making structures out of sugar, based on a system using a lead gear and a worm gear combined with
90 an ultra-fine pitch screw to deliver a syrup contained in a syringe. To obtain a quickly solidification of
91 the sugar, an air cooling system was added near the nozzle.

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

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

113

114 II) Biobased product development by additive manufacturing

115 II.1) In the medical sector

116
117 Bose, Ke, Sahasrabudhe, & Bandyopadhyay (2018) dichotomizes the two categories of 3D printing
118 processes for biomaterials: acellular (ceramics, hydrogels, thermoplastics...) and cellular. Cellular-
119 category biomaterials can serve as scaffolds to print living cells that will multiply and form tissue
120 constructs. For Krujatz et al. (2017), biofabrication and bioprinting are two tightly-linked
121 bioengineering fields that are both synonymous with processes for living-cell and biomaterials. Most
122 commonly used methods are inkjet printing, extrusion-based printing and laser-assisted printing
123 (fig.1). The main biomedical applications are for 3D printing body tissue (Chia & Wu, 2015), from
124 bone and organs to blood vessels, nerves, and more. Almela et al. (2017) demonstrated that 3D
125 printing could be used to fabricate a human bone-like calcium-scaffold microstructure, and their
126 study opens promising perspectives for bone grafting. However, despite the opportunities these
127 techniques bring to medicine for building or regenerating organ tissue *in situ*, there are a number of
128 technical issues still to overcome, as highlighted by Gudapati, Dey & Ozbolat (2016), such as the
129 droplet-based bioprinting technique that leads to narrow range of available bioink material, cell
130 damages induced by bioprinting, restrictions on the size of constructs due to lack of vascularization
131 and porosity... Over and above complex ethical or regulatory issues, there are also fundamental
132 technical bottlenecks to contend with, like the narrow range of available biomaterials, the cellular
133 lesions induced by the bioprinting process, or the mechanical and structural integrity of the tissue
134 constructs that will affect the vascularization—and therefore the viability—of 3D-bioprinted tissue
135 organs. Jakab et al. (2010) assert that it is crucial to design a fully-controllable cellular environment in
136 order to provide a biomimetic paradigm that can place the right cells in the right place and with the
137 right phenotype to make functional assemblies. The authors also underscore the core role of the
138 scaffold in the tissue fabrication process, as it is the scaffold, designed from biodegradable material,
139 that serve as the template providing the tissue with specific topological features at nano, micro and
140 macro scale. However, the use of biodegradable scaffolds leads to the residual presence of polymer
141 fragments, which may disrupt the normal organization of the vascular wall (Jakab et al., 2010;
142 confirmed by Gudapati et al., 2016). Several studies (Melchels et al., 2012; Inzana et al., 2014; Munaz
143 et al., 2016; Wlodarczyk-Biegun & Del Campo, 2017; Shanjani et al., 2017) deal with ways to
144 implement the scaffolds, which are absolutely crucial architectures for fabricating tissue.
145 Wlodarczyk-Biegun & Del Campo (2017) reviewed recent achievements in bioprinting major
146 structural proteins like collagen, silk and fibrin that confirm how porous and networked scaffolds are
147 readily 3D printable. Note that it is possible to use different cellular types or materials simultaneously
148 or sequentially during the same tissue engineering process. Scaffolds or hydrogels which offer the
149 advantage of being biocompatible (Melchels et al., 2012) and providing a suitable environment for
150 the cells due to their high water content and low polymer content (Wlodarczyk-Biegun & Del Campo,

151 2017). There are still-unresolved technical challenges with using them (rheological properties,
152 crosslinking density, and more), but natural compounds (like gelatin or hyaluronic acid) can be
153 already combined with synthetic polymer network components like methacrylamide to promote
154 crosslinking (Melchels et al., 2012).
155 Collagen gels in 3D bioprinting can serve in medical applications for targeted cell placement to
156 generate a given form, and extend cellular viability. Dunn, Yarmush, Koebe & Tompkins (1989), cited
157 by Melchels et al. (2012), showed that hepatocytes conserved their functions for several weeks when
158 sandwiched between two layers of collagen gel, against just a few days with a single layer. After
159 observing similar effects, Munaz et al. (2016) concluded that the longer cellular viability conferred by
160 this collagen hydrogel was because it keeps the cells better hydrated and better aggregated for a
161 long time, without settling. Smith et al. (2004) developed a script to construct an artery branch of a
162 pig heart using bovine aortic endothelial cells suspended in type-1 collagen. This data, even if it
163 comes from the medical sector, suggests that 3D-printed foods containing collagen may hold an
164 excellent level of hydration, which in turn would have a positive influence on their texture or
165 mouthfeel.

166 II.2) In the food sector

167
168
169 Godoi, Prakash & Bhandari (2016) claim that AM technology holds huge potential to fabricate foods
170 with complex geometries, advanced textures and tailored nutritional contents, but Liu, Zhang,
171 Bhandari & Wang (2017) noticed only few studies dealing in the degree of precision required to make
172 structurally-controlled foods by AM. In reality, the major difficulties for 3D printing novel foods stem
173 from a number of factors, including material properties, printing-process parameters and post-
174 processing parameter (methods of cooking, conservation, and so on). Even if some authors find that
175 uptake of AM in the specialty food industry has ultimately disappointed (Gausemeier, Echterhoff,
176 Kokoschka & Wall, 2011, cited by Mawale, Kuthe & Dahake, 2016), there are nevertheless signs of an
177 emerging trend for culinary applications tied to the 'food design' movement, with several recent
178 papers addressing these applications (Pallottino et al., 2016). The European project
179 PERFORMANCE—Personalised Food using Rapid Manufacturing for the Nutrition of Elderly
180 Consumers (Lipton, Cutler, Nigl, Cohen & Lipson, 2015; Liu et al., 2017), had even set out to use 3D
181 printing for the development or appealing new foods for seniors. 3D printing can thus be used to
182 enhance certain foods and make them more attractive to consumer populations, or simply to create
183 new forms or structures for commercial profit. The technological angle may be interesting—printer
184 customization, open source, programming, and so on—and the societal angle may be important—
185 food attractiveness to certain populations—but there are legitimate grounds to stop and question

186 the real scientific impact value of studies focused exclusively on food design. For example, Zhao et al.
187 (2018) investigated the potential reach of programming with the aim of fashioning a personalized
188 food product that can be printed with a face from a photo.

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

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

220

221 III) Impact of additive manufacturing processes on food macromolecules

222
223 Le Tohic et al. (2018) explain an AM process as subjecting the product to two types of constraints: 1)
224 thermal treatment as the product melts, and 2) shear strain as the product extrudes through the
225 nozzle. Process used thus has one or more effects on macromolecules making up the food product
226 which will modify its properties. A majority of studies on compounds of interest in food applications
227 of AM have focused on the 'printability', where printability is the set of material properties that lend
228 a product enough stability in space to support its own weight (Godoi et al., 2016).
229 Although it is relevant to study a food in whole, in the case of the design of a food with therapeutic
230 aim, it can be necessary to have elements in connection with the main macromolecules of nutritional
231 or structural interest. Moreover, within the scope of the 3D printing of a food intended to be
232 consumed by people within the framework of a deficiency or of a pathology, it is perfectly
233 conceivable to resort to a basic medium having the form of a hydrogel containing meat proteins,
234 which could be enriched in vegetable proteins, lipids and carbohydrates. In this case, understanding
235 the interactions between the printing process and all the compounds taken one by one is
236 fundamental.

237 238 III.1) Impact on proteins

239
240 Relatively few animal protein-rich products have been studied for applicability in AM. Exceptions
241 include various types of pureed meat (Lipton et al., 2015), collagen (Inzana et al., 2014) and gelatin
242 (Farag & Yun, 2014). Nevertheless, certain studies are hugely instructive on the difficulties posed by
243 this kind of food matrix: For Godoi et al. (2016), materials should be homogenous, have appropriate
244 flow properties for extrusion and should support its structure during and after printing process. For
245 Wang, Zhang, Bhandari & Yang (2018), as a mixture, each component (proteins, carbohydrates, lipids
246 and water) can undergo changes that will influence the fusion and the plasticization of the food. For
247 example, printability of fish surimi gels systems was the best with a sodium chloride (NaCl)
248 concentration of 1.5 g/100 g surimi (Wang et al., 2018). Gracia-Julia, Hurtado-Pnol, Leung & Capellas
249 (2015) (cited by Severini et al., 2016) observed a better printability of beef-based preparations when
250 the myofibrillar proteins were solubilized, due to salt adding. Electron microscopy showed that the
251 added NaCl had led to myofibrillar protein crosslinking, enabling free amino acids to bind to the
252 proteins, shrinking the void spaces, and changing the structure of the gel into a fine-strand network
253 (Wang et al, 2018). This effect is maximal, and holds constant, at 1.0 g NaCl/100 g surimi. Protein
254 printing is thus governed by the properties of the proteins, and crucially protein aggregation, which is
255 further governed by the isoelectric point (pI). Godoi et al. (2016) assert that AM technologies can

256 create new textures by intercalating layers of food proteins with layers of polysaccharide materials
257 like alginate, applying temperature or mechanical stresses, or incorporating acid or base compound
258 ingredients in the AM process to promote aggregation. Finally, Liu et al. (2017) posited that precise
259 and accurate 3D food-based structures cannot be successfully printed without adding texturizers like
260 hydrocolloids or gelable proteins, which has since been confirmed by Yang, Zhang, Bhandari & Liu
261 (2018) for 3D food printing with turkey meat.

262 The major structural proteins (collagen, elastin, and fibrin) have already been studied for fabrication
263 of complex-architecture scaffolds as a step towards performing cell-by-cell deposition. The
264 organization of these fibrous proteins, governed by alignment constraints, diameter constraints and
265 pore structure constraints, varies according to type of tissue and has a huge influence on its
266 mechanical properties. Fibrin is a protein produced naturally by the body where it is used to repair
267 injury, but it can also be 3D-printed in gel form (Melchels et al., 2012; Chia & Wu, 2015). Fibrin is
268 used in AM for fabricating scaffolds to repair bone, neurons or heart valves (Munaz et al., 2016).
269 Collagen, which is the most abundant protein in mammals, can be bioprinted as a gel, after
270 extraction and enzymatic digestion. According to Wlodarczyk-Biegun & Del Campo (2017), printable
271 collagen-based solutions vary in concentration between studies, from 0.2 mg/mL up to 20 mg/mL in
272 an ionic strength adjustment solution. Choice of concentration will depend on the mechanical
273 properties targeted, such as maintaining tissue integrity, or the viability characteristics of the seeded
274 cells. For example, a 1 mg/mL gel can generate cohesive and reproducible structures, provided that
275 pH is kept under control, as a high pH can clog the printhead nozzles. Pure collagen lacks the stability
276 needed to form a 3D structure, so it has to be combined with other polymers. Furthermore, without
277 inducing added crosslinking, collagen will form mechanically inferior hydrogels. Crosslinking is
278 inducible by chemical reaction using formaldehyde or glutaraldehyde or by enzymatic reaction using
279 transglutaminase (Wlodarczyk-Biegun & Del Campo, 2017). Inkjet, extrusion and laser-assisted
280 bioprinting processes have all been mobilized for difficult-to-print collagen solutions (Inzana et al.,
281 2014; Jakab et al., 2010; Wlodarczyk-Biegun & Del Campo, 2017). Extrusion processes can already
282 work with multi-printhead and/or crosslinking system-coupled 3D printers (Smith, Christian, Warren
283 & Williams, 2007; Hinton et al., 2015). However, according to Murphy, Skardal & Atala (2013), and
284 Wlodarczyk-Biegun & Del Campo, (2017), the main difficulties with using collagen as an extrusion-
285 process bioink are the gel time, which is long, and swelling, which was also flagged up by Munaz et al.
286 (2016) who concluded that despite being easily constructed for 3D structures, collagen biomaterial
287 molecules will eventually lose shape due to swelling or dissolution, which are the main limits to
288 further use.

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

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

309 Both Lipton et al. (2015) and Godoi et al. (2016) talk up the use of transglutaminase to build complex
310 geometries out of meat. Transglutaminase is an enzyme that can catalyse new protein matrices by
311 forming covalent bonds between lysine and glutamine residues, in a calcium-dependent reaction.
312 This process thus manages to enzymatically crosslink proteins present in meat purees, giving rise to
313 self-supporting hydrogels. However, the use of additives like transglutaminase, even if has potentially
314 valuable effects in terms of the resulting mechanical properties, runs counter to the current market
315 trend of getting back to more ‘natural’ foods. This means that any product developed via this kind of
316 process is likely to meet with consumer resistance, let alone regulatory hurdles in certain countries.
317 The biggest challenge for printing food, then, remains getting the right kind of texture to deliver an
318 appreciable mouthfeel. Proteins, as key structural macromolecules, are no exception to the rule. The
319 next step forward is to engineer printing strategies that can deliver fully-controlled structures—and,
320 if possible, without using texture-stabilizing additives (fig. 2).

322 III.2) Impact on lipids

323
324 Even though 3D printing studies have tackled high-fat-content foods like chocolate, very few have
325 investigated the effect of 3D printing on lipids and, *vice versa*, the effect of lipids on printability. To

326 the best of our knowledge, only Le Tohic et al. (2018) and Lille, Nurmela, Nordlund, Metsä-
327 Kortelainen & Sozer (2018) have tackled the issue. Le Tohic et al. (2018), working with an untreated
328 (i.e. non-extruded) cheese matrix, showed that the fat globules were round and homogeneously
329 distributed in a continuous protein phase. A comparable structure was observed in cheese melting at
330 75°C, although with bulkier fat globules due to heat ramp-induced coalescence. Cheese extrusion-
331 printed at 4 mL/min and 75°C showed heavily altered microstructure: the protein phase had become
332 discontinuous and the fat globules had changed morphology—losing sphericity and gaining volume—
333 with the appearance of interstitial fat. However, the print parameters also have a visibly major effect,
334 since fat globule size and distribution were more homogeneous after printing at 12 mL/min (75°C),
335 likely due to a higher shear rate in this condition. Protein–lipid interactions are though to explain the
336 rheological changes observed to occur in 3D-printed cheeses, i.e. a softer texture that is not as sticky
337 due to the greater amount of surface fat released during the shear processes.

338 Lille et al. (2018) examined the role of lipids during food printing processes by working on milk
339 powder as a source of both proteins and fat. They tested two formulations presenting equivalent
340 protein contents (21% and 22%, respectively) in solutions of water with skimmed (0.4% fat) and
341 semi-skimmed (9% fat) milk powder. They showed that the skimmed-milk formulation gave a highly-
342 viscous and difficult-to-print paste that was too sticky to evenly deposit, and when the milk powder
343 concentration was upped from 50% to 60%, printing became simply impossible, whatever the nozzle
344 diameter used, whereas with the semi-skimmed formulation, even at 60% concentration, printability
345 proved to excellent, both in terms of precision and of holding printed shape. Lille et al. (2018)
346 explained that fat had acted as a lubricant in the extrusion system and that the biomaterial was more
347 fluid. Note that carbohydrate content differed substantially between the two formulations (32% and
348 23%, respectively), which may also have influenced fluid flowrate.

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

355

356 III.3) Impact on carbohydrates

357

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

361 Bae & Park (2018), using methyl cellulose as reference biomaterial to simulate the printability of
362 various food-inks, showed that 9%, 11% and 13% hydrocolloid concentrations were able to scaffold
363 28 mm-diameter cylindrical constructs with heights of 20 mm, 40 mm and 80 mm, respectively,
364 without collapse. Working on printable pectin-based formulation, Vancauwenberghe et al. (2017)
365 tested the effect, at otherwise-constant print parameters, of different formulations involving
366 different stirring speeds and different concentrations of pectin, calcium chloride, bovine serum
367 albumin (BSA) and sugar syrup. A coherent and lasting 3D structure was only achievable by adding
368 CaCl_2 to partially crosslink the pectin. This study showed that pectin and sugar syrup concentrations
369 directly influenced viscosity of the mixture, and that BSA stabilized and aerated the mixture.
370 Vancauwenberghe et al. (2017) thus demonstrated the feasibility of 3D printing textured variable-
371 microstructure foods.

372 Starch, a commonplace food additive, has also been investigated. Liu, Zhang, Bhandari & Yang (2018)
373 led research on 3D printing low-starch to high-starch potato purees and found that a puree had to
374 contain at least 2% starch to be printable. In this condition, the material showed an increase in elastic
375 limit, and better extrudability. However, at 4% starch content, despite the material comfortably
376 holding its 3D shape and structure, it had poor extrudability due to over-high viscosity. Yang et al.
377 (2018) also confirmed that complex sugars like potato starch are 3D printable. Their study, which
378 paired lemon juice and starch (at 15 g/100 g), managed to determine the optimal print-process
379 parameters—nozzle diameter, printhead speed and extrusion rate—that fabricating smooth-surfaced
380 constructs with zero deformation. Research by Lille et al. (2018) demonstrated, much like for lipids
381 (see section III.2), that a 15% starch solution had better printability when the formulation contained
382 semi-skimmed milk powder instead of skimmed-milk powder. However, feedrate through the
383 extrusion system was dependent on the particle size of the food components, as for plant-based
384 foods containing protein, starch and fibre, the viscous aspect of the starch, which comes from the
385 presence of particles, quickly clogs up the system.

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

392

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

394 IV.1) Solutions for safe fabrication

395

396 If uptake of food engineering/manufacture by AM finally takes off, then the health–safety issue is
397 going to come up during the process, but also during the food preservation stage, both in terms of
398 microbiological safety (pathogenic and spoilage bacteria, fungus) and food chemistry (oxidation,
399 newly-formed compounds). Most current 3D printers for food products were originally developed in
400 laboratories, where easy-to-clean and/or easy-to-decontaminate design is not generally a concern.
401 3D printers tomorrow will need to be made in stainless steel and meet strict industry standards
402 (Lipton et al., 2015) to prevent cross-contaminations between foods while minimizing the amount of
403 time the 3D-printed food product is exposed to open air (presence of oxygen, high temperatures,
404 and so on). This is confirmed by Severini, Derossi, Ricci, Caporizzi & Fiore (2018a). They 3D-printed a
405 fruit-and-vegetable-based smoothie and monitored its microbiological profile over 8 days when the
406 product was stored at 5 °C in air (20% O₂ and 80% N₂) or under modified atmosphere (5% O₂ and 95%
407 N₂). Microbial concentrations (mesophilic flora, psychrophilic microorganisms and yeasts) in the
408 samples started high, at between 4 and 5 log CFU·g⁻¹, on Day 0, remained stable between Day 0 and
409 Day 6 whatever the food preservation conditions, then showed a decrease at Day 8. The authors
410 explained this initially high microbial contamination as introduced by the printer itself, via its pistons,
411 its tubes or the extruder, as they had carefully washed the ingredients beforehand.

412 According to King et al. (2017), global population is expected to reach at least 9 billion by the year
413 2050, requiring 70% more food and requiring fully-sustainable food production systems. Meeting this
414 food security challenge needs to be part and parcel of tackling equally big strategic issues for food
415 research, such as the ageing demographics with a growing population of immunocompromised
416 persons, and rising consumer demand for clean-label foods. The authors thus raised the hypothesis of
417 ‘extra-safe’ food fabrication processes to make irradiated, sterilized, or pasteurized foods that are
418 targeted to higher-risk populations. On 3D food printing, King et al. (2017) raised a number of
419 concerns, chiefly the fact it could make everyone a food manufacturer without having any real
420 control over the water activities and pH of their self-created food, which will necessarily bring food
421 safety risks. Personalized diets, which we touched on earlier, are also a concern for King et al. (2017).
422 As consumers put more focus on the nutritional aspects than on food safety, there is a risk that
423 modifying, for example, the microbial flora of foods could create unintended food safety issues by
424 changing their gut microflora. Clearly, the 3D food printing, where industrially or at home, needs to
425 be tightly regulated to compensate for the evident lack of lookback experience on this technology
426 and eliminate all risks to health.

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

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

442 443 IV.2) The post-processing issue

444
445 Post-processing operations like drying, cooking and frying, but also pre-treatments like ultrasound
446 and radiofrequency processing, affect the rheology of food materials, especially gel formation. For
447 more substance-dense foods like lean beef paste, transglutaminase has to be added 0.5% by weight
448 to maintain shape fidelity after cooking (Liu et al., 2017). Lille et al. (2018), among others, think that
449 post-processing treatments could have a positive impact on 3D-printed foods. An example would be
450 drying, which could increase their stiffness. Lille et al. (2018) showed that freeze-drying preserved 3D
451 shapes much better than oven-drying, which tended to cause shrinkage. Water content of the
452 product is an equally important parameter, as more water to remove means more risk of losing
453 shape.

454 The data gap on post-processing steps in the 3D printing literature is manifest—a number of articles
455 underline that further studies are needed to determine the most suitable pre- and post-processing
456 (Liu et al., 2017), and that firm control of the physical-chemical, rheological and mechanical
457 properties of the printed foods is essential (Godoi et al., 2016). Furthermore, the health–hygiene
458 dimension has gone completely ignored. However, it is assuredly conceivable to design very precise
459 post-processing processes, e.g. systems using a laser beam or hot air jet, which are directly coupled
460 to the 3D printing system and which would, at the same time, ensure cooking and microbial
461 decontamination of the food.

462 463 **V) Eco-design and sustainability of additive manufacturing**

464 V.1) Energy consumption and use of raw materials

465
466 A number of studies essentially dealing with the fabrication non-food objects, and not foods, have
467 focused on the environmental effects of AM, or at least attempted to investigate the potential
468 effects ahead of widespread industrial-scale uptake (Burkhart & Aurich, 2015; Jackson et al., 2016).
469 This effort translates into energy (electricity) consumption assessments or into raw material savings
470 estimates (Huang et al., 2012). Although the scholarship appears unanimous that there is raw
471 material gain inherent to geometric adjustment (Jin, Du & He, 2017), there is much less consensus on
472 the electricity consumption issue. According to Kellens, Mertens, Paraskevas, Dewulf & Duflou
473 (2017), the specific energy consumption for AM unit processes is one to two-fold higher than
474 conventional machining and injection moulding processes, and according to Yoon et al. (2014), even
475 up to a hundred times higher. However, this higher environmental impact could be minimized by
476 optimizing the parts manufactured and making lighter parts, especially transport-sector applications
477 for road, rail and flight industries. According to Huang et al. (2012) and Peng (2016), 3D printing
478 processes generally outperform traditional manufacturing processes on environmental impacts.
479 However, as full industry uptake of AM methods has not yet taken off, quantifying its effects in mass
480 production remains a difficult exercise. Nevertheless, Mognol, Lepicart & Perry (2006) have shown
481 that optimized machine build parameters can save 40% to 60% energy on certain machines. Although
482 they reached similar conclusions, Griffiths, Howarth, De Almeida-Rowbotham, Rees & Kerton (2016)
483 toned down the prospects for transposing machine build parameter optimization to other processes,
484 and highlighted the importance of developing design-specific models for AM. Implementing a more
485 global approach based on lifecycle analysis, Le Bourhis, Kerbrat, Dembinski, Hascoet & Mognol (2014)
486 showed that it was entirely possible to develop environmental impact analysis tools assessing AM-
487 specific electricity, material and fluids flows. They also highlighted that materials consumption
488 actually had a bigger environmental impact than electricity consumption in AM processes. Watson &
489 Taminger (2018) very recently developed a model for comparing additive vs subtractive
490 manufacturing based on energy consumption. Their model accounts for the entire end-to-end
491 fabrication-process lifecycle, from production, transport and recycling of process materials through
492 to post-production waste processing and the energy used by the equipment on standby. Their
493 conclusions, which were fairly disappointing on balance, underline how certain data is difficult to get,
494 especially energy values for producing certain materials, and crucially, that the model results output
495 cannot be readily extrapolated for studying different AM process scripts and scenarios.
496 Peng (2016) gave five benefits of AM for reducing carbon footprint: 1) reducing the amount of raw
497 material in the supply chain, and thus the mining/processing of ores, 2) reducing the need to use
498 energy-intensive processes like casting and wasteful/harmful input materials like cutting fluid for
499 CNC machining, 3) flexibility for efficient process component design by optimizing operational

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

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

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

520
521 To the best of our knowledge, only Lupton & Turner (2016) and Lupton (2017) touch on the fact that
522 3D-printed foods could be environment-positive, by reducing waste, reducing the footprint of
523 transport via local-locale fabrication, reusing foodstuff material categorized as human-inedible, using
524 substitute foods, or developing edible packaging.

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

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

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

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

556 Muscle is not the only carcass component that AM can upvalue. As discussed earlier, the collagen is
557 also used, especially in the medical sector as a scaffold material (Inzana et al., 2014; Shanjani et al.,
558 2017). This structural protein, which is considered a by-product as it comes from the skin, bones and
559 tendons of animals, also finds an array of food-industry applications (gelatin) and could well find
560 great usability in fabricating functional foods engineered by AM (fig. 2). Mobilizing the structural
561 potential of collagen via AM could be a way to develop foods based on undervalued meat or offal
562 that have a texture suitable for young or senior citizens. Indeed, the only studies available to date on
563 AM-engineered meat-based foods (Gracia-Julia et al., 2015; Godoi et al., 2016), used purees or
564 ground beef, except those reporting whole-tissue fabrication by culturing stem cells (Lipton et al.,
565 2015). Research led by Shanjani et al. (2017) to spur orthopaedic applications could well inspire new
566 avenues for research in the food sector. Collagen-based architectures (scaffolds) with purpose-
567 defined motif and pore structure could serve as the build platform for fabricating texture-controlled
568 meat-based foods.

569

570 VI) Towards personalizable functional foods

571
572 Spurred by the rapid development of 3D technologies for food, authors like Wegrzyn, Golding &
573 Archer (2012), Sun et al. (2015a), Derossi et al. (2018), Liu et al. (2017), Severini et al. (2018a) and
574 Kousani et al. (2017) all believe that personalization holds bright prospects for the sector, which
575 could really take off if ‘home’ 3D food printers become mainstream kitchen appliances—something
576 that companies like Natural Machines, with their Foodini system, and Print2Taste, with their Bocusini
577 system, are already offering. The paper by Liu et al. (2017) gives insight into the various applications
578 of personalized food—for populations with medical conditions, for soldiers, for astronauts, and so
579 on—and the inherent difficulties involved—shape fidelity for delicate objects with architectural
580 complexities, printing speed, and so on. Among these target populations, the most widely cited in
581 the literature is elderly people with sarcopenia or dysphagia. Thompson (2007) explains that
582 sarcopenia is a loss of skeletal muscle mass resulting in a reduction of physical strength that can lead
583 to loss of independence, pain, and prolongation of hospitalizations. It is projected that the global
584 population of people aged 60 years and over will reach 1.4 billion by 2030 and 2.1 billion by 2050
585 (including 202 million people aged 80 years and over by 2030 and 434 million by 2050), yet there are
586 no effective therapeutic interventions against this age-related disease. One therapeutic strategy is
587 diet interventions to supply essential specific nutrients for this population (Luo, Lin, Li & Liu, 2017).
588 This is where food-sector AM can prove helpful by proposing new controlled-composition foods with
589 adapted flavours. Dysphagia or swallowing troubles affects 15%–25% of seniors (Sun, Peng, Yan, Fuh,
590 & Hong, 2015b), and the incidence is high in patients who have had stroke, paralysis, Parkinson’s
591 disease, the list goes on. In response, as the swallowing reflex is impaired, the food given has to be
592 made texture-appropriate, i.e. purees and thickened fluids (Kousani et al., 2017). Food texture is thus
593 a central concern for these ageing-related syndromes. Food design by 3D printing could make it
594 easier for these populations to intake animal protein-packed foods that do not have to be mashed
595 into a puree.
596 Derossi et al. (2018) underlined how people struggle to meet the nutritional guidelines on getting 5
597 fruits and vegetables per day, with only 10% of the Italian population following these
598 recommendations. The upshot is that there are many children and teenagers with vitamin and
599 mineral deficiencies, especially for iron and calcium, which is partly due to parents struggling to get
600 their children to eat certain foods. Personalization by 3D printing could serve to develop foods or
601 food supplements that are nutritionally targeted to this population by playing on tastes and texture.
602 Derossi et al. (2018) 3D-printed a snack devised to provide the recommended nutritional
603 requirements, and composed of the following ingredients: banana (for palatability), dried
604 mushrooms, white beans, skimmed milk powder, lemon juice, ascorbic acid (an antioxidant), and

605 pectin (11% to get consistency and avoid phase separation). All these ingredients were blended then
606 3D-printed to a set geometry while controlling for print speed and flow level. The results showed that
607 flow level had a big effect on microstructure: low flow resulted in irregular structures and filament
608 breakup, whereas higher flow led to better filament fusion but worse porosity (enlarged total
609 volume). Despite running into technical problems, chiefly rheological issues, this study has proven
610 that it was entirely possible to 3D print functional foods targeting a specific population. However, it
611 would have been useful to capture the target population's experience of the food, especially in terms
612 of organoleptics and acceptability.

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

622 Lipton (2017), who is primarily focused on western populations, asserts that there are two main
623 reasons to use AM for the food industry: one is health, the other is consumer preferences. Lipton
624 (2017) takes the example of the US population, where 4% of people have food allergies, where a
625 substantial fraction of the population has digestive disorders (like lactose intolerance), where 60 to
626 70 million Americans are on dietary adjustments due to diseases (like Crohn's disease or irritable
627 bowel syndrome), and where 69% of the population is overweight or obese—and all this without
628 counting all the people that have difficulty chewing and/or swallowing. Lipton (2017) believes that
629 automated (i.e. computer-controlled) mass customization of food would not only help make life
630 easier for certain people with special food needs but also make food contamination by allergens far
631 less likely, or even completely eliminate an ingredient.

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

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

642

643 **VII) Consumer acceptability of an innovative process**

644

645 The big consumer demand trend is towards less-processed additive-free foods. That said, how would
646 perceptions change in the case of diagnosis-confirmed and severe malnutrition-related conditions
647 when AM can design a supplemented food, say a protein-supplemented food, offering optimal
648 mechanical and nutritional properties? It would then be possible to define two separate spaces for
649 3D food printing applications: additive-free foods for masses, and foods for therapeutic intervention
650 that entail a higher level of food processing. However, would they still be perceived as 'foods'? And,
651 if so, how could these foods be integrated into daily diet?

652 Earlier we touched on muscle tissue fabrication by culturing stem cells as potential application for 3D
653 food printing. The studies by Siegrist & Sutterlin (2017) and Carocho, Morales & Ferreira (2015)
654 showed that consumers were looking for foods that were as natural as possible and had better
655 perceptions of traditionally-farmed meat than *in vitro* meat, even if *in vitro* (cultured) meat is more
656 environment- and animal welfare-conscious. However, these same studies also underline how
657 consumers will evaluate a food based on symbolic but high-impact information signals. An in-depth
658 survey on consumer attitudes to a new technology and the release of short, sharp, and
659 straightforward information would provide consumers relevant insight on the value and utility of a
660 new process or a new way to eat. Brunner, Dellez & Denkel (2017) tackled this objective by polling
661 2047 people, and learned that consumers had a poor understanding of 3D food printing. However,
662 they were able to test the positive effect of consumer-targeted information by explaining that the
663 new technology could help them prepare healthy, personalized meals, all while injecting a dose of
664 fun. This is confirmed by Lupton (2017) who argued that for a new technology or a new food to win
665 acceptance, it must first convince the consumers of its potential and its value, while at the same time
666 offering them reassurances. As we have seen throughout this paper, 3D food printing cannot
667 currently do without additives (Hamilton, Alici & In Het Panhuis, 2018), chiefly texture stabilizers,
668 especially when printing meat products. Evans, de Challemaison & Cox (2010) revealed that in terms
669 of prompting consumer deviation from 'natural', chemical changes were more potent than physical
670 changes. AM today, though, aggregates both types of processing, which is precisely why 3D food
671 printing research needs to press ahead, to attempt to minimize the use of additive inputs while
672 further improving process output. Lupton & Turner (2016) state that 3D food printing technologies
673 will only expand if they manage to keep the food 'natural'. This vision would enable consumers to
674 hold onto their affective ties with food and turn a blind eye to the transgressive side of the

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

681 3D food printing could well find a place as a new process in the collective consciousness, and become
682 no more revolutionary than the microwave oven back in its day. Even if, as Brunner et al. (2017)
683 concluded, simply drawing comparisons between an old and a new technology is not enough to
684 break down reticence and resistance to the new one, food neophobia will always crystallize, or even
685 galvanize, in some people. Generation Z today (the demographic cohort born after the year 2000), in
686 France alone, will represent 75% of the working population tomorrow. This new generation is set to
687 turn today's food patterns upside down, using digital devices that will become ubiquitous. Round-
688 the-clock home delivery, the influence of social networks on the way we eat, and diet tracking via
689 dedicated apps will emerge new ways to feed our bodies—ways where AM is expected to flourish.

690 Note that several surveys are already reporting that one in two 18–24-year-olds is ready to use a 3D
691 food printer sometime in the future (The NPD Group, 2017; Kantar TNS, 2017). According to analysis
692 by The Nielsen Company (2015), four different categories of Millennials (the demographic cohort
693 born between 1980 and 2000, also labelled Generation Y) are set to coexist: Consumers who are
694 environmentally conscious and concerned about the environmental impact of food-related processes
695 will stand next to people drawn by high-tech, people concerned about their purchasing power, or
696 people who embrace innovation yet hold onto certain more 'traditional' values. Researchers and
697 engineers need to compose with all of these audiences in order to develop the uptake of 3D printing.

698 Another category of people—a multigenerational demographic this time—could also shape the way
699 we eat, particularly meat: they are the flexitarians. Flexitarianism is a diet–lifestyle movement in
700 which meat consumption is kept moderate, reduced or even minimized, but not entirely excluded.

701 While around 1.7% of the French population are vegetarian and another 0.5% vegan, 34% of
702 households are flexitarians, and 19% of flexitarians are under-35s (Kantar Worldpanel, 2016). This
703 population, which is convinced climate change is a very real problem, could be receptive to the
704 arguments for 3D food printing based on upcycling animal by-products and minimizing food waste.

705 Flexitarians could also be a first-line target audience for the design of new foods built with different
706 protein sources, as discussed earlier in this paper. The study by Noort, Van Bommel & Renzetti (2017)
707 offers a good foundation for avenues to progress on these challenges. On top of building a pilot-scale
708 3D food-printing facility that can print 60 full meals per hour and using a multi-scale approach to
709 deliver a personalized food texture, they also ran fortified composition tests. Working on plant-based

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

718

719 **CONCLUSION**

720

721 3D printing is unquestionably a technology with a bright future in a whole number of sector spaces.
722 The food chain industry can also use these innovative processes to tackle today's issues for
723 tomorrow's generations. Providing custom-tailored turnkey nutritional solutions to populations that
724 have thus far been excluded from certain markets due to their health conditions, deprived of regular
725 access to food resources, or simply too short of buying power, represents a series of issues that,
726 although complex and challenging, are not impossible to overcome. Resolving these issues will
727 undoubtedly revolve around some degree of mass customization of new additive manufacturing
728 processes, or by new product value-streaming processes. This review arrives at the conclusion that
729 3D food printing is on a trajectory to further progress and development. A number of products are,
730 or soon will be, ready to go to market. Nevertheless, the meat-based foods problem, where the main
731 technological hurdle remains texturizing the printed foods, has yet to be resolved. The major
732 challenge for the coming years will be to work on using 3D printing to develop meat products or
733 products blending alternative protein sources that remain perfectly structured without having to use
734 additives. A substantive work remains to be done at this level by seeking to increase the cohesion
735 between the layers of the product by optimizing the 3D-printing parameters, but also by adapting the
736 physical and / or chemical properties of the printed product with no adding of chemical substances.
737 Once this step is completed, research will be essential to enable the manufacture of healthy foods,
738 both from a microbiological and chemical point of view. To achieve this, tomorrow's 3D printers for
739 foodstuffs have to be think from now so that their design accounts for easy cleaning and integration
740 of a post-processing system (cooking, drying ...), and why not, a system of packaging, in order to limit
741 the handling of product and thus the risks of external contamination. From a chemical point of view,
742 the printing times being, for the moment, relatively long, it is therefore necessary to pay careful
743 attention to the immediate environment of the food being printed in order to preserve its various
744 constituents from the oxidation phenomena (printing under nitrogen atmosphere...). If all these

745 various challenges are raised, the manufacture by 3D-printing of microbiologically and chemically
746 stable foodstuffs that could be then conserved at room temperature will then be a reality, thus
747 leading to a real sustainable development approach. The final step will then be to garner consumer
748 acceptance for these 3D-printed foods. If consumers are properly briefed on the methods employed
749 and the benefits offered, then we see no real barriers to wider acceptability, especially among the
750 future generations coming of age, many of whom will likely embrace both flexitarianism and
751 hyperconnectedness. Today, the signs and signals suggest additive manufacturing is about to usher in
752 the next new industrial revolution. So why not in food manufacturing? Time will tell.

753

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755

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Figure captions

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1028 **Figure 1:** Schematic representation of the operating principles of the main 3D printing methods used
1029 in the food sector: A) extrusion-based printing in the form of pneumatic, piston-driven or
1030 screw-driven robotic dispensing systems, in which a continuous stream of hydrogel is
1031 dispensed; B) thermal inkjet printers which are configured with a heater creating air-
1032 pressure pulses to generate droplets at the printhead. In piezoelectric inkjet printing, an
1033 actuator produces a mechanical pulse to force the bio-ink to flow from the nozzle as
1034 droplets. C) laser-assisted printing system which consists of a laser-absorbing layer - called
1035 the ribbon - a feeding layer of cell-laden hydrogel beneath, and a receiving substrate.

1036 **Figure 2:** Evolution under consideration for the 3D printing of new proteinaceous-based foods in the
1037 next years.

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1040 ***Balck and white print is required for the figures.***

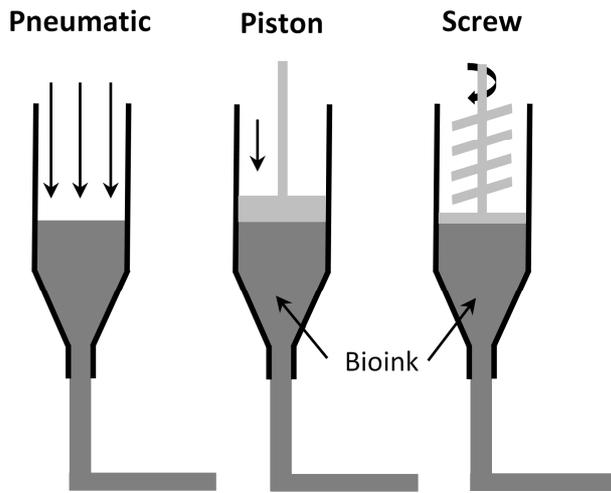
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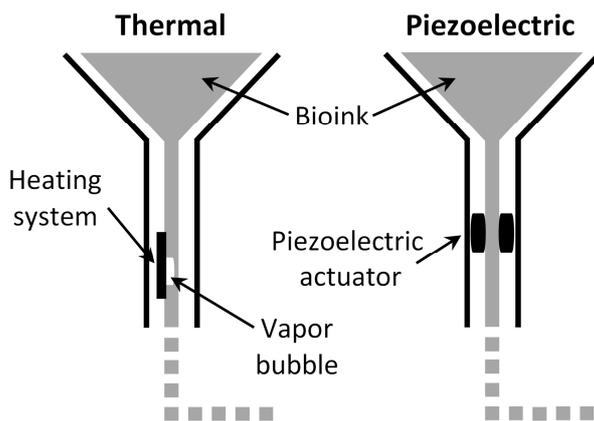
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A - Extrusion-based printing

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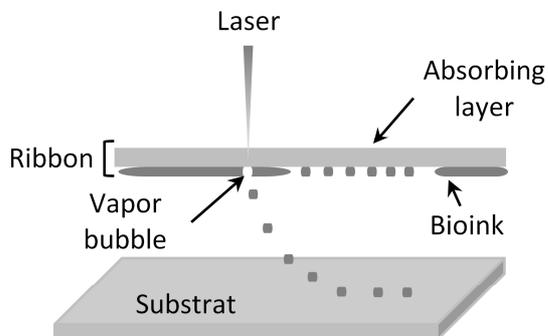
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B - Inkjet printing

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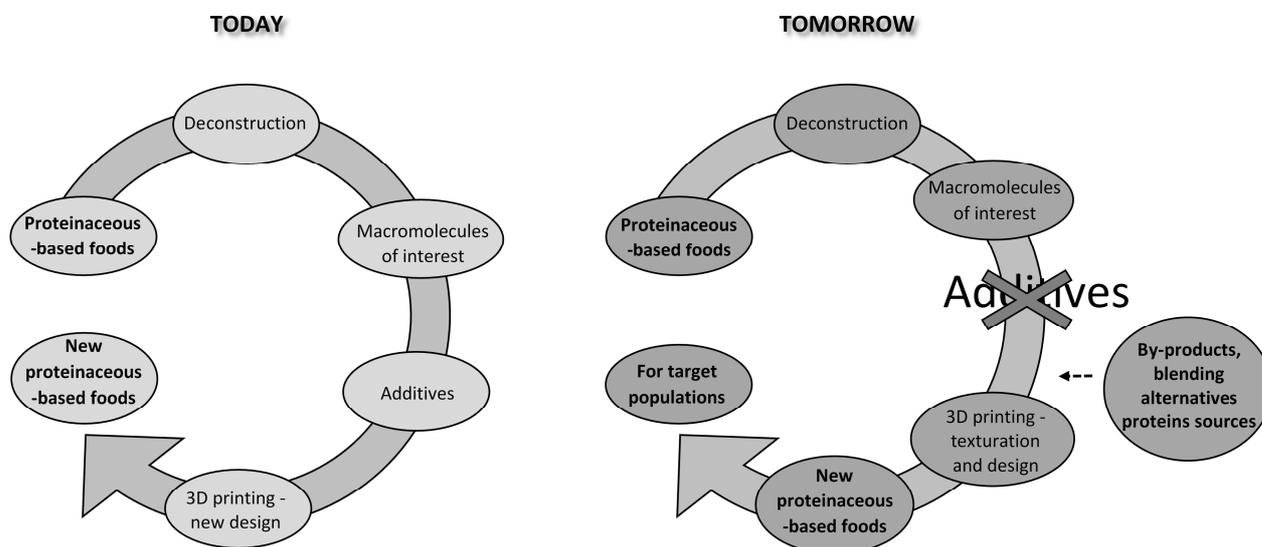


C - Laser-assisted printing

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1051 **Figure 1**

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Figure 2

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.

ACCEPTED MANUSCRIPT

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