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Review article

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Personalized, digitally designed 3D printed food towards the reshaping of food manufacturing and consumption

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The emerging world of 3D food printing is reviewed. Its role in food manufacturing, including benefits and impacts, underemphasized gastrophysical aspects, and limitations are discussed. Foods can be digitally designed and physically prepared using the layer-by-layer deposition of food components, unleashing opportunities to deliver nutritionally personalized food and new food-human interactions. Existing bottlenecks, under-researched gastropsychophysical aspects, and the lack of harmonized standards hindering its use for mass production are mentioned.

Definition of 3D food printing

According to the Merriam-Webster dictionary (https://www.merriam-webster.com/dictionary/3D%20printing), 3D printing is "*the manufacturing of solid objects by the deposition of layers of materials in accordance with specifications that are stored and displayed in electronic form as a digital model*". In addition, 3D printing can integrate materials, structures, and functions[1]. As a representative example, the capability of depositing two distinct materials having different behaviors during heating enables the generation of dynamic shape changes during dehydration[2]. Similarly, color modulation of 3D-printed food has been triggered by depositing layers of materials having different colors when in contact with acidic solutions[3].

Although the first experiment on 3D printing dates back to 1960[4], its transition to the food sector started only recently. The user creates 3D digital models, which are converted into information that drives the path of the printer and the amount of material deposited locally. Although several food printing technologies are now available[5], the most common 3D food printing (3DFP) method is based on a controlled layer-by-layer deposition of a food ink by cold or hot extrusion followed eventually by a final post-treatment[6,7].

Technical background and critical challenges

The first phase of 3DFP involves designing digital 3D models and generating the codes that drive the movement of the printer. Apps for beginners (e.g., Tinkercad) or more professional software (e.g., Rhino 3D, Blender, Fusion 360) can be used to design almost any conceivable structure. While on a laboratory scale, small and simple geometries such as cubes and cylinders[8–10] are preferred to ascertain the influence of printing variables[11,12], unusual structures are currently also available (https://blurhapsody.com/en/; https://revo-foods.com/). Once the digital model has been designed, the slicing phase literally shaves the 3D model into layers while the user defines the printing conditions. Such a process must accurately define dozens of printing parameters to ensure the equilibrium between the printer's movements and the material deposition, such as printing speed, layer height, extrusion rate, nozzle diameter, etc.[13]. For example, the optimization of the thickness of the layers is a prerequisite to ensure very good printing precision and structural stability and has been subject to a number of investigations[14,15]. The majority of the results recognize that an appropriate layer height is 80% of the nozzle diameter to ensure high adhesion and structural stability[15,16]. Often, the slicing software estimates and the actual movements of the printer diverge[15], thus hindering the potential benefits of

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the degrees of freedom offered by this technology. The slicing software (Cura, Prusa, Slic3R, etc.) has primarily been designed for plastic materials/filaments with highly stable properties, while food is a metastable material with a large degree of physical and chemical variability. Such software requires the setting of printing variables that are irrelevant when it comes to "food inks". For instance, the diameter of the plastic filament is compulsory, and an essential input data that modulates the movement of the stepper motor which feeds the nozzle. However, this is a requirement that can never be fulfilled for foods since they are primarily provided as semi-liquid colloids. Although advanced 3D printers have significantly improved with proprietary slicing software—e.g., Prometheus (https://www.roboze.com/en/software.html)—such issues remain essentially unsolved unless the writing of custom G-code[17] or the using of innovative novel G-code designer such as FullControl GCode designer[18]. Although this and other slicer parameters are irrelevant for 3DFP, they significantly affect the deposition of food. Derossi et al.[16] reported a detailed experiment showing the effect of the diameter of the filament on the printing quality of a cereal-based snack. Hence, developing slicing software and deposition systems specifically designed for food materials will be essential for the scaling up 3DFP. The second phase bridges the digital and the physical realm including developing printable food formulae, executing the printing process, and applying any post-printing treatment (e.g., baking, drying).

Printability, which encompasses all of the rheological properties for precise food printing deposition, becomes vital at this stage[19]. Three printing sub-phases are involved[20]: extrusion, during which the viscosity, shear-thinning behavior, and yield stress characterize the ability of the food to flow easily through the nozzle; recovery, where thixotropy defines how fast the materials regain their initial state; regeneration/self-supporting, in which the loss and storage modulus moduli and the yield stress inform the structural stability of the printed object. These rheological attributes have been widely used to estimate printability[20,21]. Overall, the food formula should capture a non-Newtonian shear-thinning behavior[19,22] and yield stress between 500 and 1500 Pa[23,24]. Although selecting materials with appropriate rheological properties can improve printability, such material may simply not be extrudable[19] because of the settings of the printing or other engineering variables, e.g., the pressure exerted by the stepper motor may be insufficient to overcome the yield stress[25] or the differences in flow properties when using a cylindrical or conical nozzle.

The evolution of food inks

Researchers have extensively tested food materials as diverse as chocolate[26], dough[27–29], beef[30], cheese[31], fruits and vegetables[32–34] (Fig. 1). These studies have demonstrated the potential use of a wide range of food materials but at the same time they also highlighted several issues attributable to the inadequate rheological properties of certain foods[33], which necessitated the use of many texturing agents—e.g., κ-carrageenan, starch, gelatin, whey protein isolate, and sodium alginate, amongst others[19,35–37]. Given the growing interest in nutritionally and sensorially personalized products, and the need for a more sustainable food system, the use of uncommon sources of nutrients and other edible colloidal components has increased (Fig. 1)[38,39]. Among them, bigels are gaining popularity given their ability to enhance printability and create delivery systems for nutrition and functional compounds[37,40–42]. Food-grade bigels, obtained by mixing aqueous-based and oil-based gels, exhibit mechanical stability and spreading properties, as

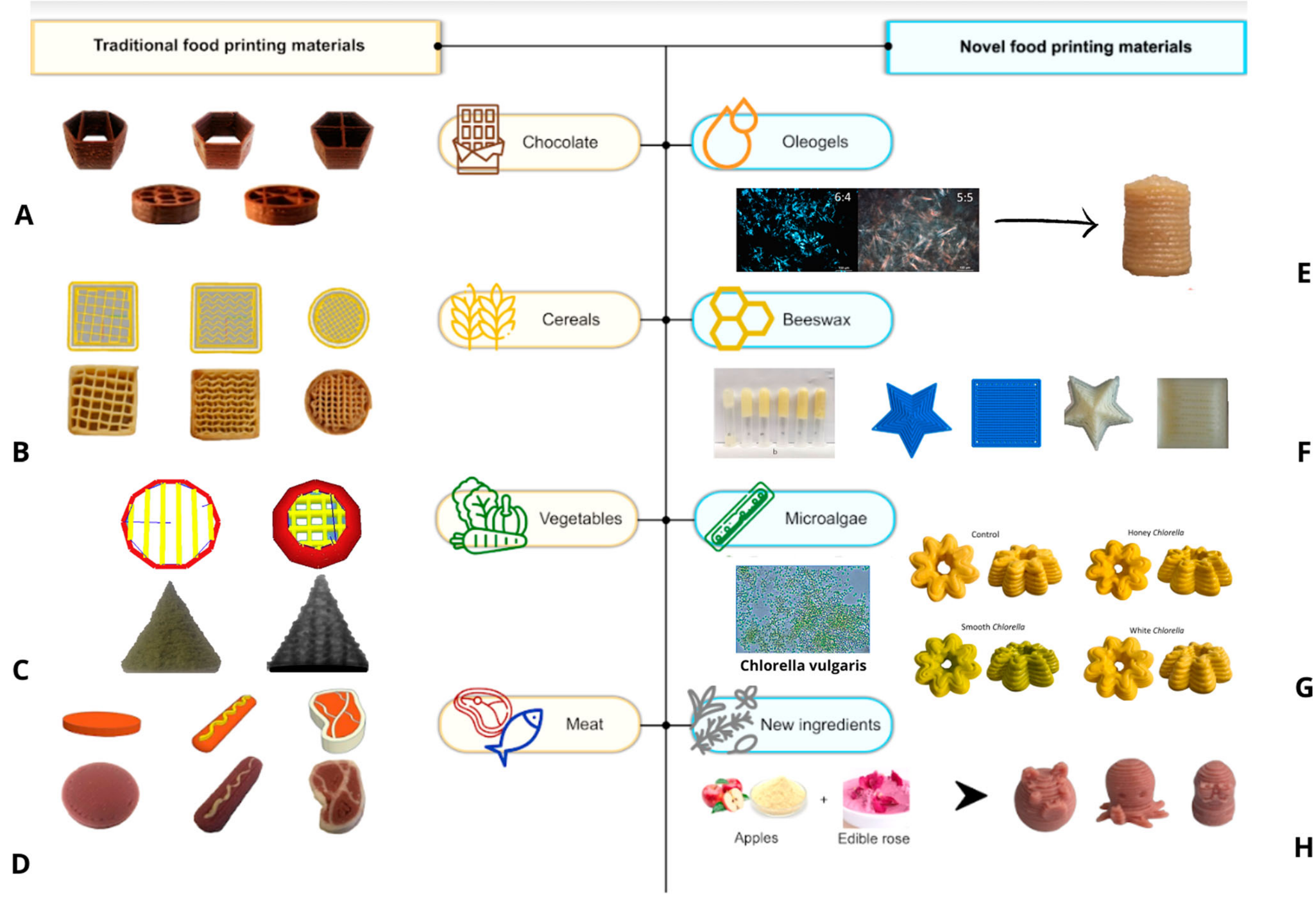

Fig. 1 | Traditional and novel science-driven food printing materials. Representative examples of traditional and innovative food printing materials. **A** 3D chocolate (adapted from Manthial et al.[113]); **B** biscuits (adapted from ref. 81); **C** vegetable-based snacks (adapted from Severini et al.[114]); **D** meat products (adapted from Dick et al.[115]); **E** Oleogels (adapted from ref. 116); **F** beeswax and potato-starch system (adapted from Shi et al. [117]); **G** microalgae (adapted from refs. 118 and; 119); **H** apple and edible rose (adapted from ref. 44).

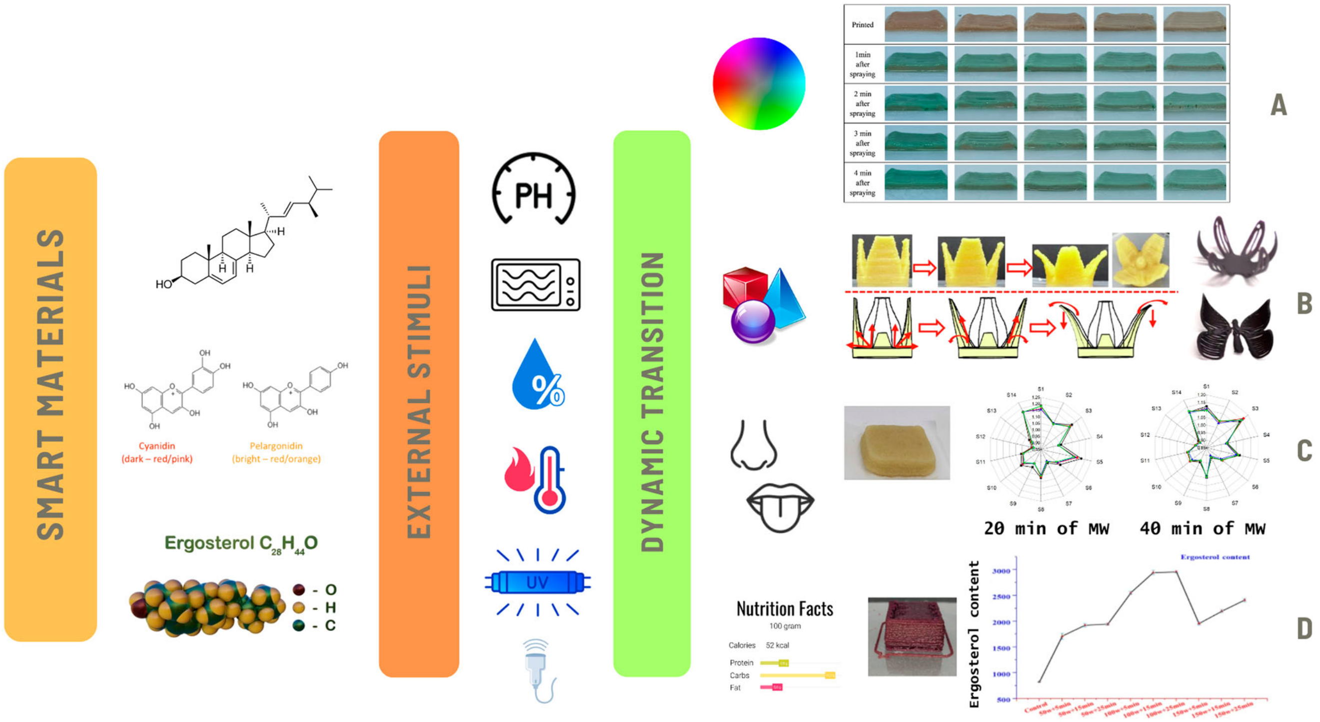

Fig. 2 | Principles and applications of 4D Food Printing. Smart materials are exposed to external stimuli to trigger the dynamic transition of some food properties: **A** color changes activated by pH (adapted from Chen et al.[120]); **B** shape change (adapted from ref. 52); **C** flavor changes (adapted from ref. 60); **D** nutritional changes (adapted from ref. 49). Chen et al.[120], Guo et al.[52], Phuhongsun et al.[121], —all permissions have been obtained. See files ‘Permission_Figure_2a’, ‘Permission_figure_2_b’, ‘Perimssion_figure_2_c’, ‘Permission_figure_2_d’. All other minor images/symbols have been obtained from Wikimedia Commons.

well as being highly tunable, sustainable, renewable, and crucially are nontoxic[40]. Beeswax and candelilla wax have been used in 3D food printing for their thermal reversibility and high hardness at room temperature[41–43]. Microalgae[28], edible rose flowers[44], and gelatin from salmon by-products[45,46] are other compounds used for their high protein content, their properties as fat replacers, and their ability to enhance the sensory profile and rheological properties. Moreover, the high flexibility in ingredient sourcing obviously allows for the integration of side streams, thus contributing to a more sustainable food sector.

Dynamic food printing

3D food printing is not limited to the three-dimensional space. That is, a growing number of researchers are harnessing the programmable dynamic changes of esthetic, nutritional, and functional properties of 3DPF. To do this, several stimulus-responsive materials and external stimuli have been used to trigger changes in morphology, color, and even more complex sensorial attributes (Fig. 2). For instance, researchers at MIT designed a gelatin/ethyl cellulose bilayer in which hot water during cooking triggers an inhomogeneous shape transformation based on the differential water-absorption capacity of its components[47]. Other morphological changes, i.e., bending angles, may be induced by harnessing microwave dehydration inhomogeneities arising from local differences in dielectric properties of the food formulas obtained by modulating salt, fructose, and butter[48]. Alternatively, bending can be activated during drying due to the different shrinking properties of two overlaid food/paper layers[34,49,50]. However, only few authors have obtained a rapid shape-shifting (less than 90 s) of a complex 3D-printed object[51,52] by using microwave heating as an external stimulus. Dynamic color changes, which resonate with consumer acceptance[53,54], are another example of 4D food printing (4DFP). Chromophore-loaded single ingredients or compounds (e.g., purple sweet potato flour, curcumin, anthocyanin) can be prepared so that they respond to pH, temperature, or moisture changes[55,56]. The precise layout of components is crucial to facilitate gradual exposure to the stimulus and elicit the desired dynamic response. Examples include anthocyanins color changes in purple mashed potato after spraying with a solution at different pHs[57], curcumin color shifting by HCO_3^- releasing triggered by heating[58], and spontaneous color changes (i.e., without the need for external stimuli) by controlled diffusion of hydrogen ions between layers of 3D-printed anthocyanin potato-starch and lemon gel[59]. Another exciting development concerns dynamic changes in the aroma. For instance, Phuhongsung et al.[60] prompted a significant change in aromatic compounds 5 h after spraying a pH 8–10 solution on a printable food material consisting of soy protein isolate, pumpkin, and beetroot mixture. Furthermore, microwaved heating triggered an aroma change in a complex food formula enriched with cinnamaldehyde compound (which smells pleasantly like cinnamon)[36].

Main gaps for the mass production of 3D-printed food

It is possible to imagine some of the many benefits that might result from adopting 3DFP for mass production, yet, the technology is still immature. First, 3DFP is very slow when compared to other food processes and additive manufacturing of non-food materials. The typical printing speeds for food inks are 20–60 mm/s[61,62], with only few reports achieving >70 mm/s[16,63]. These speeds translate into printing times of 1–20 min per single food piece, depending on the complexity of its morphology. Low printing speed is not an inherent limitation of this technology (e.g., thermoplastic materials are printed at 250 mm/s)[64] but, rather, stems from the difficulty of depositing food materials at high speed, i.e., beyond 100 mm/s, without compromising the structural properties of the food. Another challenge in 3DFP is ensuring consistency in, for example, the rheological properties of the ink-food, particularly when living, dynamic materials with a high degree of inherent variability are used[65,66]. Striving for consistency in printing quality has led to the extensive use of thickening and gelling agents—i.e., starch, gelatin, carrageenan, pectin, alginate, xanthan, gellan gums etc.—[67] as ingredients in food inks, increasing shape repeatability at the expense of clean labels[22]. With the aim of improving consistency, Chieregato et al.[68] patented a starch dispersed in a pregelatinized liquid gel capable of rapid stiffening when submitted to hot extrusion. Other engineering limitations arise from printing multi-materials and post-processing. Most of the printers on the market (e.g., FoodBot, By-

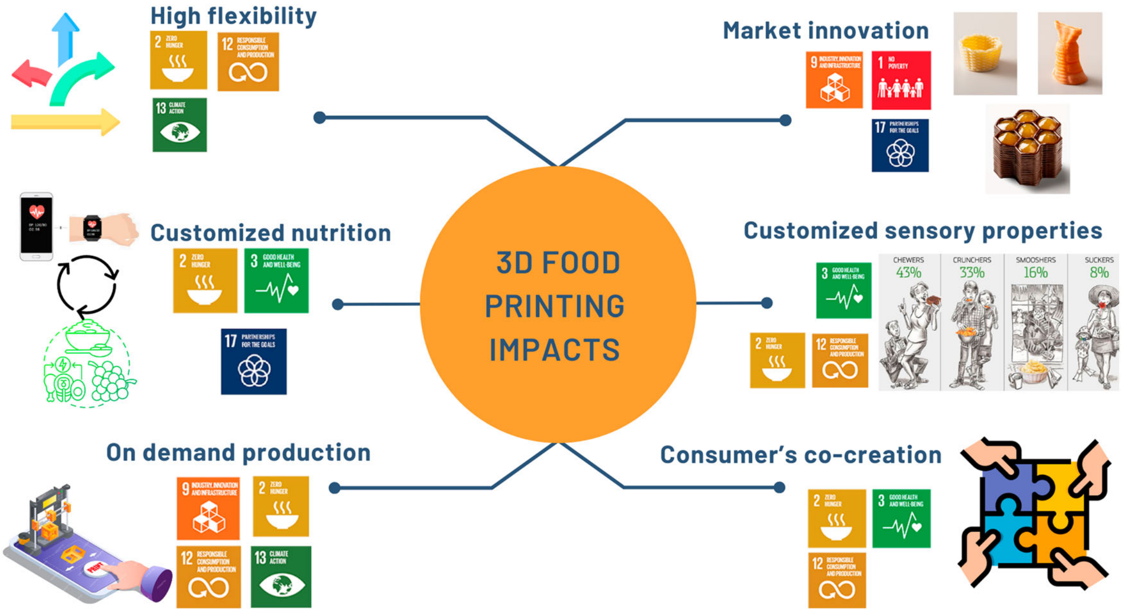

Fig. 3 | Impacts of 3D Food Printing on Sustainable Development Goals of the UN. Most important benefits of 3DFD and impacts of 3D Food Printing on the Sustainable Development Goals (adapted from UN[122] [all SDGs are downloadable and reusable with permission]; Blurhapsody[123] [the images of the 3D-printed pasta are reported on the website: https://blurhapsody.com/]; Morgestern & Kim[124] [from this paper is reported that the original figure was designed by https://www.robshepperson.studio/. I sent to Rob Shepperson for receiving permission to reuse his image]. The figure was entirely designed by the authors of the paper reusing SDGs icons and few other images as indicated in the legend. All other symbols/icons used in the figure were obtained by using a specific tool of the software CANVA—professional version.

flow, Felix printer, etc.) consist of one or two cartridges/printing heads, limiting the possibilities of complex properties and nutritional profiles. Some companies, such as Revo Foods, and research groups[17,69] are currently working on systems that are capable of printing multiple ingredients in parallel, an essential feature when it comes to delivering personalized food products. Post-processing of 3DFP is crucial for mass production since it determines the printed food's structural stability, and shelf life as well as modifies the sensory, textural and nutritional properties. Thermal processing (e.g., baking, drying, etc.) of 3D-printed food often causes the loss of the designed shape, due to the lowering of the materials' viscosity, which fails under the weight of the other layers. Layer-by-layer heating has been proposed to stabilize structural properties as printing progresses. For instance, heating the ink can also harden the ink, through starch gelatinization[68]. To this end, the use of print heads equipped with heating systems, such as lasers[17] or ohmic heating, are currently being tested[70]. Ohmic heating is a developing technology able to heat a liquid non-dielectric fluid or solid with quasi-isotropic heating. Inflow ohmic heating of starch-based inks (pound cake batter as a model system) has been considered in refs. 70–72; such technology gives access to high-throughput performance in the case of 3D printing. Post-processing also affects the capability of transporting 3D-printed foods without compromising their structural integrity. Finally, there is a need for robust scientific data regarding the microbiological safety of 3D-printed food as well as their shelf life in line with the eventual envisioned mass production of 3D-printed food.

Social, economic, and environmental impacts of the 3D Food Printing

But at a more fundamental level, why should food be printed? This is a good question, considering that when people manually prepare foods and taste, several symbolic and social relationships are generated, creating the so-called gastronomic identity[73]. However, the urgent need for research and innovation (R&I) breakthroughs to help reach the Sustainable Development Goals (SDGs) should be recalled at this point. The commitment to *end hunger* (SDG2), *ensure healthy lives and promote well-being for all at all ages* (SDG3) is expected to be fulfilled by 2030. However, the world might fall short of this target unless significant breakthroughs are identified and, more importantly, enacted[74,75]. Interestingly, the icon of 3DFP appeared on the cover of "*Food Industry 4.0—Novel and Efficient Food Processing*"[75] and in the EU report "*Food 2030— Pathways for Actions*"[76] as a future tool to tackle the aforementioned issues. In addition, the recent "*Foresight meeting on new food sources and production systems*" by FAO[77] has analyzed the main advantages and limits of 3D/4D Food Printing. 3DFP enables the creation of unconstrained, novel, and unequaled food shapes and internal structures that can be digitally designed and printed to deliver new sensory experiences more appealing than those offered by the original form of raw materials. This helps to include nutrients and healthy compounds from ingredients that people consider unpleasant or side streams from food processing (Fig. 3). As extensively demonstrated by cognitive neuroscience, visual appearance contributes to food pleasantness[78] and chefs know how food plating can maximize sensory perception and bias food choice[79].

3DFP could generate food shapes based on consumers' demographics and different scenarios. For instance, in the case of the elderly, 3D-printed food should replicate original foods to help people recognize such food products. Contrarily, the use of non-food shapes—e.g., geckos, flowers, etc.—could encourage children to adopt a more nutritious and healthy diet[80]. However, 3DFP is not a technology just for esthetic purposes. 3D-printed foods can be used as prototyping tools to study and analyze the properties of food products along the food chain. Fast and effective prototyping can reduce innovation time and costs, help optimize processing conditions to reduce energy consumption and enhance food stability by modulating/controlling chemical and physical reactions through material compartmentalization. For example, after digitally designing biscuits with different shapes and internal properties, Derossi et al.[81] identified the structures enabling the fastest cooking rate and the lowest acrylamide formation. Furthermore, by designing the shapes of internal structures, the amount of calories could potentially be modulated by using a lower infill level. This, in addition, can significantly modify texture, supporting new ways to fulfill consumer preferences or physical requirements (e.g., patients with mastication or swallowing problems)[12,82]. All these technological aspects become opportunities for societal impact as they could shape a new consumer understanding of healthy foods (Fig. 3). There is a large body of

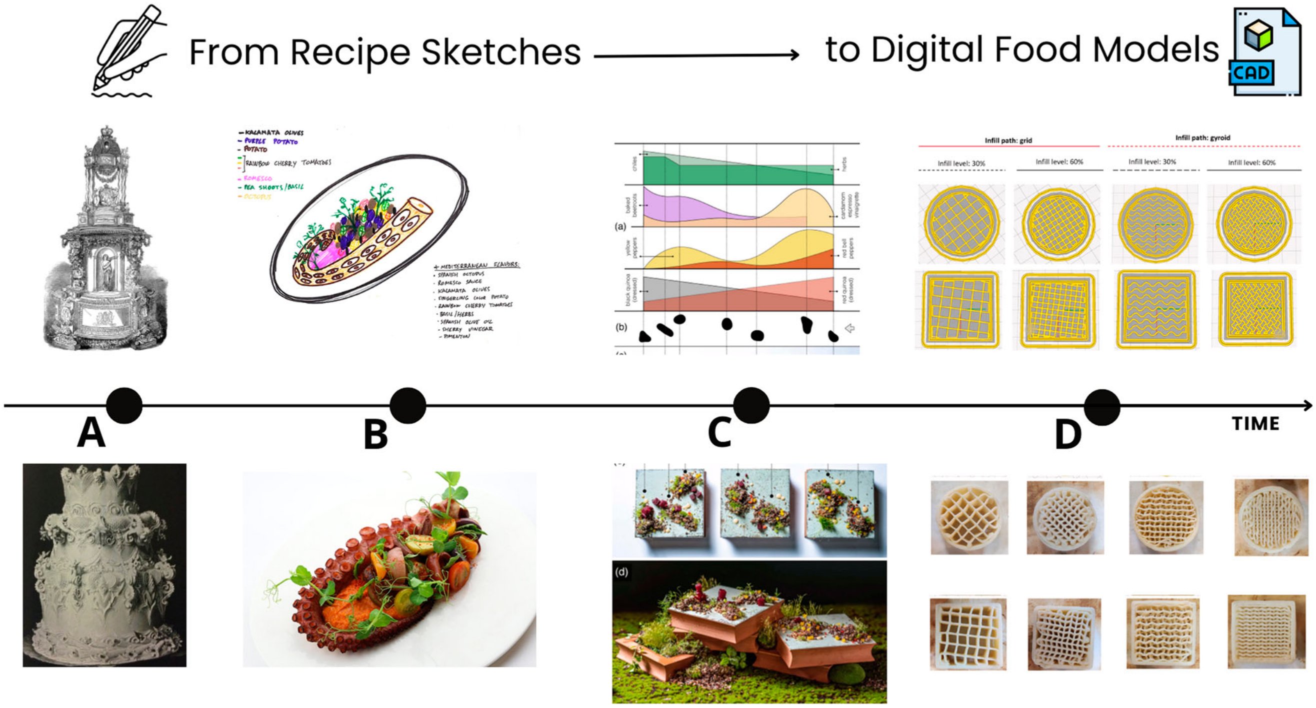

Fig. 4 | Schematic representation of the evolution of food design. Evolution of the food design from recipe sketches to digital food models: **A** examples of first cake design (Lange[125] [Permission obtained. See file 'Permission_figure_4_cake_design']; **B** example of Chef's sketching to design new recipes (The Seafire Grill[126] [Permission asked to the restaurant. See file 'Permission_figure_4_b']; **C** digital representation of ingredient located in the plate to extend/personalize sensory properties of the dish (Zoran et al.[109] [Permission obtained. See file 'Permission 'Figure_4_c']; **D** 3D digital models and 3D-printed biscuits (Derossi et al.[81]).

evidence of the interplay between food-intrinsic sensory properties, consumers' interest and the consumption of nutritional information and healthy eating[83]. The unique ability of locally depositing food materials in 3D space can help to reduce the intake of salt/sugar/unhealthy ingredients by exploiting the benefits of the odor-induced taste effect (OITE)[84,85] or the shape-taste effect[86,87]. For instance, 3D-printed layers of chocolate with different thicknesses on rice waffles affect sweetness perception, fullness and liking of samples[88]. Meanwhile, the inhomogeneous distribution of NaCl in 3D-printed foods significantly increases perceived saltiness by enhancing sensory contrasts and preventing 'taste adaptation'[89,90]. In addition, the properties of the ink-food, complex geometries, and internal structures would allow protecting bioactives and modulating the release kinetics of nutrients and functional compounds adjusted for individual needs. For instance, a higher release of catechin and quercetin was obtained by modulating the oleogel/hydrogel ratio in bigels systems[42]. Curcumin and resveratrol included in 3D-printed oleogels were protected from the oral and gastric environment, thus increasing their bioavailability by about 1.3 times compared to the control[91]. Creating foods with programmable textural properties[27,92] can facilitate mastication and nutrient uptake for dysphagic patients (8% of the global population)[93–96]. Moreover, modulating food texture can increase mastication, thus increasing satiety even when energy intake is limited[97,98]. Tailored, highly appreciated sensory properties could help to reduce food waste, preventing the disposal of valuable nutrients and misuse of resources (e.g., energy)[99] since the main drivers of food waste in schools (2–49% in the USA and 20–29% in Italy) are food preference, taste, and appearance[100]. In terms of nutritional quality, the aforementioned flexibility (Fig. 3) of 3DFP in using different kinds of ingredients, from powders to liquids, enables the valorization of 'inferior' and uncommon sources of nutrients such as microalgae, insect flours, by-products or waste products[101–104]. For instance, Pant et al.[103] formulated an ink-food using spinach stems and kale stalks to convert these wastes into sensory-acceptable food products. In addition, the precise dosing of the ingredients in individual food products can be coupled with data-driven approaches, e.g., wearables and machine learning methods, to fulfill personalized dietary recommendations[103] even in the same family or household and then printed into tangible ready-to-eat or ready-to-cook products. Another potential economic and environmental benefit of 3DPF is reducing the gap between producers and consumers, i.e., on-demand production. Furthermore, co-creation approaches and user-centric food chains, in which people would be directly involved in the digital design of their food products, can be operationalized by 3DFP. Consumers, for instance, could print only what they should or would eat (i.e., exact weight), resulting in a significant reduction of food waste at households. Co-creation envisions the opportunity for new business development. In addition, the co-creation of food—i.e., consumer's participation in making food for themselves—increases the liking for that food, based on the so-called "IKEA effect"[104,105]. New digital supportive ecosystems such as repositories of food digital designs, digital recipes to get printable food formulae, and user-friendly software can be envisioned. Interestingly, Rogers and Srivastava[99] proposed three food chain models; generative/premium, facilitative/deluxe, and selective/standard services, supported by including 3DFP in the food supply chain. In addition, the on-demand nature of 3DFP has triggered considerable interest for military and long-duration space missions[106,107].

Gastrophysics of 3D-printed food

Consumers might perceive digitally designed foods and their production using additive manufacturing as unnatural and synthetic. However, its basic principles have been used since the 18th century, especially in traditional gastronomy, of which 3DFP can be considered a natural evolution in the digital era (Fig. 4). While the gingerbread replicas of visiting dignitaries were the first examples of food design during the reign of Elizabeth I, the "art of cake design" significantly evolved to celebrate many events, particularly weddings, for which tradition requires three layers representing the engagement, wedding, and eternity rings (https://www.confectionarychalet.com/history-of-cake-decorating). More recently, chefs literally sketch the plate on a page before creating new dishes (https://guide.michelin.com/sg/en/article/features/chefs-draw-creative-process). The chef George Zappas (https://cookingenie.com/content/blog/the-art-of-food-plating-how-to-

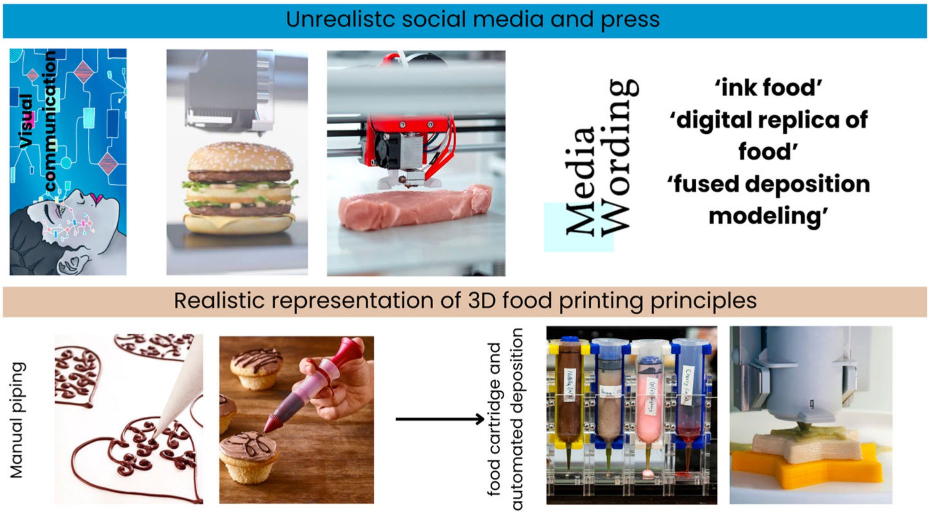

Fig. 5 | Mistaken and appropriate representation of 3DFP principles. Unrealistic vs. more realistic and appropriate images and wording used to communicate the main principles of 3D Food Printing. (Adapted from Marr, 127 [Permission requested to Bernard Marr. See file 'Permission_picture_-Bernard_Marr']; Blutinger/Columbia Engineering, 128 [Permission obtained. See file 'Permission_-from_Jonhatan_Blutinger']; Hy-vee[129]; Kooihousewares, 130 [Permission obtained. See file 'Permission_picture_kooihouse']; Lange[125]; Naturalmachines[131]).

present-deliciously-appetizing-meals/), identified some benefits from food plating design: improved portion control; higher nutrient density; increased flavor contrast; a modern experience; opportunity for self-expression. Following the principles of food material science and rational food design[108], 3DFP uses edible materials to create 3D architectures aimed at delivering nutritional and sensorially enhanced experiences[90,91]. For instance, Fahmy et al.[89] 3D-printed a wheat starch-egg white powder mixture with predesigned inhomogeneous distribution of NaCl, which resulted in enhanced saltiness perception and a reduction in overall NaCl content. Food design has been accelerated by the latest advancement in food science and digital technologies[109–112]. Digital gastronomy, as proposed by Zoran[110], has opened new avenues to design, prepare and cook food products. The author envisioned how digital tools could help with the precise manipulation of ingredients, including the definition of the best quantity and its distribution in the 3D space. 3DFP integrates all aforementioned aspects by using computer-aided design to digitally draw the desired shape, dimension, internal structure and localized ingredient deposition.

Another critical aspect to be considered is how the technology itself is communicated to the public. The frequent use of terms such as "food printing," "food ink", and "layered food deposition" in the scientific literature[9] and newspapers are often associated with unnatural/synthetic food products. Furthermore, newspapers and online representations of 3DFP are unrealistic, often distorted, and could be off-putting to consumers, such as the images communicating the possibility of printing an apple, although there would be no reason to print vegetables or fruits (Fig. 5).

To conclude, the emerging world of 3D-printed foods is growing rapidly because it offers new ways to reshape how foods are manufactured and consumed. Digitally designing a 3D food model and replicating it by depositing food components in a layer-by-layer process has many beneficial impacts. Unprecedented and modulable/customizable interactions between sight, hearing, smell, and touch and food products can maximize sensory acceptance and can sustain the adoption of a healthier diet and food waste reduction. The high freedom of movements of 3D printing enables the creation of complex shapes and internal structures, which offer the opportunity to reduce mastication and facilitate swallowing for the elderly, modulating satiety, reducing the intake of calories, salt, and sugars, and controlling the release kinetics of nutrients. The use of a large range of food materials to print, together with the local deposition of food components, enables the production of new delivery systems of nutrients and bioactives. Moreover, the high flexibility in ingredient sourcing (e.g., from side streams and novel food components) and the modulated dosing make 3DFP the only candidates for nutritionally customized food manufacturing. Furthermore, 3D printing is an on-demand technology that can benefit the sustainability of the food sector. On the other hand, low printing speed, lack of a system for multi-material deposition, inconsistency in printing performance of the food formulas, the difficulty of printing multi-ingredient ink-food due to difficulty of estimating the rheological properties when changing the food formula, and the limited information regarding the safety and the shelf life of 3D-printed products, still hamper the widespread use of 3DFP in gastronomy and at industrial levels.

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References

1. Yang, J. et al. 3D printing technology series. In *Multimaterial 3D Printing Technology* (eds Yang, L. et al.) 1–10 (Elsevier, 2021).
2. Kang, Z., Wang, Z., Zhang, W. & Fang, Z. 4D printing of edible insect snacks: color changes with external pH stimulation. *Food Biosci.* **55**, 102971 (2023).
3. Qiu, R. et al. Exploration of bigel 4D printing with spontaneous colour change for monitoring bio-actives kinetic behaviour based on the dual-units 3D printer. *J. Food Eng.* **367**, 111861 (2024).
4. Su, A. & Al'Aref, S. J. In *History of 3D Printing* (eds Al'Aref, S. et al.) 1–10 (Academic Press, 2018).
5. Liu, Z., Zhang, M., Bhandari, B. & Wang, Y. 3D printing: printing precision and application in food sector. *Trends Food Sci. Technol.* **69**, 83–94 (2017).
6. Kim, H. W., Bae, H. & Park, H. J. Classification of the printability of selected food for 3D printing: development of an assessment method using hydrocolloids as reference material. *J. Food Eng.* **215**, 23–32 (2017).
7. Uribe-Alvarez, R., Murphy, C. P., Coleman-Vaughan, C. & O'Shea, N. Evaluation of ionic calcium and protein concentration on heat- and cold-induced gelation of whey protein isolate gels as a potential food formulation for 3D food printing. *Food Hydrocoll.* **142**, 108777 (2023).
8. Shi, H., Li, E., Yang, H., Liu, D. & Yin, J. Microscale 3D printing of fish analogues using soy protein food ink. *J. Food Eng.* **347**, 111436 (2023).
9. Venkatachalam, A., Balasubramaniam, A., Wilms, P. F. C., Zhang, L. & Schutyser, M. A. I. Impact of varying macronutrient composition on the printability of pea-based inks in extrusion-based 3D food printing. *Food Hydrocoll.* **142**, 108760 (2023).
10. Lee, S. H., Lim, H. W. & Park, H. J. Integrated design of micro-fibrous food with multi-materials fabricated by uniaxial 3D printing. *Food Res. Int.* **165**, 112529 (2023).
11. Wang, M. et al. Rheological and physicochemical properties of *Spirulina platensis* residues-based inks for extrusion 3D food printing. *Food Res. Int.* **169**, 112823 (2023).

12. Yun, H. J., Jung, W. K., Kim, H. W. & Lee, S. Embedded 3D printing of abalone protein scaffolds as texture-designed food production for the elderly. *J. Food Eng.,* **342**, 111361 (2023).
13. Derossi, A., Caporizzi, R., Ricci, I. & Severini, C. Critical Variables in 3D Food Printing (eds Bhandari, G. F. & Zhang, B.) Ch. 3, 41–91 (Academic Press, 2019).
14. Huang, M., Zhang, M. & Bhandari Assessing the 3D printing precision and texture properties of brown rice induced by infill levels and printing variables. *Food Bioprocess Technol.* **12**, 1185–1196 (2019).
15. Ma, Y., Schtyser, M. A. I., Boom, R. M. & Zhang, L. Predicting the extrudability of complex food materials during 3D printing based on image analysis and gray-box data-driven modelling. *Innov. Food Sci. Emerg. Technol.* **73**, 102764 (2021).
16. Derossi, A., Paolillo, M., Caporizzi, R. & Severini, C. Extending the 3D food printing tests at high speed. Material deposition and effect of non-printing movements on the final quality of printed structures. *J. Food Eng.* **275**, 109865 (2020).
17. Blutinger, J. D. et al. Precision cooking for printed foods via multiwavelength lasers. *NPJ Sci. Food* **5**, 24 (2021).
18. Allum, J., Moetazedian, A., Gleadall, A. & Silberschmidt, V. Interlayer bonding has bulk-material strength in extrusion additive manufacturing: new understanding of anisotropy. *Addit. Manuf.* **34**, 101297 (2020).
19. Outrequin, T. C. R., Gamonpilas, C., Siriwatwechakul, W. & Sreearunothai, P. Extrusion-based 3D printing of food biopolymers: a highlight on the important rheological parameters to reach printability. *J. Food Eng.* **342**, 111371 (2023).
20. Liu, Z., Bhandari, B., Prakash, S., Mantihal, S. & Zhang, M. Linking rheology and printability of a multicomponent gel system of carrageenan-xanthan-starch in extrusion based additive manufacturing. *Food Hydrocoll.* **87**, 413–424 (2019).
21. Álvarez-Castillo, E. et al. A rheological approach to 3D printing of plasma protein-based doughs. *J. Food Eng.* **288**, 110255 (2021).
22. Cheng, Y. et al. Rheology of edible food inks from 2D/3D/4D printing, and its role in future 5D/6D printing. *Food Hydrocoll.* **132**, 107855 (2022).
23. Liu, Y. et al. Rheological and mechanical behavior of milk protein composite gel for extrusion-based 3D food printing. *LWT* **102**, 338–346 (2019).
24. Maldonado-Rosas, R. et al. Evaluation of rheology and printability of 3D printing nutritious food with complex formulations. *Addit. Manuf.* **58**, 103030 (2022).
25. Pospischil, M. et al. Paste rheology correlating with dispensed finger geometry. *IEEE J. Photovolt.* **4**, 498–503 (2014).
26. Mantihal, S., Prakash, S. & Bhandari, B. Textural modification of 3D printed dark chocolate by varying internal infill structure. *Food Res. Int.* **121**, 648–657 (2019).
27. Derossi, A., Caporizzi, R., Paolillo, M. & Severini, C. Programmable texture properties of cereal-based snack mediated by 3D printing technology. *J. Food Eng.* **289**, 110160 (2021).
28. Letras, P., Oliveira, S., Varela, J., Nunes, M. C. & Raymundo, A. 3D printed gluten-free cereal snack with incorporation of Spirulina (*Arthrospira platensis*) and/or *Chlorella vulgaris*. *Algal Res* **68**, 102863 (2022).
29. Kewuyemi, Y. O., Kesa, H., Meijboom, R., Alimi, O. A. & Adebo, O. A. Comparison of nutritional quality, phenolic compounds, and antioxidant activity of conventional and 3D printed biscuits from wholegrain and multigrain flours. *Innov. Food Sci. Emerg. Technol.* **83**, 103243 (2023).
30. Dick, A., Bhandari, B. & Prakash, S. Effect of reheating method on the post-processing characterisation of 3D printed meat products for dysphagia patients. *LWT* **150**, 111915 (2021).
31. Wang, D. et al. Whey protein isolate nanofibrils as emulsifying agent to improve printability of Cheddar cheese for 3D printing. *Food Hydrocoll.* **142**, 108807 (2023).
32. Tomašević, I. et al. 3D printing as novel tool for fruit-based functional food production. *Curr. Opin. Food Sci.* **41**, 138–145 (2021).
33. Liu, Z., Bhandari, B., Prakash, S. & Zhang, M. Creation of internal structure of mashed potato construct by 3D printing and its textural properties. *Food Res. Int.* **111**, 534–543 (2018).
34. Liu, Z. et al. 3D printing of shiitake mushroom incorporated with gums as dysphagia diet. *Foods* **10**, 2189 (2021).
35. Riantiningtyas et al. 3D printing of a high protein yoghurt-based gel: effect of protein enrichment and gelatine on physical and sensory properties. *Food Res. Int.* **147**, 110517 (2021).
36. Liu, Z. et al. Dehydration-triggered shape transformation of 4D printed edible gel structure affected by material property and heating mechanism. *Food Hydrocoll.* **115**, 106608 (2021).
37. Guo, J., Gu, X., Du, L. & Meng, Z. *Spirulina platensis* protein nanoparticle-based bigels: Dual stabilization, phase inversion, and 3D printing. *Food Hydrocoll.* **135**, 108160 (2023).
38. Celis-Morales, C. et al. Effect of personalized nutrition on health-related behaviour change: evidence from the Food4Me European randomized controlled trial. *Int. J. Epidemiol.* **46**, 578–588 (2017).
39. de Oliveira, S. P. A. et al. Investigating the effects of conventional and unconventional edible parts of red beet (*Beta vulgaris* L.) on target bacterial groups and metabolic activity of human colonic microbiota to produce novel and sustainable prebiotic ingredients. *Food Res. Int.* **171**, 112998 (2023).
40. Okonkwo, C. E. et al. Application of biogels for bioactives delivery: Recent developments and future research insights. *Appl. Food Res.* **2**, 100238 (2022).
41. Fernandez, A. S. et al. Bigels as potential inks for extrusion-based 3d food printing: effect of oleogel fraction on physical characterization and printability. *Food Hydrocoll.* **144**, 108986 (2023).
42. Xie, D., Hu, H., Huang, Q. & Lu, X. Influence of oleogel/hydrogel ratios and emulsifiers on structural and digestion properties of food-grade 3D printed bigels as carriers for quercetin and catechin. *Food Hydrocoll.* **144**, 108948 (2023).
43. Tian, H. et al. Effect of hybrid gelator systems of beeswax-carrageenan-xanthan on rheological properties and printability of litchi inks for 3D food printing. *Food Hydrocoll.* **113**, 106482 (2021).
44. Qiu, L., Bhandari, B., Chitrakar, B. & Chang, L. Investigation of 3D printing of apple and edible rose blends as a dysphagia food. *Food Hydrocoll.* **135**, 108184 (2023).
45. Carvajal-Mena, N., Tabilo-Munizaga, G., Perez-Won, M. & Lemus-Mondaca, R. Valorization of salmon industry by-products: evaluation of salmon skin gelatin as a biomaterial suitable for 3D food printing. *LWT* **155**, 112931 (2022).
46. Zhang, L. et al. Sea bass protein-polyphenol complex stabilized high internal phase of algal oil Pickering emulsions to stabilize astaxanthin for 3D food printing. *Food Chem.* **417**, 135824 (2023).
47. Navaf, M. et al. 4D printing: a new approach for food printing; effect of various stimuli on 4D printed food properties. A comprehensive review. *Appl. Food Res.* **2**, 100150 (2022).
48. He, C., Zhang, M. & Devahastin, S. Microwave-induced deformation behaviors of 4D printed starch-based food products as affected by edible salt and butter content. *Innov. Food Sci. Emerg. Technol.* **70**, 102699 (2021).
49. Chen, F., Zhang, M., Liu, Z. & Bhandari, B. 4D deformation based on double-layer structure of the pumpkin/paper. *Food Struct.* **27**, 100168 (2021).
50. Noree, S., Pinyakit, Y., Tungkijanansin, N., Kulsing, C. & Hoven, V. P. Shape transformation of 4D printed edible insects triggered by thermal dehydration. *J. Food Eng.* **358**, 111666 (2023).
51. Shi, Y., Zhang, M. & Phuhongsung, P. Microwave-induced spontaneous deformation of purple potato puree and oleogel in 4D printing. *J. Food Eng.* **313**, 110757 (2022).
52. Guo, C., Zhang, M., Bhandari, B. & Devahastin, S. Investigation on simultaneous change of deformation, color and aroma of 4D printed

starch-based pastes from fruit and vegetable as induced by microwave. *Food Res. Int.* **157**, 111214 (2022).

53. Spence, C., Okajima, K., Cheok, A. D., Petit, O. & Michel, C. Eating with our eyes: from visual hunger to digital satiation. *Brain Cogn.* **110**, 53–63 (2016).
54. Spence, C. On the changing colour of food & drink. *Int. J. Gatron. Food Sci.* **17**, 100161 (2019).
55. Chen, S. et al. 4D printing of a citrus pectin/β-CD pickering emulsion: a study on temperature induced color transformation. *Add. Manuf.* **56**, 102925 (2022).
56. Lin, Q. et al. Peanut protein-polysaccharide hydrogels based on semi interpenetrating networks used for 3D/4D printing. *Food Hydrocoll.* **137**, 108332 (2023).
57. He, C., Zhang, M. & Devahastin, S. Investigation on spontaneous shape change of 4D printed starch-based purees from purple sweet potatoes as induced by microwave dehydration. *ACS Appl. Mater. Interfaces* **12**, 37896–37905 (2020).
58. Shen, C. et al. 4D printing system stimulated by curcumin/whey protein isolate nanoparticles: a comparative study of sensitive color change and post-processing. *J. Food Eng.* **342**, 111357 (2023).
59. Ghazal, A. F., Zhang, M. & Liu, Z. Spontaneous color change of 3D printed healthy food product over time after printing as a novel application for 4D food printing. *Food Bioproc. Tech.* **12**, 1627–1645 (2019).
60. Phuhongsung, P., Zhang, M. & Devahastin, S. Influence of surface pH on color, texture and flavor of 3D printed composite mixture of soy protein isolate, pumpkin, and beetroot. *Food Bioproc. Tech.* **13**, 1600–1610 (2020).
61. Leine, M. D. R., Ahmadzodeh, S., Van Bockstaele, F. & Ubeyitogullari, A. Development of a pH-responsive system based on starch and alginate-pectine hydrogels using coaxial 3D food printing. *Food Hydrocoll.* **153**, 109989 (2024).
62. Anusha, A. & Negi, P. S. Edible insects as innovative ingredients: processing technologies and insect incorporated foods. *J. Insects Food Feed* **9**, 1003–1005 (2023).
63. Diañez, I. et al. 3D printing in situ gelification of κ-carrageenan solutions: effect of printing variables on the rheological response. *Food Hydrocoll.* **87**, 321–330 (2019).
64. Chauvette, J. F. et al. High-speed multinozzle additive manufacturing and extrusion modeling of large-scale microscaffold networks. *Addit. Manuf.* **47**, 102294 (2021).
65. Zhu, S., Stieger, M. A., van der Goot, A. J. & Schutyser, M. A. I. Extrusion-based 3D printing of food pastes: correlating rheological properties with printing behaviour. *Innov. Food Sci. Emerg. Technol.* **58**, 102214 (2019).
66. Xu, K. et al. Rheological properties, gel properties and 3D printing performance of soy protein isolate gel inks added with different types of apricot polysaccharides. *Int. J. Biol. Macromol.* **242**, 124624 (2023).
67. Kuo, C. C., Qin, H., Cheng, Y., Jiang, X. & Shi, X. An integral manufacturing strategy to fabricate delivery system using gelatin/alginate hybrid hydrogels: 3D printing and freeze-drying. *Food Hydrocoll.* **111**, 106262 (2021).
68. Chiaregato, B. M. et al. Method of additive manufacturing by hot extrusion. https://data.epo.org/publication-server/document?iDocId=6919658&iFormat=0 (2023).
69. Klomp, D. 3D food printing from nutritional advice to personalized product. Oral communication. In *9th International Conference in Food Chemistry and Technology*, 27–29 November, Paris (2023).
70. Khoider, O. et al. Study of continuous cake pre-baking in a rectangular channel using ohmic heating. *Innov. Food Sci. Emerg. Technol.* **67**, 102580 (2021).
71. Niane, M. L. et al. In *8th International Food Operations & Processing Simulation Workshop* (FoodDops, Rome, 2022).
72. Le-Bail, A. et al. Possible solutions to increase the throughput of 3D printers in the case of food application. In *8th International Conference on Food Chemistry and Technology* (FCT-Rome, 2022).
73. Del Pozo Arana, C. & Zúñiga, E. M. How to define gastronomic identity from cultural studies: the Peruvian case. *Int. J. Gatron. Food Sci.* **27**, 100476 (2022).
74. FAO. *The State of Food Security and Nutrition in the World*. https://www.fao.org/3/cc0639en/cc0639en.pdf (2022).
75. Fit4Food. *Food Industry 4.0 - Novel and Efficient Food Processing*. https://fit4food2030.eu/wp-content/uploads/2020/10/Breakthrough-inventory-cards-v.12.pdf (2023).
76. EU, Food 2023 Research and Innovation—*Pathways for actions 2.0* https://research-and-innovation.ec.europa.eu/news/all-research-and-innovation-news/new-report-food-2030-research-and-innovation-pathways-action-20-2023-12-04_en (2023).
77. FAO. *The Future for Safety of New Production Systems* https://www.fao.org/food-safety/news/news-details/en/c/1662307/ (2023).
78. Spence, C. & Piqueras-Fiszman, B. *The Perfect Meal: The Multisensory Science of Food and Dining* (Wiley-Blackwell, 2014).
79. Spence, C. The psychological effect of food colors. In *The Psychological Effects of Food Colors*, Ch. 2 (Woodhead Publishing Series in Food Science, Technology and Nutrition, 2016).
80. Tagami, T. et al. 3D printing of gummy drug formulations composed of gelatin and an HPMC-based hydrogel for pediatric use. *Int. J. Pharm.* **594**, 120118 (2021).
81. Derossi, A., Corradini, M. G., Caporizzi, R., Oral, M. O. & Severini, C. Accelerating the process development of innovative food products by prototyping through 3D printing technology. *Food Biosci.* **52**, 102417 (2023).
82. Ekonomou, S. I. et al. Advancing dysphagia-oriented multi-ingredient meal development: optimising hydrocolloid incorporation in 3D printed nutritious meals. *Food Hydrocoll.* **147**, 109300 (2024).
83. Fakhreddine, L. B. & Sánchez, M. The interplay between health claims and sensory attributes in determining consumers' purchase intentions for extra virgin olive oil. *Food Qual. Prefer.* **106**, 104819 (2023).
84. Aveline, C. et al. Influence of obesity on saltiness and sweetness intensity enhancement by odors. *Food Qual. Prefer* **102**, 104685 (2022).
85. Spence, C. Factors affecting odour-induced taste enhancement. *Food Qual. Prefer* **96**, 104393 (2022).
86. Motoki, K. & Velasco, C. Taste-shape correspondences in context. *Food Qual. Prefer* **88**, 104082 (2021).
87. Juravle, G., Olari, E. L. & Spence, C. A taste for beauty: on the expected taste, hardness, texture, and temperature of geometric shapes. *I-Percept.* **19**, 13 (2022).
88. Zhu, S., Ribberink, M., De Wit, M., Schutyser, M. & Stieger, M. Modifying sensory perception of chocolate coated rice waffles through bite-to-bite contrast: an application case study using 3D inkjet printing. *Food Funct.* **11**, 10580–10587 (2020).
89. Fahmy, A. R. et al. Sensory design in food 3D printing—structuring, texture modulation, taste localization, and thermal stabilization. *Innov. Food Sci. Emerg. Technol.* **72**, 102743 (2021).
90. Spence, C. Physico-chemical and sensory nudges to reduce people's salt consumption. *Foods* **11**, 3092 (2022).
91. Kavimughil, M., Leena, M. M., Moses, J. A. & Anandharamakrishan, C. 3D printed MCT oleogel as co-delivery carrier for curcumin and resveratrol. *Biomaterials* **287**, 121616 (2022).
92. Bugarin-Castillo, Y., Rando, P., Clabaux, M., Moulin, G. & Ramaioli, M. 3D printing to modulate the texture of starch-based food. *J. Food Eng.* **350**, 111499 (2023).
93. Caporizzi, R. Severini C., Oral O., & Derossi A. Modulating 3D food architecture for new sensorial perceptions. In *8th International Conference on Food Chemistry & Technology* (2022).

94. Pant, A. et al. 3D food printing of fresh vegetables using food hydrocolloids for dysphagic patients. *Food Hydrocoll.* **114**, 106546 (2021).
95. Guedes, J. S., Bitecourt, B. S. & Augusto, P. E. D. Modification of maize starch by dry heating treatment (DHT) and its use as gelling ingredients in fruit-based 3D-printed food for dysphagic people. *Food Biosci.* **56**, 103310 (2023).
96. Bitencourt, B. S. et al. Mineral bioaccessibility in 3D printed gels based on milk/starch/k-carrageenan for dysphagic people. *Food Res. Int.* **170**, 113010 (2023).
97. Wallace, M. et al. Combined effect of eating speed instructions and food texture modification on eating rate, appetite and later food intake. *Appetite* **184**, 106505 (2023).
98. Caporizzi, R., Derossi, A., Marinaro, G. & Severini, C. Structuring crispy vegetable-based food products by additive manufacturing for a more sustainable and healthy diet. In *9th International Conference on Food Chemistry & Technology* (2023).
99. Rogers, H. & Srivastava, M. Emerging sustainable supply chain models for 3D food printing. *Sustainability* **13**, 12085 (2021).
100. Martins, M. L., Rodrigues, S. P. S., Cunha, L. M. & Rocha, A. Factors influencing food waste during lunch of fourth-grade school children. *Waste Manag.* **113**, 439–446 (2020).
101. Donn, P., Prieto, M. A., Mejuto, J. C., Cao, H. & Simal-Gandara, J. Functional foods based on the recovery of bioactive ingredients from food and algae by-products by emerging extraction technologies and 3D printing. *Food Biosci.* **49**, 101853 (2022).
102. Zhang, W. et al. Effect of compositions and physical properties on 3D printability of gels from selected commercial edible insects: role of protein and chitin. *Food Chem.* **433**, 137349 (2024).
103. Pant, A., Leam, P. X. N., Chua, C. K. & Tan, U. X. Valorisation of vegetable food waste utilizing three dimensional food printing. *Virtual Phys. Prototyp.* **18**, e2146593 (2023).
104. Norton, M. I., Mochon, D. & Ariely, D. The IKEA effect: when labor leads to love. *J. Consum. Psychol.* **22**, 453–460 (2012).
105. Spence, C. *Gastrophysics: The New Science of Eating* (Viking Penguin, 2017).
106. Santhoshkumar, P., Negi, A. & Moses, J. A. 3D printing for space food applications: advancements, challenges, and prospects. *Life Sci. Space Res.* **40**, 158–165 (2024).
107. Tan, J. D. et al. 3D printability and biochemical analysis of revalorized orange peel waste. *Int. J. Bioprinting* **9**, 776 (2023).
108. Aguilera, J. M. Rational food design and food microstructure. *Trends Food Sci. Technol.* **122**, 256–264 (2022).
109. Zoran, A. Cooking with computer: the vision of digital gastronomy. In *Proceedings of the IEEE*. Vol. 107, N. 8 (IEEE, 2019).
110. Zoran, A., Gonzalez, E. A., Mizrahi, A. B. & Lachinish, A. Z. Cooking with computers: the vision of digital gastronomy. *Gastron. Food Sci*. https://doi.org/10.1016/B978-0-12-820057-5.00003-0 (2021).
111. Datta, A. et al. Computer-aided food engineering. *Nat. Food* **3**, 894–904 (2022).
112. Deng, J. et al. Sketching the future of human-food interaction: emerging directions for future practice. *Int. J. Gastron. Food Sci.* **31**, 100629 (2023).
113. Mantihal, S., Prakash, S., Godoi, F. C. & Bhandari, B. Optimization of chocolate 3D printing by correlating thermal and flow properties with 3D structure modeling. *Innovative Food Sci EmergTechnol*. **44**, 21–29 (2017).
114. Severini, C., Derossi, A., Ricci, R., Caporizzi, I. & Fiore, A. Printing a blend of fruit and vegetables. New advances on critical variables and shelf life of 3D edible objects. *J. Food Eng.* **220**, 89–100 (2018).
115. Dick, A., Bhandari, B. & Prakash, S. 3D printing of meat. *Meat Sci.* **153**, 35–44 (2019).
116. Oliveira, S. M., Martins, A. J., Fuciños, P., Cerqueira, M. A. & Pastrana, L. M. Food additive manufacturing with lipid-based inks: evaluation of phytosterol-lecithinoleogels. *J. Food Eng.* **341**, 111317 (2023).
117. Shi, Y. et al. Effect of addition of beeswax oleogel on 3D printing of potato starch-protein system. 100176 (2021).
118. Giura, L., Urtasun, L., Ansorena, D., Astiasaran, I. & Raymundo, A. Printable formulations of protein and Chlorella vulgaris enriched vegetable puree for dysphagia diet. *Algal Res*. **79**,103447 (2024).
119. Sidabutar, R. et al. Treatment of effluent from the upflow anaerobic sludge blanket-hollow centeredpacked bed fermentor by utilizing Chlorella vulgaris in a fed-batchsystem. *Case Stud. Chem. Environ. Eng* **9**, 100756 (2024).
120. Chen, Y. et al. Extrusion-based 3D printing of pickering high internal phase emulsions stabilized by flaxseed protein-sodium alginate complexes for encapsulating curcumin. *Colloids. Surf. A: Physicochem. Eng. Asp*. **673**, 131863 (2023).
121. Phuhongsung, P., Zhang, M. & Bhandari, B. 4D printing of products based on soy protein isolate via microwave heating for flavor development. *Food Res. Int.* **137**, 109605 (2020).
122. United Nations (UN). Communication Materials. https://www.un.org/sustainabledevelopment/news/communications-material/ (2024).
123. Blurhapsody. https://blurhapsody.com/ (2024).
124. Morgesten, M. P. et al. Dynamic texture perception of solids foods. Conference paper. https://www.researchgate.net/publication/264196036_Dynamic_texture_perception_of_solid_foods (2014).
125. Lange. The Hystory of cake decorating. https://www.kathleenlangecakes.com/post/history-of-cake-decorating (2024).
126. The Seafire Grill. https://theseafiregrill.com/ (2024).
127. Marr, B. What Is 3D Printed Food? https://bernardmarr.com/what-is-3d-printed-food/ (2021).
128. Blutinger, J. D. et al. The future of software-controlled cooking. *npj Sci Food* **7**, 6 (2023).
129. Hy-vee. https://www.hy-vee.com/recipes-ideas/advice-how-tos/holidays/valentines-day/pipe-chocolate-hearts (2024).
130. Kooihousewares. https://www.kooihousewares.com/ (2024).
131. Naturalmachines. https://www.naturalmachines.com/ (2024).

Author contributions

D.A. conceived the idea, collected scientific literature, wrote the manuscript, conceived and prepared the professional figures; Sp.C. conceived the idea, collected the literature information, wrote the paper and revised the manuscript; F.A.R. conceived and prepared the professional figures, and revised the manuscript; C.M.G., J.M., C.R., D.S., M.J.A., LB.A., Z.W., Z.M., B.B., and Se.C. revised the manuscript.

Competing interests

Z.W. is the Associate Editor of *npj Science of Food*. Z.W. was not involved in the journal's review of, or decisions related to, this manuscript. The remaining authors declare no competing interests.

Additional information

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