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Review

Could 3D food printing help to improve the food supply chain resilience against disruptions such as caused by pandemic crises?

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Summary The ongoing COVID-19 pandemic is having a tremendous effect on the current food system. The situation urges us to face many issues never experienced before, aimed at mitigating a multitude of sanitary and social risks. The current pandemic has affected the food system in many ways: significant changes in dietary habits and in the health status of people; the food chain is broken, which has an effect on food security (including making it difficult to find or to buy fresh food at affordable prices); unemployment or underemployment is rising due to the damages of the food sector; there is a lack of food-socialising events which has an effect on people's mental status; and there are concerns about food safety. To mitigate all these issues, the implementation of innovative technologies urges. We have mapped the scientific studies and online information on 3D food printing (3DFP) about the effects of 3DFP on the food system and people's health when adopted in food industry, restaurants, hospitals, schools, offices, homes, etc. Finally, this information has been examined in light to the future challenges of the food chain also considering the ongoing COVID-19 pandemic, demonstrating its potential benefits to mitigate this and future pandemics.

Keywords Digitally modulated sensory properties, food security and nutrition, immune system, social distancing, personalised food manufacturing.

Reference scenario

After the first cases of COVID-19 were reported in the province of Hubei, China, in November 2019, the virus spread at a dizzying rate. By March 2020, cases were registered in over 164 countries across the globe, and the outbreak of COVID-19 was officially declared a 'pandemic' by the WHO. The COVID-19 virus (SARS-CoV-2) has many clinical similarities with SARS-CoV and MERS (Das, 2020), but it is the only one that has been declared a pandemic. The main symptoms are ranging from a cough and fever to gravely impacting the respiratory system, which can ultimately lead to death mainly for people with a low immune system (diabetics, people with cardiac diseases), as well as the elderly. Several months have passed since November 2019, but the current crisis is unprecedented with a continuously changing global scenario; at the moment of writing this paper, in fact, globally there have been 172.630.637 confirmed cases of COVID-19, including 3.718.638 deaths (WHO, 2021). During the last 15 months, the world completely changed and, especially for what regards the chain of production and transportation of food with tight interrelations with virus transmission, the quality of daily diet to sustain immune systems and the mental and physical health, modern society discovered several weaknesses that need novel approach and technologies.

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Pandemic crisis, food security and nutrition

The COVID-19 pandemic has unleashed the profound weaknesses of the current food system, such as food security and nutrition, food safety and sustainability (Galanakis, 2020). For instance, the negative impact of the pandemic on food security and nutrition (FSN) is enormous, highly complex, completely interrelated and profound in intensity (De Paulo Farias & dos Santos Gomes, 2020; Rizou *et al.*, 2020). If the 2030 Agenda

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for Sustainable Development of the United Nations already counted that over 820 million people go to bed hungry every day and 130 million people are suffering from acute hunger, the COVID-19 pandemic increased this number to double (United Nations World Food Programme, 2020). The food insecurity – from moderate to severe levels – is a strong detrimental factor to a people's mental and physical health (FAO, 2018; Abrams *et al.*, 2020), and these troubles have been observed to increase during the COVID-19 pandemic, with people in Texas that experienced food insecurity well above the common 25% rate (Abrams *et al.*, 2020). The essential reasons that generate these situations have been the shortage of basic food commodities due to panic buying (Kassas & Nayga, 2021) and the disruption of the agri-food chain because of the lack of migrant 'farm-workers' that were limited in travelling (Barman *et al.*, ; Meuwissen *et al.*, 2021). In addition, the pandemic has reduced the people's income forcing them towards a reduction in food quality and food quantity. This weakens people's immune system, thereby augmenting the risk for pandemic progression (Committee on World Food Security (CFS), 2020). With the low income, the eating habits shifted from fresh produce to highly processed food with a longer shelf life (Goel *et al.*, 2020) which in general has a higher energy density and a reduced nutritional quality. In addition, the stay-at-home period has limited the access to fresh foods creating obstacles for a healthy and varied diet with augmented negative effects in a condition in which sport activities are hampered (WHO, 2020b, 2020c, 2022a). WHO (2020a, 2020b, 2020c) strongly has recommended avoiding panic buying while it sustains a more efficient use of food by planning the daily meals with the aim to use food are already at home in line with its shelf life making possible to mitigate the food waste and related food shortage.

Food chain as potential vehicle for the transmission of SARS-CoV-2

A completely different point regards the relation between the spread of COVID-19 and food chain that may be summarised by the following question: '*Might COVID-19 transmissions be facilitated by food manufacturing or food consumption*?'. As first, retail and informal food markets are crowded places where social distancing may be very hard to keep and the exposure time in which a customer is in close proximity to a potential infected customer may be significant (Ying & O'Clery, 2021). A study of US people reported that the 41% of people were worried when buying food in person at a grocery store or supermarket (International Food Information Council, IFIC, 2020). Also, although there is no robust evidence of a link between food, food containers, packaging and the increased transmission of COVID-19, it is widely reported that the SARS-CoV-2 can survive on surfaces of the objects (FDA, 2020) and that people who touch such surfaces and then touch their own mouth, nose or eyes might fall ill (FDA, 2020). In addition, all information agrees on the ability of other coronaviruses to survive in a wide range of environmental conditions such as humidity, temperature (Ijaz *et al.*, 1985; Kampf *et al.*, 2020a,2020b) and material surfaces (van Doremalen *et al.*, 2020) which fall in the range of several fresh and packaged food products (Rizou *et al.*, 2020; Han *et al.*, 2021). So, the potential transmission of the virus by touching fresh food – vegetables, fruits, baked goods, etc. – after they were touched by infected people (Bundesinstitue fur Risikobewertung (BfR), 2020) cannot be undervalued. This was observed in Singapore where some people were infected with COVID-19 after sharing food (Pung *et al.*, 2020) and in China where at least 9 occurrences on the packaging materials were observed for frozen raw foods (Han *et al.*, 2020). Among the kind of food, particular attention is needed for meat products (seafood, beef, poultry and pork) being rich in heparin sulphate which is required for SARS-CoV-2 to interact with tissue epithelia (Mycroft-West *et al.*, 2020). This made the meat products as the potential strongest route for the transmission of COVID-19 infection (Han *et al.*, 2021) also at processing stage where the industries should carefully check the health status of the personnel in direct contact with meat.

Considering these potential ways of transmission along the food chain, we have to recall that unfortunately, no protocols or specifications to prevent SARS-CoV-2 at manufacturing stages (Oliveira *et al.*, 2020) have been approved. The inactivation with chemical disinfectants is a safe way (Kampf *et al.*, 2020a,2020b) but often they are not compatible with human health (Oliveira *et al.*, 2020). Apart from the chemicals, the virus has been found to be highly stable at 4 °C and it is expected to remain infectious at −20 °C for up to 2 years (World Health Organization, WHO, 2020a, 2020b, 2020c) making the transmission from frozen food to people a real possibility (Rizou *et al.*, 2020). Furthermore, SARS-CoV-2 was found to be extremely stable over a broad pH range (between 3 and 10) extending the portfolio of food products that could be vehicle of infection by touching food at supermarket. Fortunately, the data reported from Chin *et al.* (2020) proved that SARS-CoV-2 was inactivated by exposure to 70 °C for 5 min, highlighting that the common cooking methods are a valid solution. Based on these findings, it is imperative to use the four key principles for food safety: clean, separate, cook and chill (Centers for Disease Control & Prevention (CDC), 2020; Foodsafety, 2020), and furthermore, a social distance of approximately 6 feet (1.8 m) in food production facilities is strongly suggested (FDA, 2020) or, when impractical, the industry should adopt high-level hygiene practices (FDA, 2020).

Needs of innovative technologies supporting safety measures in the food chain to mitigate the risks of the pandemic

Rizou *et al*. (2020) have reported seven traditional measures to take inside the food chain aiming to reduce the spread of COVID-19 including '*be healthy*', '*wash hand*', '*disinfected surfaces*', '*working environment*', '*preparation*', '*delivery*' and '*social distance*' (Fig. 1). However, the authors distributed these measures differently along the food chain neglecting, for instance, the importance of the social distance at processing/manufacturing stage. This is in disagreement with FDA and UK government (FDA, 2020; UK, 2020) which suggest a minimum distance of approximately 2 metres between the workers at manufacturing places or, if not practical, to use novel technological solutions to reduce the contact between the workers. Also, the use of systems to delivery ingredients, packaging, etc., to the industry would be very useful to avoid people-to-people and people-to-surface contact since many infections have been reported due to the interaction with couriers (Yaprak *et al*., 2021). On these bases, new approaches and technologies have been recently proposed/introduced in the food chain to address emerging safety rules and to reduce the dangerous effects of COVID-19 on people health. Such approaches work at three main levels: 1. to reduce the spread of COVID-19 as much as possible, 2. to minimise the changes in dietary habits during the pandemic and 3. to foster the immune response of people by a correct diet as main contribution for prophylaxis or medical treatments against COVID-19.

Considering the first point, examples are the introduction of innovative technologies for food distribution (e.g. drones) allowing people to maintain physical

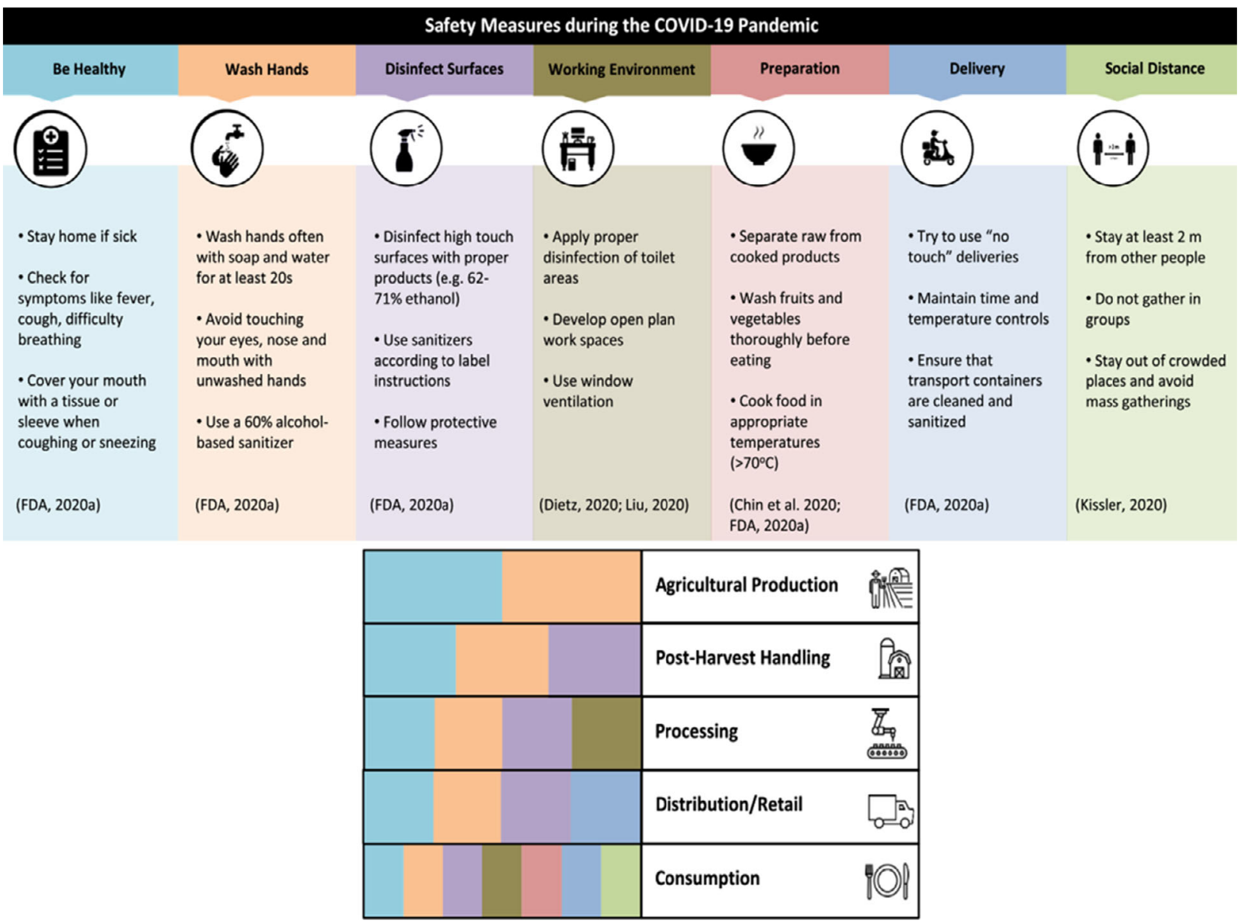

Figure 1 Schematic representation of the most important safety measures to adopt during the COVID-19 pandemic (from Rizou *et al*., 2020).

distance (Yaprak *et al.*, 2021), the use of automation thereby reducing the transmission of viruses in the processing area (Hobbs, 2021) and the adoption of technologies enabling people to avoid crowded places such as restaurants and supermarkets. For instance, the sector of food vending has introduced innovations limiting the number of risky contacts or the use of contactless payments (Arthur, 2020; Dimitrova, 2020) as well as the use of novel smartphone apps showing the number of peoples that are using the vending machine helping to avoid crowded places (Matipay, 2020).

Another important possibility comes from the usage of common pipeline (a single side online market) and innovation in online food delivery (Oncini *et al.*, 2020; Gavilan *et al.*, 2021). The development and the use of food delivery apps (FDAs) have suddenly increased during pandemic (Eurostat, 2019; Kumar & Shah, 2021) based on the opportunity to satisfy personalised consumer's demand (Sheth, 2020), safety doubt, efficient food delivery and convenience (Zhao & Bacao, 2020) and also fostering the survival of catering companies, restaurants and other food shops (Kumar & Shah, 2021). Buying food online is made possible by more innovative platforms and systems that add value to the consumers, local products and reduce the risks of COVID-19 (Parker *et al.*, 2016; Gavilan *et al.*, 2021). For instance, in Italy, the online sales increased by 91.9% from 23 February to 29 March 2020 compared with the same period in 2019 (Bracale & Vaccaro, 2020). The Chinese platform MEITUAN launched a food delivery service 'without-contact' based on customers' requirements to drop off the food ordered in a specific area and subsequently to retrieve it by using a contactless system with the aim to increase the distance between customers and couriers (Culpan, 2020; Retail Institute, 2020).

Food preparation, nutritional content and COVID-19

Recalling the safety measures as reported in Fig. 1, the 'preparation' it is only analysed in terms of the aforementioned key principles for food safety (i.e. clean and separate) but there is no mention on the importance of preparing and stabilising a high nutritional food product to sustain the health status and immune system against the effect of COVID-19. This is unexpected considering the growing body of evidence of the role that nutrients could play to reduce the effect of the COVID-19 pandemic (Caccialanza *et al.*, 2019; Abbas & Kamel, 2020; Adem *et al.*, 2020; Barazzoni *et al.*, 2020; Butler & Barrientos, 2020; De Almeida Braisel, 2020; Dhar & Mohanty, 2020; Dhar & Mohanty, 2020; Galanakis, 2020; Handu *et al.*, 2020; Panyod *et al.*, 2020) particularly in the current period characterised by a tremendous change in dietary habits (Di Renzo *et al.*, 2020; Zeigler *et al.*, 2020). The overall data showed an increased consumption of hot beverages, vegetables, cereals and homemade products and a significant reduction in fresh fish and fresh fruits (Di Renzo *et al.*, 2020). Contrarily, it has been reported an increase in the consumption of food with a longer shelf life (Bracale & Vaccaro, 2020) and a reduction in milk consumption has been recorded, with negative effects on the daily intake of calcium and vitamin D which is exacerbated by the lack of the contact with sunlight during quarantine (EUFIC, 2020). Shifting to the data of American people aged 18 to 80, more than 8 in 10 (85%) people changed their food habits (International Food Information Council, IFIC, 2020) with an increase in consumption of snacks than before the lockdown (41% of parents with children against 29% without children).

On the other hand, the overall knowledge clearly suggests that through the diet would be possible to reinforce the immune system reducing the risks of COVID-19 (Butler & Barrientos, 2020). In general, the adoption of a typically Western diet rich in saturated fatty acids (SFAs) could inhibit our adaptive immune system with a negative effect on COVID-19 patients (Tashiro *et al.*, 2017; Xu *et al.*, 2020a, 2020b). In contrast, the use of bioactive ingredients is one of the four main pillars to cope with COVID-19 (Galanakis, 2020). The Mediterranean diet, rich in antioxidants and anti-inflammatory components, helps to reduce the virulence of SARS-CoV-2 (Di Renzo *et al.*, 2020; Romano *et al.*, 2020). The well-known effect of vitamin C in supporting the immune function could, in some cases, reduce infection in the lower respiratory tract (Carr & Maggini, 2017). Similarly, vitamins D and E may improve resistance to COVID-19 (Wang *et al.*, 2019) and hesperidin and rutin are good candidates to dock the main protease (Mpro) of COVID-19 as starting point for therapeutics facing COVID-19 (Adem *et al.*, 2020). Furthermore, our immune response is eroded by a general deficiency in micronutrients. Zinc, for example, has important anti-inflammatory able to kill infected cells (De Almeida Braisel, 2020) but although the recommended daily amount of zinc stands at 11 mg for males and 8 mg for females, people often show a deficiency, suggesting the need for zinc supplementation.

Finally, particularly mention should regard the role of our gut microbiota, which are able to prevent lung disease, as reported by Dhar & Mohanty (2020) and Keely *et al.* (2012), or, more generally, the relationship between our gut microbiota and our immune system (Negi *et al.*, 2019). A daily diet that enhances the number of the gut-commensal bacteria Bifidobacterium and includes the consumption of low fat, dietary fibre, protein extracts from peas and whey or prebiotics may improve our response to viruses. Dhar & Mohanty (2020) reported that for COVID-19 patients, especially for elderly and immune-compromised people, it is essential to personalise the diet with the aim to modulate the gut microbiota to strongly reinforce the immune response in addition to current therapies (Fig. 2). So, any invention of tools making the creation of personalised food a reality would be of great importance against COVID-19 or other pandemics.

The emerging technology of 3D food printing could contribute to challenges posed by the pandemic on different levels

In the past decades, the Human-Computer-Food Interaction (HCFI) that occurs during processing, transportation, storage and consumption received much attention from both academia and companies (Choi *et al*., 2014; Hashimoto *et al*., 2017). This is a promising development based on a broad range of benefits prompted by the introduction of computer-aided food preparation, cooking, serving, etc. (Betran *et al*., 2019). On the HCFI website, several workshops such as Cooking with Computers (Betran *et al*., 2019; Blutinger, 2020), Multimedia Cooking and Eating Activities and Multimedia Assisted Dietary Management have been running showing the unprecedented potentials of this emerging field of research (Mori *et al*., 2012; Hashimoto *et al*., 2017) such as the use of machine-learning approach to convert a text recipe into a practical workflow or the use of robotic technology in the kitchen.

3D food printing (3DFP) is a computer-aided process that turns the way in which food manufacturing is commonly thought of upside down. 3DFP perfectly falls in the field of human–computer interaction because the workflows that create novel 3D-printed edible structures start from a digital model designed by CAD programming which is then converted into Standard Tessellation Language (.STL). Subsequently, the STL file format is converted into a geometric code (G-code) that instructs the movement of the printer in 3D space, allowing layer-by-layer material deposition. To convert from STL file format to G-code, it is necessary to define the printing variables by using slicing software that literally cuts the CAD model in parallel slices and controls the movement in 3D space – X, Y and Z axes (Derossi *et al*., 2019).

3D food printing is a general term belonging in the broad group of additive manufacturing (AM) comprising different technologies such as selective laser sintering (SLS), fused deposition modelling (FDM), binder jetting, inkjet printing and extrusion-based system

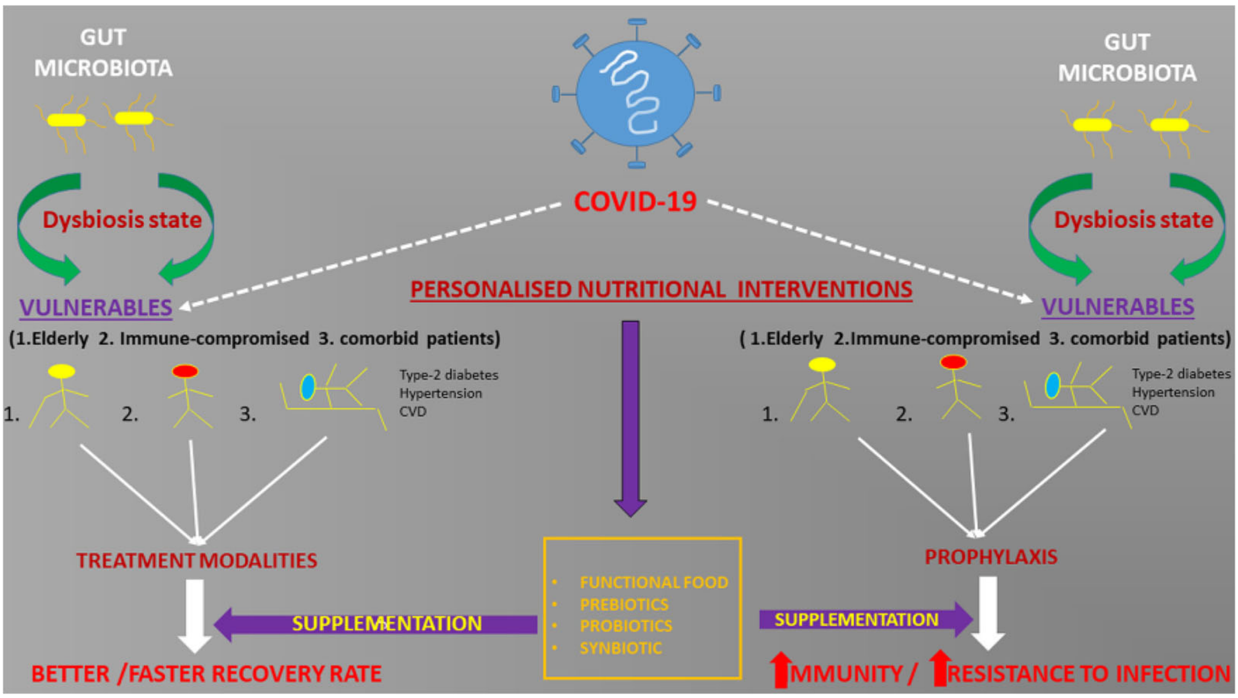

Figure 2 Schematic representation of the adoption of personalised nutrition as prophylaxis intervention and in-treatment supplementation (from Dhar & Mohanty, 2020).

(Dankar *et al*., 2018; Liu *et al*., 2019a, 2019b). Currently, the extrusion of food pastes by using screw-based or syringe-based systems is the most used (Godoi *et al*., 2018a, 2018b; Severini *et al*., 2018a,2018b,2018c,2018d; Perez *et al*., 2019) although, for example, SLS has been used to create sugar-based 3D structures (Candyfab, 2020).

3D food printing has the attention of researchers and companies owing to its unique properties, such as being able to create products with customised nutritional content and programmable texture, its hyper-flexibility of both shape and dimension, its multi-material deposition capability, its true computer-aided manufacturing character and the possibilities that it offers with respect to decentralisation of production, and the reduction in food waste (Godoi *et al*., 2018; Derossi *et al*., 2020a, 2020b, 2020c, 2020d, 2020e). In addition, being essentially based on a digital model, 3DFP sustains the sharing of basic resources among small firms or singular users (D'Aveni, 2015) and it naturally fosters for open contributions due to its open design, thereby accelerating innovation and business creation (Beltagui *et al*., 2020). The past ten years have seen the publications of over 170 published papers, many thematic conferences and one dedicated book (Severini *et al*., 2016; Wang *et al*., 2018; Feng *et al*., 2020; Pulatsu *et al*., 2020a,2020b; Xu *et al*., 2020a, 2020b; Derossi *et al*., 2021). The first theme addressed was gaining a better understanding of all essential technological aspects to generate edible structures with high printing fidelity. With this aim, researchers focused their experiments on the effects of printing variables (Liu *et al*., 2017; Guo *et al*., 2019; Derossi *et al*., 2020a, 2020b, 2020c, 2020d, 2020e) and the rheological properties of the food paste that are essential for achieving good printability (Vancauwenberghe *et al*., 2017; Gholamipour-Shirazi *et al*., 2019; Liu *et al*., 2019a, 2019b). We suggest the following references among the most relevant for the practical application of 3DFP (Godoi *et al*., 2018; Lee *et al*., 2019; Zhu *et al*., 2019a, 2019b; Derossi *et al*., 2020a, 2020b, 2020c, 2020d, 2020e; Feng *et al*., 2020).

Despite the large scientific bibliography essentially centred on technical aspects to create innovative food products, it is worth noting that 3DFP has many features useful to mitigate the bottleneck of the current system, thus helping to alleviate the aforementioned risks of the COVID-19 pandemic. On this basis, we propose a different point of view on the 3DFP by highlighting the positive relationship between the application of 3DFP and the most important measures to reduce the weaknesses of the current food chain, especially under the risks of COVID-19. Table 1 reports a description of the main benefits given by the adoption of 3D printing in food sector.

Table 1 3D food printing features and advantages on the reduction in COVID-19 pandemic risks

Advantages/Attributes	Descriptions
Social distancing	Being a computer-aided technology, it reduces the number of people working (inter-human contact) in the area of manufacturing.
Minimum food contact	Being digital technology 3DFP reduces food –human contact and during manufacturing.
Food design innovation impacts	Co-creation is an opportunity to create food with improved sensory acceptance fostering the adoption of a correct diet during period of confinement. Designing 3D structures allows controlling satiety and to reduce overeating during isolation periods.
Personalised foods	Creation of customised food for people uniqueness. Capability of fulfil nutritional needs and reinforce immune systems responses to COVID-19.
Unemployment and underemployment	Start-ups creation offering novel products and services as co-creation apps, digital library of innovative and customised recipes; new 3D food printing system for industry, supermarket and home usage.
Social impact	3DFP sustains socialising process (reducing stress from isolation) fostering the co-creation and sharing among people of ideas, experiences and tangible food thought for specific people or events.
Food security	3D food printing creates only what people want to eat reducing the food waste helping to mitigate food shortage at supermarket.

3D food printing sustains social distancing and reduces food contact

3D food printing is a technology that produces complex shape and dimension with almost no human involvement (Eq ubal *et al*., 2021), thereby quenching the potential transmission of the viruses at processing stage and during transportation. This is because 3D printing has the potential to manufacture products close to the final customer (Gao *et al*., 2015; Chan *et al*., 2018) and, in addition, owing to its digitalised nature, the technology does not require direct inter-human contact or proximity when formulating, testing, creating and validating new food products, shapes or structures. Furthermore, 3DFP reduces the tech-human contacts during processing. Considering the first key point – that is food manufacture decentralisation – it would be possible to reduce the dependency from the traditional supply chain (Longhitano *et al*., 2021) and to get natural and fresh items (Barman *et al*.,). Fig. 3 schematically depicts what the food

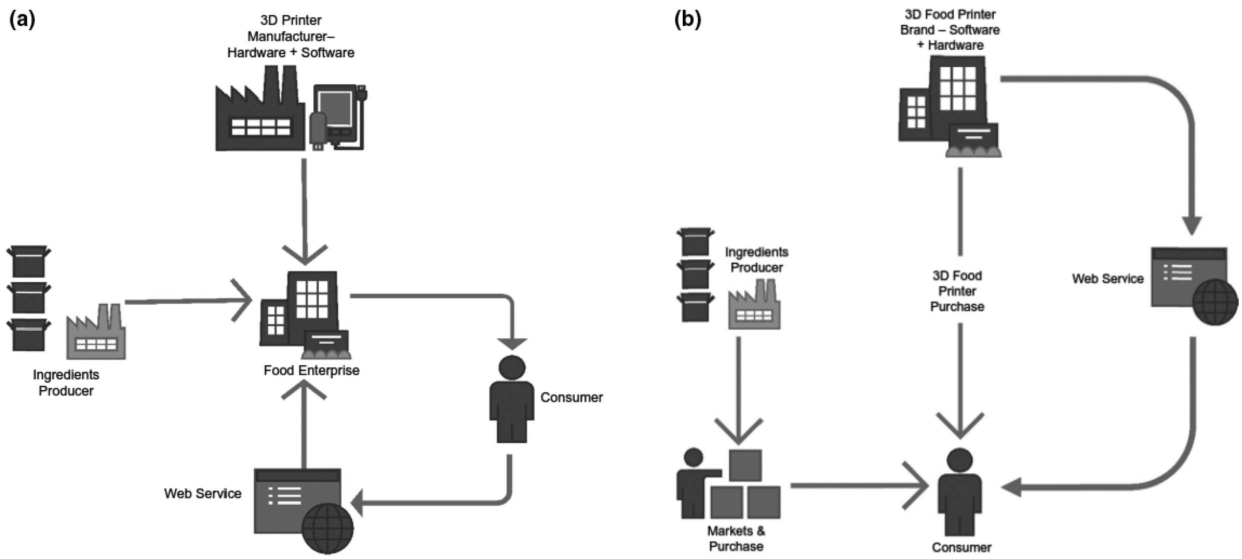

Figure 3 Schematic representation of the food chain when 3D food printing is introduced at an industrial scale (a) or at home (b) (from Jayaprakash, 2017).

chain would be if the 3D food printing was introduced at an industrial stage or for home use (Jayaprakash *et al.*, 2019).

When 3D printers are introduced at an industrial or retail level, the consumer could select individual ingredients or food formulations, shapes and dimensions, textures, etc., by using a web platform based on their references. One example is MAYA, a company that, working for the OREO brand, developed a vending machine able to select different biscuit bases that could be filled with a range of different creams and cream combinations, thus potentially generating hundreds of personalised combinations (Maya, 2020). If this proximity between producer and consumer is fully realised, food transportation of final products may be significantly reduced, allowing small firms to also actively participate. An analysis of the online news reporting application of 3D food printing (Lupton, 2017) asserts that 3D food printing could be more efficient for people in restrictive or emergency conditions. More specifically, an article published in 2017, The Guardian argued that '*drones could be combined with 3D printed food technologies to deliver food in emergency-affected areas*'.

When 3D printing could be used at home, people could purchase the ingredients online and, after home delivery, those ingredients could be used to print any food product desired, either stand-alone or through the use of digital food models and online recipes. As reported from Longhitano *et al.* (2021) who studied the role of 3D printing during COVID-19 pandemic, people who have a 3D printer do not need to have professional experience to produce parts because 3D CAD model can be easily found on open-design repositories. Furthermore, the benefits of using 3D printing at home on people's health would be exponentially reinforced by the use of a data-driven approach. After a proper medical analysis, specific personalised data could be translated in nutritional advice (Verma *et al.*, 2018) usable to drive the printing of personalised food items. Alternatively, in other locations such as schools and universities, people with special requirements – for example in the case of a food allergy – could pre-order recommended/personalised meals to eat while socially distancing, increasing their safety. At present, authorities are re-activating the in-class learning in fall, although this situation raises concern in the parents of children with food allergies, as the chance of these children coming into contact with other foods increases, prohibiting of food sharing is made more difficult, and completely sanitised surfaces may be hard to find (Greenhawt *et al.*, 2020). In these and similar situations, 3D food printing prepared at home or in class by the school could help to avoid cross-contamination given by contact with other foods.

Personalised foods by 3DFP to improve health and the immune response

Ever since the medical world has shown that we respond differently to the same diet due to the singularity of each person in terms of phenotypic and genotypic profiles as well as the bacteria inhabiting the gut (Galanakis, 2019; Galimberti *et al.*, 2019; Rozga, *et al.*, 2020), the interest in personalised nutrition has increased consistently. However, there is a big discrepancy between what the nutritious and healthy foods are, and what consumers decide to buy and consume on a daily basis. The choice of food and eating it is more than just providing energy and nutrients to the body, as claimed by Konig *et al.* (2017). Our choices are affected by several complex and interrelated variables (Derossi *et al.*, 2020a, 2020b, 2020c, 2020d, 2020e). Additionally, the timing of meals is pivotal in weight regulation (Reid *et al.*, 2014). Therefore, we must extend the meaning of personalised food beyond the nutritional content and include aspects such as sensory preferences, age, sex, lifestyle, habits, ethics and food-neophobia (Hannelore *et al.*, 2016; Derossi *et al.*, 2020a, 2020b, 2020c, 2020d, 2020e); all these aspects play an important role in people's daily diet.

This realisation has broken the common way of food production, with great benefits for society. Several companies and start-ups arose focusing on the preparation and delivery of personalised ready-to-eat meals for a limited number of people. Others provided tailored advice for the preparation of correct meals based on a data-driven approach, such as specific information on DNA, biomarkers, lifestyle and food preferences (Habit, 2020; Metabolic Meals, 2020; ONO, 2020; Eat this Much, 2020; Blu Apron, 2020, Diet-to-go, 2020; Nutrifit, 2020). The idea of personalised food manufacturing is inextricably connected to data-driven technologies (Song *et al.*, 2020) by which nutrition and medicine share the main goal of achieving personalised treatments for specific individuals, increasing the effectiveness of diagnosis, treatments and prevention (Karczewsky & Snyder, 2018).

Through 3D food printing, highly personalised food can be prepared, using data that delineates specific consumer requirements. It allows the computation of the energy and nutritional needs for each specific individual (Lipton, 2017). Considering the risk associated with COVID-19, 3DFP could help with the creation of 3D personalised foods to guarantee the consumption of a correct diet preventing general diseases (Oliveira *et al.*, 2021), to provide the aforementioned nutrients – that is bacteria (Yoha *et al.*, 2021) – capable of reinforcing the immune response to viruses, to reduce the risk of malnutrition of hospitalised COVID-19 patients or for people in quarantine, to create products with designed textural properties capable of alleviating mastication and swallowing problems in the elderly and to foster the assumption of a healthy diet by creating food matching personalised sensorial preferences. Liu *et al.* (2020) realised some 3D-printed mashed potatoes enriched with probiotic strain *Bifidobacterium animalis subsp. Lactis* BB-12 has a beneficial effect on the gut and immune function. Yoha *et al.* (2021) studied the synergistic effects of the encapsulation of *Lactiplantibacillus plantarum* (NCIM 2083) and 3D food printing to provide new insight on the design of personalised 3D-printed probiotic foods helping to modulate the immune systems by the inhibition of pathogenic colonies. Zhang *et al.* (2018) adopted 3D printing to create innovative cereal-based structures containing probiotic bacteria (*Lactobacillus plantarum WCFS1*) and they proved that the viable count in the 'honeycomb' edible structure exceed 10^6 CFU g^{-1} after baking.

NASA studied the use of 3D food printing to see whether it could deliver macro- and micronutrients and increases the sensorial acceptability of meals for long space missions (Liu *et al.,* 2017). A printed fruit-based snack for children designed to provide the 5%–10% of energy, calcium, iron and vitamin D needed for children of 3-10 years old was created by Derossi *et al.* (2018a, 2018b). Such results were obtained by an accurate design of the printable food formula and prepared by mixing several ingredients such as banana, dried mushrooms and white beans Also, the fruit-based snack is a good example of customised sensorial properties, because the higher weight fraction of banana is in line with children's appreciation of this fruit. Noort & van Bommel (2020) hypothesised an interesting scenario (Fig. 4) in which a 3D food printing vending machine placed in a gym could work based on a data-driven approach by combining personal data from the exercises

Figure 4 Schematic representation of a possible scenario of 3D personalised food printing (from Noort & van Bommel, 2020).

completed by and the sensorial preferences of the individual resulting in a printed nutritious bar that aids recovery after heavy exercise.

Interestingly, the company Nourished (Nuorished, 2020) prints a stack of vegan-gel layers formulated for specific requirements, for instance to improve the immune system, by mixing several vitamins, minerals and bioactives. Other examples show that the controlled enrichment of food with specific nutrients or bioactives is open to a hundred levels of personalisation (Lille *et al*., 2018; Severini *et al*., 2018a,2018b,2018c,2018d; Zhang *et al*., 2018; Perez *et al*., 2019).

Another important general concern during the COVID-19 pandemic is the aforementioned weight gain in adults and children (Zeigler *et al*., 2020). In this regard, 3D food printing would be able to apply the so-called 'perceptual-illusion control mechanism' in order to manage satiation (Lin *et al*., 2020). Summarised, CAD models with internal food structure paths may necessitate increased chewing time and larger jaw movements, resulting in a direct increase in the perceived satiation (Fig. 5). In this way, we can decrease the consumption of food during a period of sedentary life in which physical inactivity negatively affects the risks of chronic diseases (Jribi *et al*., 2020).

In the case of hospitalised COVID-19 patients, oral nutrition should be customised, not only considering the nutritional value but also taking comorbidity and any chewing and swallowing problems into account (Cava & Neri, 2020). This last issue can be successfully tackled by 3D food printing. The EU-funded project PERFORMANCE '*Personalized Food for the Nutrition of Elderly Consumers*' with the aim to create nutritionally enriched smooth food is highly appreciated. Other 3D-printed foods for elderly people have been prepared by Kouzani *et al*. (2017). The traditional purée and mashed food created at home, in hospitals or nursing homes are unappetising and lead to loss of interest, lack of appetite and malnutrition (CORDIS, 2020), resulting patients within an increased vulnerability to viruses. The University of Copenhagen has been involved in a research project aimed to use the 3DFP technology to help vulnerable hospitalised patients by creating personalised meals without needing more people preparing the meals (University of Copenhagen, 2017). In addition, this is perfectly in line

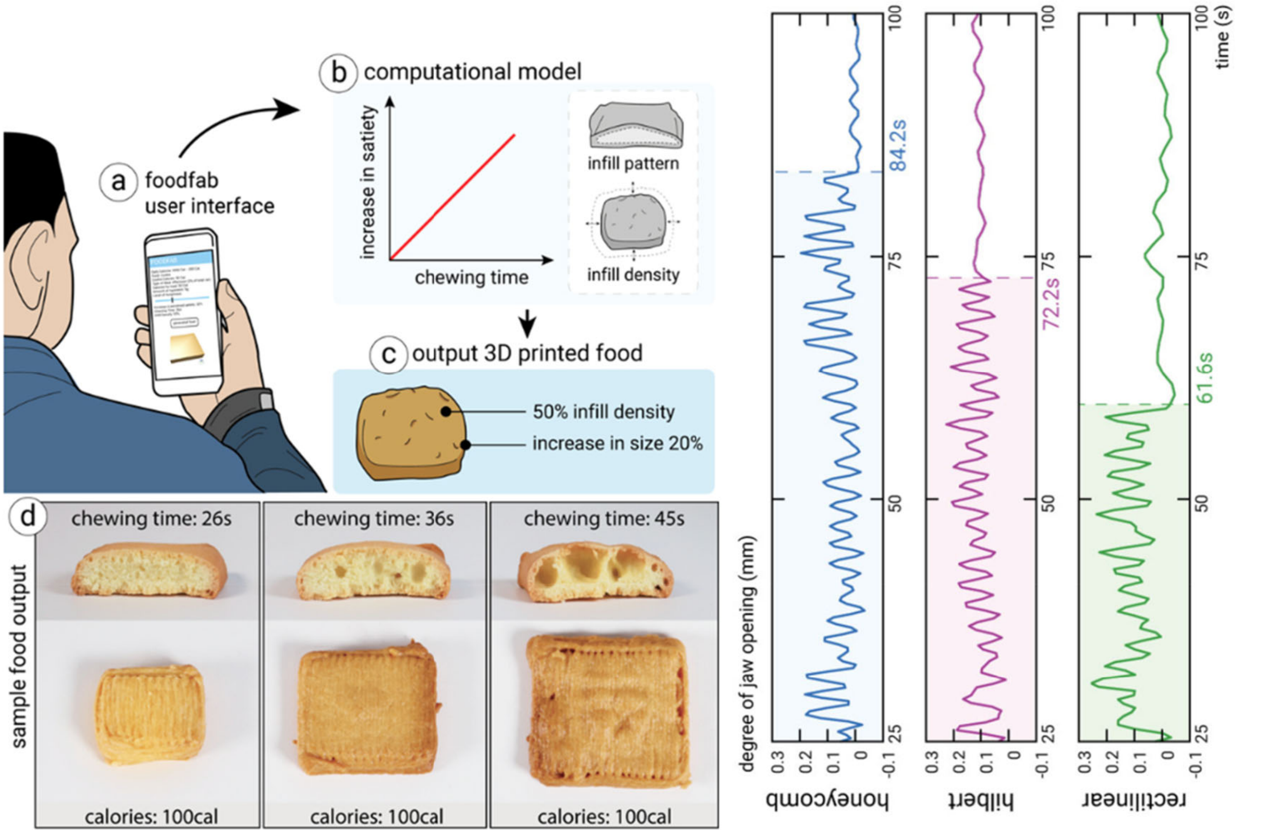

Figure 5 FoodFab system to control perceived satiation by modifying the internal structure of 3D-printed food (from Lin *et al*., 2020).

with the principle of social distancing in a potential pandemic situation.

More recently, instead of printing food paste, 3DFP has been used to create programmable food textures – from rigid to fragile structures – based on controlling the printing path and on the generation of voids inside 3D structures (Vancauwenberghe *et al*., 2017; Derossi *et al*., 2020a, 2020b, 2020c, 2020d, 2020e; Feng *et al*., 2020). The authors created a pectin-based (Vancauwenberghe *et al*., 2017), cereal structure (Derossi *et al*., 2020a, 2020b, 2020c, 2020d, 2020e) and yam and potato snacks (Feng *et al*., 2020) with different textures– hardness, chewiness, etc. – by modulating the pore sizes and their position inside the 3D structure. Fig. 6 shows the digitalised programmed structure and the corresponding printed food.

Finally, we want to briefly analyse the role of 3D printing in the creation of customised food products using the specific sensory preferences as a powerful tool to promote the acceptance of a correct diet, the right nutrients, bioactive compounds and probiotics, all aspects that help to improve the body's response to viruses such as SARS-CoV-2 or other potential pandemics (Chesnut *et al*., 2021; Oliveira *et al*., 2021).

This is relevant particularly for US children between 4 and 8 years of age of which <15% eat enough fruit and vegetables (Schindler *et al*., 2013). They reject foods based on their sensory features such as texture or aroma (Moding *et al*., 2020): '*Children eat what they like*' (Estay *et al*., 2019). In this scenario, 3D printing is an exceptional tool to improve food acceptance, not only for its ability to create customised shapes, textures and colours, but also because it can involve children in a food co-creation system, both at home and at school. As reported by Sun *et al*. (2015), different foods that children usually dislike could be used to create 3D-printed innovative food items with a high level of acceptance.

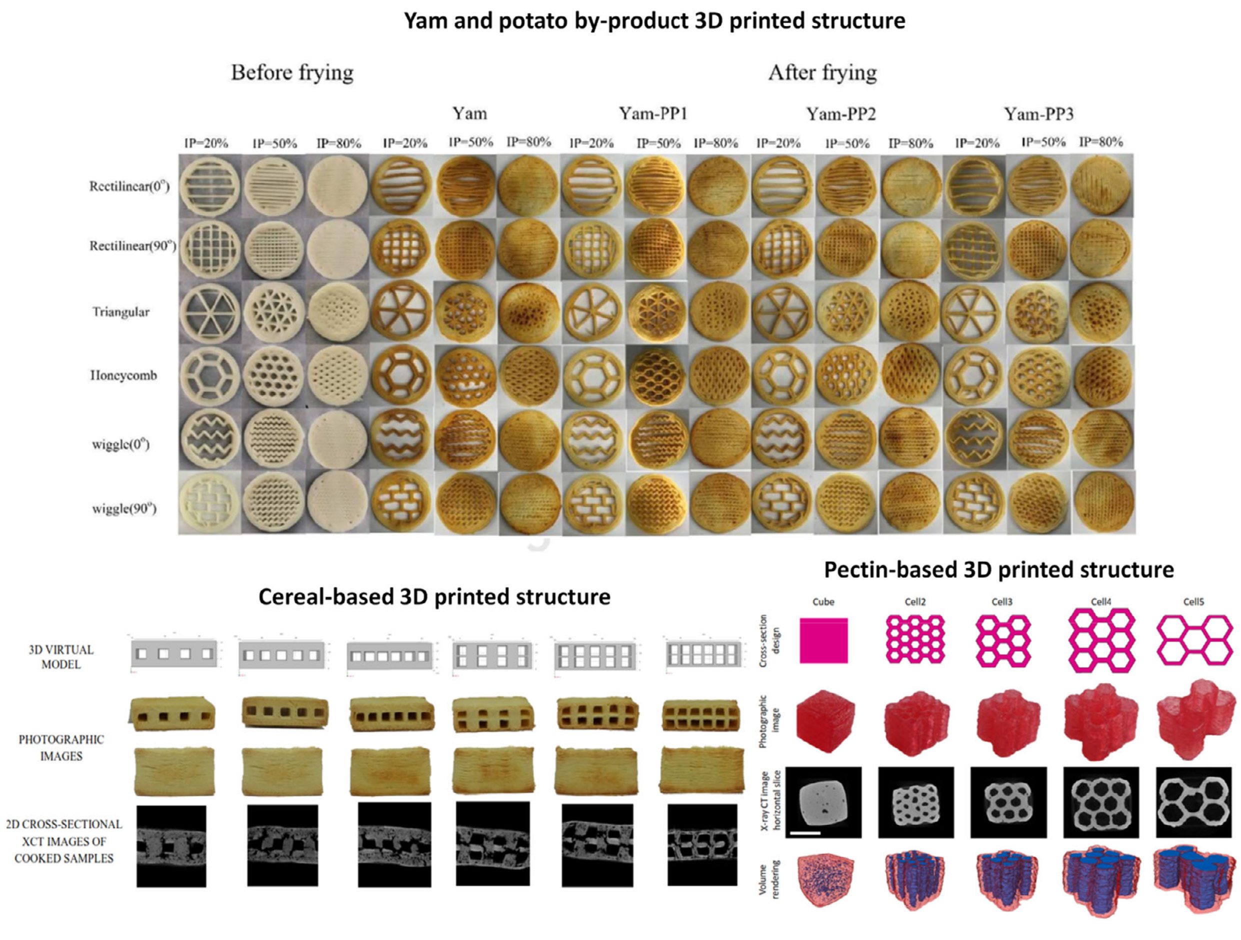

Figure 6 Examples of programmable food texture created by using 3D printing technology: Yam and potato snacks (from Feng *et al*., 2020), pectin-based snacks (from Vancauwenberghe *et al*., 2017) and cereal-based snacks (from Derossi *et al*., 2020).

3D printing allows consumers to take part in the production process by enabling them to specify ingredients and features improving their satisfaction (Caulier *et al.*, 2020). Caulier *et al.* (2020) evaluated the consumer's attitude before and after consuming 3D-printed food products, showing that when consumers experienced 3D-printed foods and are free to customise their products, contributed to consumer acceptance.

3D food printing impact on socialisation and business creation in a period of human restriction

During the COVID-19 pandemic, people face uncertainty and are immersed in a new reality characterised by the lack of social contact with family, friends and colleagues, working from home, home-schooling, temporary unemployment and physical confinement. In this situation, stress, anxiety, fear, anguish and worry are all normal (WHO, 2020a, 2020b, 2020c). Social contact and emotional social connections are essential to humans (Liberman, 2013), and COVID-19, with the related isolation measures taken to minimise the spreading of the virus, has a profound negative effect on people's instincts and motivations (Hagerty & Williams, 2020). Social is defined as '*needing companionship and therefore best suited to living in communities*' (Oxford English Dictionary, 2020), moreover being social the ability to share within communities and to be distinct but to belong. 3D printing may have a significant positive social impact in this respect, especially in a period of social detachment. By co-creating, sharing and producing with parents, friends, colleagues, etc., goods we like in our lives, people gain the ability to share not only ideas, opinions and words but also tangible items. This ability improves the quality of life by sharing memories and experiences with anyone, anywhere in the world. During a pandemic situation, the power of being able to remember family meals or dinners with friends and to print – at a social distance – specific food items greatly fuels our memories, experiences and feelings. 3D printing itself can be viewed as a socialising process. The social engagement of creating together and seeing the modification of a 3D model of a favourite meal, the creation process of 3D printing enhances the socialising aspect. Imagine organising a social e-dinner with your friends/family, each of which designs a 3D CAD model for another person participating in the e-dinner. Imagine that during the e-dinner all people discover in real life what was designed and created for them. Alternatively, imagine that people can work together to design a personalised cake for the birthday of a friend or relative. 3D printing also allows bypassing the traditional business and delivery systems. After the era of socialising with blogs, networks, apps, etc., 3D printing allows the sharing not only of idea but also of tangible goods as well, combining food, sensory properties and taste with emotions and memories. Through 3D printing, food can be designed, shared and personalised by users and transported from a virtual world to real life.

Finally, we want to take into account the social impact of 3D food printing. It opens up the possibility to develop and sustain new businesses in a period in which recent data show that in all countries, COVID-19 is negatively impacting the world of work, increasing un- and underemployment (Australian Government, 2020; BLS, 2020; European Commission, 2020). Tao *et al.* (2015) analysed the evolution of additive manufacturing on the market by mainly considering the effect of sharing. They propose three main subjects of discussion: the degree and scope of resource sharing, the value of creation and the degree of user participation. The authors quoting a paper of Samaddar *et al.* (2005) reported that sharing resources is a key point to increasing competition. In the food sector, this could be the creation of start-ups offering a library of 3D recipe models to print food at home or a specific design service for the co-creation of personalised food structures. This means that the role of user changes from the old '*buy*' and '*choose-and-buy*' to the current and innovative '*buy, choose and design*', which strengthens the role of consumers and the drive towards customised and personalised demand (Hu, 2013). For instance, users could create a schematic representation of the desired food structure, including ingredients, shape, colour and taste and then submit this representation to the food producers that, after analysis, return the printed result. In co-creation system, modifications are worked out, reducing costs and time and improving client satisfaction. 3D printing is designated to be the first step in the transition from 'current manufacturing' to 'social manufacturing' or, in other words, the rise of *prosumers* (Mohajeri *et al.*, 2016) in which active customers participate in all the steps of the food manufacturing process.

Current limits to bring 3D food printing at high readiness technology level

3D food printing is a young field of research with less than 200 scientific publications against more than 28,000 recently retrieved on Scopus data bank (Derossi *et al.*, 2020a, 2020b, 2020c, 2020d, 2020e). Since 2007, when the first paper on 3DFP was published, the researchers and the food industry focused the work essentially on the aim of replicating the 3D digital model by using different kinds of food (vegetables, cereals, cheese, etc.) and modulating printing variables (Yang *et al.*, 2018; Derossi *et al.*, 2019) aiming to get innovative shape. Although very promising results have been obtained, increasing the confidence in the benefits and future perspectives of using 3DFP, several limits still hamper its practical application both at home level and at industrial level (Palaniappan *et al.*, 2020; Tomašević *et al.*, 2021). The most important obstacles may be resumed in the following points: 1. the low speed of manufacturing, 2. the enormous effect of the properties of food formula and the related need to use specific printing conditions, 3. a more profound understating of the post-processing to prolong the shelf life of 3D food printed and 4. the needs of software interfaces (i.e. CAD and slicing software) planned, developed and optimised on the properties of food materials. The first two points are strictly connected because is not feasible to accelerate the printing if the food formula is characterised by a low printability. The global 3D food printing experiments rarely used an average print speed greater than 70 mm s^{-1} while values greater than 300 mm s^{-1} are very common for the printing of thermoplastic materials (Derossi *et al.*, 2020a, 2020b, 2020c, 2020d, 2020e). This is because at high speed the imbalance between the printing movements and the extrusion rate – the amount of material deposited per unit of time – may cause stretching, ruptures and under-deposition, thereby reducing the printing quality (Le-Bail *et al.*, 2020). On the other hand, the printability of food materials, defined by the ease of flow through the nozzle, a good adhesion between layers and the capability to keep the weight of overlying layers, is greatly affected by the chemical composition of any food formula and the natural variability of each utilised ingredients (Zhu *et al.*, 2019a, 2019b; Nijdam *et al.*, 2021a, 2021b, 2021c; Tian *et al.*, 2021). In fact, the majority of the scientific publication reports specific settings for the most important printing variables (i.e. flow, print speed, retraction, infill level, nozzle diameter and layer height) for each kind of food such as fruit and vegetables (Chen *et al.*, 2021; Derossi *et al.*, 2018), cheese (Baareen *et al.*, 2021; Ross *et al.*, 2021), meat (Dick *et al.*, 2021), cereal-based products (Derossi *et al.*, 2020a, 2020b, 2020c, 2020d, 2020e), chocolate (Rando & Ramaioli, 2021), fish (Kim *et al.*, 2021) and eggs (Anukiruthika *et al.*, 2020). Currently, it is challenging to find overall rheological conditions capable to obtain a good printing quality between different food materials or within a kind of food formula. On this, the needs of engineering solutions, novel slicing software and specific settings of the printer's firmwares addressing the need of optimise the movements in X, Y, Z and E axes on the basis of the rheology and adhesives of the food materials will be essential for the future application of this technology (Nijdam *et al.*, 2021a, 2021b, 2021c).

The issue of post-processing is a very urgent challenge for both the structural stability of the printed food and the need to guarantee the safety, sensorial and nutritional properties along shelf life. At first, the use of conventional cooking method based on the principle of conduction and convection to heat showed several limits. For instance, when using cereal-based food materials that must be cooked, the high temperature – in a large range between 160 and 200 °C – reduces the viscosity of the batter in the first phase of the heating often causing the lack of the shape due to the inability of the bottom layers to keep the weight of the overlying layers. Also, the occurring dehydration during cooking might cause the change in shape and dimension of the printed structure. On this point, researchers are mainly working on the composition of the food formula to gain a high structural stability also during baking (Pulatsu *et al.*, 2020a,2020b; Tian *et al.*, 2021) while some innovative studies have performed with the idea of using infrared lamp heating to get a layer-by-layer cooking (Hertafeld *et al.*, 2019) or by printing on a hot bed inducing starch gelatinisation and denaturation protein of wheat flours, thereby conferring high rigidity that avoid the crushing of the first layers (Derossi *et al.*, 2018a, 2018b). Finally, we want to recall the need of detailed experiments dedicated to the safety of 3D-printed food that, unexpectedly, has been completely undervalued till now. Whether the microbiological and nutritional quality of the food formula – before the printing process – could be obtained by using the large range of the technologies utilised for conventional food products (i.e. thermal and non-thermal process), the effect of the printing *per se* on the microbiological safety due to the contact with several mechanical parts and the need of post-printing stabilisation methods urges of detailed experiments. We have performed a search on the SCOPUS databank by using the keyword [*3D Food Printing AND (shelf life OR safety or micorbiol*)*] in date 11 June 2021, and we retrieved only 7 documents of which only Severini *et al.* (2018) performed storage experiments of fruit- and vegetable-based 3D-printed food analysing the effect on microbial growth in refrigerated conditions.

Conclusions

The spreads of SARS-CoV-2 not only directly undermine our health but also damage food security and nutrition at different angles such food chain disruption, food shortage, reduced purchasing power, incorrect eating habits, increased food loss and increase in un- and underemployment. Furthermore, the lack of socialising during eating with friends, colleagues, parents, etc., has generated stress, anxiety, fear, anguish and worry that, in turn, exacerbate the negative effects of SARS-CoV-2 on the health status of all people, mainly for vulnerable consumers such as elderly and hospitalised patients.

Mapping the scientific studies and the online news on 3D food printing, a technology belonging in the 'human-computer-food-interaction', we open a discussion that goes out of the common engineering consideration, reinterpreting 3DFP principles, ambitions and main features under the light of the current challenges posed by the ongoing COVID-19 pandemic situation.

3DFP has unprecedented and unique potential allowing realising personalised food manufacturing, social distancing, decentralisation of food manufacturing, people engagement in co-creation of food, socialising process, business and job creation. These novel perspectives might significantly help to mitigate the spreads of SARS-CoV-2, the risks on people health and negative impacts on food security and society.

First of all, for its nature of a computer-aided technology 3DFP sustains social distancing as recommended rules in food site area. 3DFP may reduce the number of people touching food before consumption as well as inter-human contact when creating, shaping, testing, validating and manufacturing food products. Also, 3DFP strongly sustains the decentralisation of food manufacturing, enabling to reduce the number of people involved in the food chain, thereby minimising food contacts.

Another crucial feature is the unique capability of 3DFP to create nutritionally personalised food that could be designed and realised according to people uniqueness for phenotypic, genotypic and microbiota profile singularity. So, nutritionally personalised food definitely would strengthen the health status and immune system in response to virus attack with great benefits of people in quarantine or hospitalised COVID-19 patients. In addition, medical data could drive the 3DFP designing specific dietary requirements of people. Also, the personalisation of sensory properties (texture, taste, visual aspect, etc.) would help to increase food acceptance fostering the consumption of a healthier diet or designed texture could modulate satiety reducing the overeating during confinement.

These novel scenarios fuel new businesses in a period in which un- and underemployment that, in turn, have reduced the purchasing power of consumers and it increased consumption of low-quality food with high energy density. 3DFP may open several business options such as the creation of novel 3D printers for home use or to be introduced in supermarket or at industrial level, the creation of novel starts-up offering library of 3D personalised recipe models, the creation of novel businesses based on data-driven approaches capable to link medical data and food manufacturing.

Finally, 3D printing technology may reduce the lack of social contacts due to physical confinement. Indeed, 3DFP is a socialising process that engages people to participate in creating and modifying recipe models to be used in social e-dinner. People, for instance, may participate in designing personalised cake for the birthday of friends or parents to be sent as digital files and directly printed at home during online birthday party. In sum, 3D food printing not only allows to share ideas, novel business but tangible foods that create emotions and memories. However, some aspects still are limiting the practical application of 3DFP both at industrial level and for home use such as the low speed of manufacturing, the lack of general printing conditions due to the great effect of each kind of food formula on the overall printability, the needs of a better understanding of the post-printing process such as innovative solutions for the cooking of printed structures; the lack of information regarding the shelf life of 3D-printed food. All these urge of novel solution for a practical application of 3DFP at home or for the mass-customisation of food products.

Conflict of interest

None.

Author contributions

Antonio Derossi: Conceptualization (lead); Data curation (lead); Investigation (lead); Methodology (lead); Visualization (lead); Writing-original draft (lead); Writing-review & editing (equal). **Bhesh Bhandari:** Writing-review & editing (equal). **Kjeld van Bommel:** Writing-original draft (supporting); Writing-review & editing (lead). **Martijn Noort:** Writing-review & editing (equal). **Carla Severini:** Investigation (equal); Methodology (equal); Supervision (equal); Writing-review & editing (equal).

Peer review

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Data availability statement

Data sharing not applicable – no new data generated.

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The paper is dedicated to an innovative application of 3D Food Printing technology. Specifically, the authors investigated the introduction of probiotic bacteria in 3D printed food. The paper help us to connect the 3DFP technology to the possibility to deliver important probiotics to the daily diet thus helping to reinforce the immune systems in the current (or future) pandemic situation.

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