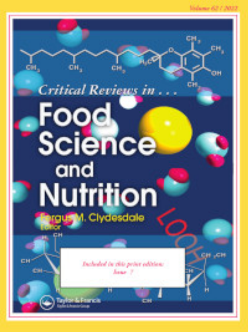

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REVIEW

Future foods: Alternative proteins, food architecture, sustainable packaging, and precision nutrition

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ABSTRACT
There are numerous challenges facing the modern food and agriculture industry that urgently need to be addressed, including feeding a growing global population, mitigating and adapting to climate change, decreasing pollution, waste, and biodiversity loss, and ensuring that people remain healthy. At the same time, foods should be safe, affordable, convenient, and delicious. The latest developments in science and technology are being deployed to address these issues. Some of the most important elements within this modern food design approach are encapsulated by the MATCHING model: *Meat-reduced; Automation; Technology-driven; Consumer-centric; Healthy; Intelligent; Novel;* and *Globalization*. In this review article, we focus on four key aspects that will be important for the creation of a new generation of healthier and more sustainable foods: emerging raw materials; structural design principles for creating innovative products; developments in eco-friendly packaging; and precision nutrition and customized production of foods. We also highlight some of the most important new developments in science and technology that are being used to create future foods, including food architecture, synthetic biology, nanoscience, and sensory perception.

KEYWORDS
Future foods; nanotechnology; structural design; sustainability

1. Introduction

Population growth, pollution, climate change, environmental stress, biodiversity loss, and increases in diet-related diseases pose a series of severe challenges to society as a whole, and to the modern food industry in particular. The global population is expected to reach nearly 10 billion by 2050 (Chapman et al. 2021) and all these people need to be fed without damaging the environment. In addition, climate change is causing severe challenges to the production of foods, as well as to life in general. Greenhouse gas (GHG) emissions arising from human activities have been identified as a major contributor to global warming (Tian et al. 2016), and agriculture and food production is an appreciable source of these emissions (Sims et al. 2015). The need to produce more foods is also putting pressure on land and water use, as well as causing an appreciable loss in biodiversity, especially due to deforestation (Calicioglu et al. 2019). There are also concerns about the quantity and quality of foods that humans are consuming on their health. In particular, diabetes, obesity, heart disease, and other chronic diseases linked to overeating and poor food quality are on the rise around the world (Verma 2017). Consequently, there is a need to sustainably produce more high quality foods to ensure a healthy planet and a growing global population.

Food safety and waste is another major issue facing the modern food industry, as ingredients and foods are produced around the world and then transported to shops, restaurants, and institutions (Meybeck and Gitz 2017). It is critical that the food industry has appropriate protocols and methods to prevent the contamination of foods with harmful chemicals and microorganisms, to remove or inactivate them, and to reliably detect their presence.

There is also growing interest in changing the types of foods that are consumed so as to improve the sustainability and healthiness of the food supply. For instance, many researchers in academia, government, and industry are trying to replace protein-rich animal products, such as those derived from meat, fish, eggs, and milk, with alternative sources of proteins, such as those produced by plants, insects, microbial fermentation, or cell cultures (McClements 2020a). This change in dietary habits could have important benefits in terms of reducing GHG production, pollution, land use, water use, and biodiversity loss (Parodi et al. 2018). Nevertheless, it is important that foods created from these alternative protein sources are healthy. The macronutrient composition of a number of these alternative protein sources is comparable to those found in animal-derived foods (Figure 1). However, it is also important to consider other aspects, such as the types

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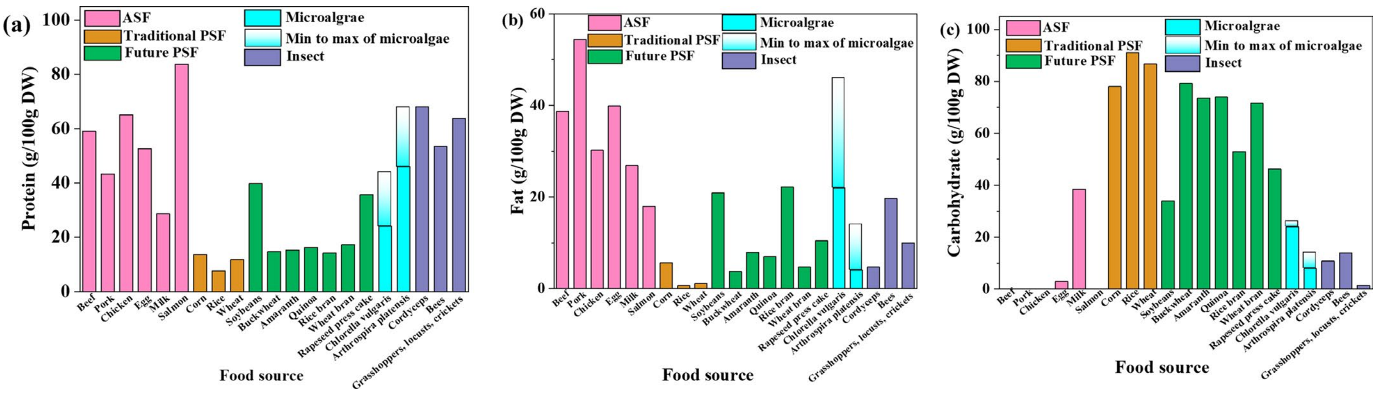

Figure 1. Comparison of the macronutrient contents of various kinds of foods. Protein, fat, and carbohydrate contents are reported as g/100 g of dry weight. ASF: animal-source foods, PSF: plant-source foods. *Data sources*: Rapeseed press cake data were extracted from Mattila et al. (2018); microalgae data was extracted from Torres-Tiji, Fields, and Mayfield (2020); insect data was extracted from Feng et al. (2018); other data was extracted from the U.S. Department of Agriculture (see Supplementary Table 1 for a list of data sources).

and concentrations of vitamins and minerals present, as well as their digestibility. Moreover, it is essential that food products made from alternative proteins are affordable, convenient, and delicious or consumers will not purchase them. Researchers are therefore using advanced technologies to create plant-based foods that have structures and compositions that mimic the look, feel, and taste of traditional animal-derived foods, such as meat, fish, eggs, and dairy products. For instance, soft matter physics, extrusion, spinning, and cutting technologies are being used to convert plant ingredients into products with meat-like qualities, while cell culture methods are being used to grow muscle tissues in fermentation tanks from cells cultivated from living animals.

Food architecture and structural design approaches are being utilized to create foods that look, feel, and taste like conventional processed foods but have lower levels of fat, sugar, and salt, thereby increasing their healthiness (McClements 2020a). Another major problem associated with the modern food supply is the quantity of food that is either spoiled or wasted. It has been estimated that around one-third of the food produced globally is currently lost, which means that all of the resources used to produce it are also wasted (Ishangulyyev, Kim, and Lee 2019). Consequently, many researchers are working to identify effective approaches to reduce the amount of food lost or wasted, as well as in converting food waste streams into valuable functional ingredients (Augustin et al. 2020). Researchers are also developing new approaches to replace petroleum-based materials known to contribute to pollution and global warming with more environmentally friendly and sustainable alternatives (Naser, Deiab, and Darras 2021). For instance, scientists are creating food packaging materials from film-forming food components (such as proteins, polysaccharides, and lipids) to replace traditional petroleum-based plastic packaging (Dhall 2013). Moreover, they are creating innovative packaging materials with novel properties, such as active and smart packaging materials, that can extend the shelf life and ensure food quality and safety (Chen et al. 2021; Biji et al. 2015).

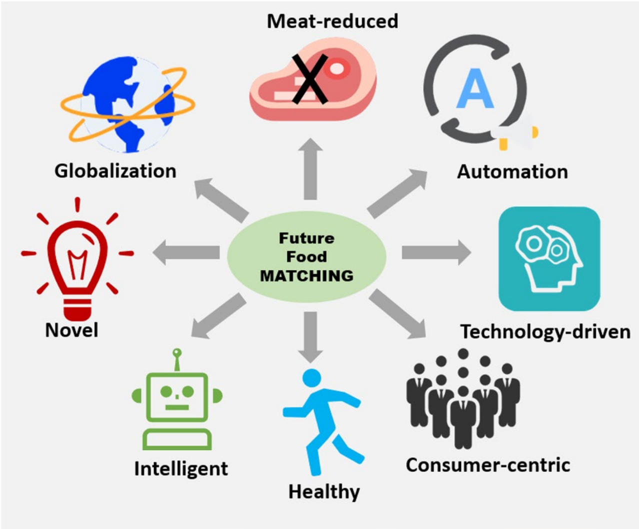

Figure 2. The MATCHING model highlights eight important areas where research is being carried out to improve the modern food system.

There is growing evidence that different people require different kinds of food to remain healthy, which has led to the concept of personalized or precision nutrition where foods are designed for specific individuals or groups of people, e.g., infants, the elderly, athletes, or those prone to specific chronic diseases (Toro-Martín et al. 2017). Databases are being developed that relate people's genetics, epigenetics, microbiomes, metabolomes, and biometrics to their health status. This information is then being utilized to tailor dietary recommendations to an individuals' specific nutritional needs.

Some of the most important trends in modern food research and development are captured in the acronym MATCHING: Meat-reduced; Automation; Technology-driven; Consumer-centric; Healthy; Intelligent; Novel; Globalization (Figure 2). A number of these areas are discussed in the current review article, so as to highlight the important scientific and technological advances that are being deployed to improve the healthiness and sustainability of the modern food supply.

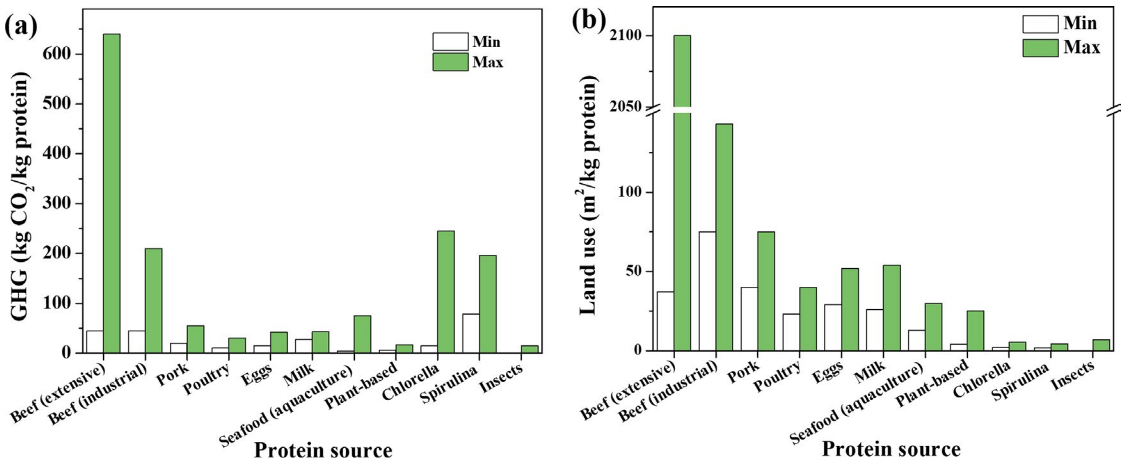

Figure 3. Dependence of greenhouse gas (GHG) production (a) and land use (b) on different protein sources. See Supplementary Table 2 for a list of data sources.

2. Alternative protein sources

2.1. Animal-derived proteins

Typically, as people become wealthier, they increase the amount of animal-derived proteins in their diet, such as those that come from meat, fish, eggs, and milk. However, the rearing of animals for food has been shown to be a major contributor to greenhouse gas production, pollution, land use, water use, and biodiversity loss (Willett et al. 2019). Moreover, the consumption of some animal-derived foods has been linked to the prevalence of certain kinds of chronic diseases, the close contact of humans and livestock may increase the risks of the transmission of zoonotic diseases, such as viruses like the one that has led to the COVID-19 pandemic (but further research is still required to ascertain the origin of this particular viral disease). Finally, there are concerns about animal welfare associated with the rearing of livestock for food, with billions of animals being confined and slaughtered every year. Consequently, there has been growing interest from many consumers in replacing animal-derived proteins with those derived from alternative sources, such as plants, insects, fungi, and other microbes (Karmaus and Jones 2021). As shown in Figure 3, reducing the amount of animals consumed for foods could have important environmental benefits.

2.2. Alternative protein sources

2.2.1. Edible insects

Insects are an abundant, affordable, and sustainable source of proteins and other nutrients (da Silva Lucas et al. 2020). More than one million species of insects have already been identified, but millions more still remain to be discovered. Around two thousand species of insects are considered to be edible, and this number is likely to grow in the future (Ordoñez-Araque and Egas-Montenegro 2021).

Nutritional profiles. Many edible insects have nutritional profiles that can meet human demands for calories, proteins, lipids, vitamins, and minerals. The proteins in edible insects are an abundant source of the essential amino acids necessary for the normal development and functioning of humans, including lysine, tryptophan, tyrosine and phenylalanine (Ordoñez-Araque and Egas-Montenegro 2021). Edible insects are also rich in monounsaturated and/or polyunsaturated fatty acids, and contain adequate levels of many vitamins (including riboflavin, pantothenic acid, biotin, folic acid) and minerals (including Cu, Fe, Mg, Mn, P, Se, Zn) (Rumpold and Schlüter 2013). *In vitro* studies have shown that protein digestibility varies between about 67% and 98% among different insects, and that the bioavailability of trace minerals (e.g., Fe, Ca, and Zn) in edible insects is similar or higher to beef (Parodi et al. 2018).

Sustainability. Compared to traditional livestock, insects are more efficient at converting feed into valuable source of proteins. Moreover, they can be fed materials that would otherwise be considered waste. The production of edible insects for food requires less water and land than traditional livestock, as well as producing fewer GHG emissions and pollution (Ordoñez-Araque and Egas-Montenegro 2021; Halloran et al. 2016). Overall, the rearing of insects for food is more sustainable than the rearing of livestock, such as cows, pigs, sheep, and chicken.

Safety. Many, but not all, species of insects are safe for consumption by most humans. However, some naturally contain substances that are toxic to humans and should therefore not be eaten. In addition, a fraction of people have allergies to the proteins found in some edible insects, which can cause adverse health effects (Imathiu 2020). For instance, the consumption of silkworms, cicada, crickets, wasps, locusts or bedbugs has been shown to induce hypersensitivity in some people (Tang et al. 2019). Insects may also be contaminated with harmful chemicals (e.g., pesticides, heavy metals, or fungal toxins) or organisms (e.g., pathogenic microbes or parasites) (Imathiu 2020). It is difficult to control the diet of wild-type insects and so they are more prone to this kind of contamination (Gravel and Doyen 2020). It is therefore important to carry out systematic studies of the allergens and contaminants present in different kinds of species to better understand any potential health risks associated with their widespread consumption.

Acceptability. Another potential hurdle to the widespread adoption of insects as foods is their consumer acceptability, especially in many Western countries. Over two billion people around the world currently eat insects as a natural part of their diet. However, in many developed countries, people are reluctant to eat insects due to food neophobia and disgust (Gravel and Doyen 2020). Food neophobia is the fear of trying new or unusual foods (Onwezen et al. 2021). This phenomenon is likely to decrease over time as people, especially younger and more adventurous consumers, become more familiar with novel foods, such as insect-based ones. Even so, acquaintance with insect foods does not necessarily mean that people will actually desire or like them (Barbera et al. 2018). It will be important to create insect-based food products that consumers find desirable, which means carefully controlling their appearance, texture, mouthfeel, and flavor (Gravel and Doyen 2020; Mishyna, Chen, and Benjamin 2020). For this reason, many researchers are trying to incorporate insects as functional or nutritional ingredients into traditional foods, such as breads, biscuits, spaghetti, hamburgers, and sausages, rather than serving them whole. This approach increases the nutritional value and sustainability of foods, while still presenting them in a form that consumers are comfortable consuming (Melgar-Lalanne et al. 2019). Information about the sustainability and environmental benefits of consuming insects instead of meat or fish may also motivate more consumers to try them and incorporate them into their diet.

In summary, edible insects are likely to be an important source of protein-rich foods in the future. For this reason, many researchers and companies are optimizing the large-scale breeding and production of edible insects, as well as developing innovative processing technologies to turn them into foods or food ingredients (Feng et al. 2018). The commercial success of edible insects will also depend on establishing global regulations about their production and consumption, as well as overcoming neophobia and disgust in many countries (Baiano 2020).

2.2.2. Microalgae

Many species of algae are nutritious foods that are suitable for large-scale and sustainable production, with yields that can surpass those of many plants. However, only a few species of microalgae are generally recognized as safe (GRAS) food ingredients by the Food and Drug Administration (FDA) in the United States, such as *Arthrospira platensis, Chlamydomonas reinhardtii, Auxenochlorella protothecoides, Chlorella vulgaris, Dunaliella bardawil,* and *Euglena gracilis*. (Torres-Tiji, Fields, and Mayfield 2020).

Nutritional profiles. The majority of algae with GRAS status (with the exception of *Chlorella gracilis*) contain all the essential amino acids required for human wellbeing and growth, making them a complete protein source (Torres-Tiji, Fields, and Mayfield 2020). Algae also contain high levels of polyunsaturated fatty acids, including two of the most important omega-3 fatty acids, eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). They also contain bioactive carbohydrates, such as algal polysaccharides, that have been reported to exhibit anticancer, anticoagulant, and cholesterol-lowering activities (Matos et al. 2017) and antioxidants (such as carotenoids, chlorophyll, phycobiliproteins, and other pigments) (Fernández et al. 2021).

Sustainability. Compared to livestock production, microalgae production is considerably more sustainable. For instance, it has been reported that the production of microalgae proteins requires much less land and water resources and produces much less CO_2 emissions than the production of the same quantity of beef proteins (Fernández et al. 2021). The environmental impact of microalgae production can be reduced by using hydrolyzed food waste as a carbon source, making it one of the most sustainable protein sources (Kusmayadi et al. 2021). Through CO_2 fixation, microalgae converts solar energy into chemical energy, which occurs at an efficiency that has been reported to be 10 times higher than terrestrial plants (Sathasivam et al. 2019). Importantly, the bio-fixation of CO_2 by microalgae can contribute to a reduction in atmospheric GHG levels (de Morais et al. 2019), which may be an important strategy for reducing global warming.

In summary, microalgae is expected to be another important source of sustainable protein-rich foods in the future, which has considerable potential for addressing food security and environmental issues (Kusmayadi et al. 2021). The quantity and composition of microalgae produced depends on many factors, including temperature, light exposure, pH, mineral concentrations, CO_2 supply, population density, growing phase, and algal type (Gouveia et al. 2008). Consequently, these parameters must be optimized to economically produce protein-rich microalgae ingredients on a commercial scale. In addition, it is important that microalgae-based foods are created that consumers find appealing to eat (Torres-Tiji, Fields, and Mayfield 2020). Consequently, further research is required to optimize the large-scale production of edible microalgae with the required yields, nutritional contents, and sensory attributes for commercial applications.

2.2.3. Plant proteins

Plant proteins are one of the most affordable and sustainable alternatives to animal proteins for feeding a growing global population. For this reason, there has been great interest in utilizing them to create a new generation of foods that will help to alleviate the environmental problems associated with producing animal proteins (Alves and Tavares 2019). Plant proteins can be isolated from a broad range of botanical species, including legumes, cereals, pseudo-cereals, and algae (Sá, Moreno, and Carciofi 2020). Plant proteins exhibit a broad range of functional attributes that make them suitable for constructing plant-based foods (such as gelling, emulsifying, thickening, binding, and water holding), as well as having good nutritional profiles (Sá, Moreno, and Carciofi 2020). However, they have distinctly different molecular structures than animal ones, which means that innovative formulation strategies are required when using them to create analogs of animal-derived foods, such as meat, fish, egg, and milk (Loveday 2020; McClements and Grossmann 2021a; McClements and Grossmann 2021b). For instance, plant proteins tend to be relatively large globular proteins that are often present as supramolecular clusters, whereas many important animal proteins have different structures: small globular proteins (such as β-lactoglobulin, α-lactalbumin, or ovalbumin); small flexible proteins (such as casein and gelatin); long rigid rods (such as collagen); or a part of complex fibrous bundles (such as actin and myosin). Consequently, innovative structural design, soft matter physics, and processing approaches a required to coax plant proteins into structures that resemble those found in animal products.

Legumes. Functional plant proteins are commonly isolated from legumes, such as peas, chickpeas, peanuts, soybeans, black beans, lima beans, and kidney beans. These proteins are typically moderately to highly digestible and it has been reported that their digestion rates exceed those of beef proteins under some circumstances (Semba et al. 2021). Soybeans are the most widely cultivated legume crop and are rich in the essential amino acids required by humans. In contrast, most other species of legumes contain relatively low quantities of essential sulfur-containing amino acids (methionine and cysteine), and sometimes lack other essential amino acids, such as tryptophan (Semba et al. 2021). For this reason, legumes (which lack methionine and cysteine) are often combined with cereals (which lack lysine) to provide meals with a more balanced essential amino acid profile, e.g., rice and beans (Sozer et al. 2015; Semba et al. 2021; Duranti 2006). Another potential challenge for formulating foods with legumes is that they may contain anti-nutritional factors (ANFs), such as tannins, protease inhibitors, and phytic acids, which may inhibit macronutrient digestion or reduce mineral bioavailability, thereby decreasing their nutritional value (Sozer et al. 2015; Semba et al. 2021). This problem can often be overcome by boiling, baking, fermenting, or germinating legumes to eliminate the majority of anti-nutritional factors (Rehman and Shah 2005; Ohanenye et al. 2020). The production of legumes requires less water than many other agricultural crops, less nitrogen-based fertilizers because of their ability to fix nitrogen, and may improve carbon sequestration in the soil due to their ability to absorb CO_2 (Conti et al. 2021). Thus, legume proteins are a good environmentally sustainable alternative to animal proteins.

Cereals. Cereals are important agricultural crops that are used as staple foods by humans around the world, including corn, rice, and wheat (Sá, Moreno, and Carciofi 2020; Shewry and Halford 2002). Cereal proteins are rich in sulfur-containing amino acids, but contain lack lysine, threonine and tryptophane, which means their essential amino acid profiles are complementary to those of legume proteins (Schweiggert-Weisz et al. 2020). Cereals naturally contain a number of other nutritional components that are beneficial to human health, such as dietary fibers, antioxidants, plant sterols, and other bioactive phytochemicals, but the majority of these constituents are concentrated in the outer layers (hulls and bran) and embryos of the grains (Galanakis 2018). During cereal processing, many of these parts of the plant are discarded, which results in a decrease in their nutritional quality. Protein-rich fractions can be isolated from cereals and then used as functional ingredients in foods. Some of the most common proteins found in cereals are prolamins and glutelin (Kawakatsu and Takaiwa 2010). Prolamins (like zein from corn) are hydrophobic proteins that are commonly used to formulate plant-based foods, such as meat analogs, due to their ability to form fibrous-like structures (Mattice and Marangoni 2020). Compared with other cereals, oats are richer in proteins, and the contents and quality of amino acids are equivalent to soybean proteins (Henchion et al. 2017). Oat proteins are finding increasing utilization in the development of plant-based dairy and meat analogs (Schweiggert-Weisz et al. 2020).

Pseudo-cereals. Unlike traditional cereals, pseudo-cereals, such as buckwheat, amaranth and quinoa, do not contain gluten. However, they are rich in proteins, and their amino acid profiles and nutritional characteristics are higher than traditional cereals (Alvarez-Jubete, Arendt, and Gallagher 2010). Moreover, lysine is not a restricting essential amino acid in pseudo-cereals, which makes them useful as a dietary supplement to cereals (Sá, Moreno, and Carciofi 2020). Pseudo-cereals also exhibit low allergenicity because they do not contain gluten, which is advantageous for formulating food products for individuals who suffer from gluten sensitivities (Mota et al. 2016).

Processing byproducts. The byproducts and waste streams of the food and agricultural industries are being explored as a potential source of plant proteins so as to increase the sustainability and profitability of the food system. Rapeseed meal (a byproduct of rapeseed oil extraction) contains 40% proteins and is rich in lysine, methionine, and cysteine, and therefore has a high nutritional value (Semba et al. 2021). Sunflower meal (a byproduct of sunflower oil extraction) is another major source of proteins (González-Pérez and Vereijken 2010) that is rich in sulfur-containing amino acids (Sara et al. 2020). It has been used to fortify various kinds of food products, including meat, dairy, infant, and baked products (González-Pérez and Vereijken 2010). However, the development of sunflower meal as a protein source is limited because it contains relatively high levels of phenolic compounds, especially chlorogenic acid, which reduces its functionality (González-Pérez and Vereijken 2010). Salgado et al. (Salgado et al. 2012) successfully obtained protein concentrates from sunflower meal that contained reduced levels of phenolic compounds and exhibited high water solubility and good antioxidant activity. Similarly, researchers have developed an extraction process to obtain sunflower albumin ingredients that had reduced levels of chlorogenic acid, phytic acid, and other antinutritional factors (Sara et al. 2020). Studies have shown that sunflower proteins can be used as functional ingredients in infant formula, powdered milks, milk substitutes, baked products, spreads, and salads (Sozer et al. 2015).

2.2.4. Cellular agriculture proteins

Another source of alternative proteins that is likely to become increasingly important in the future is cellular agriculture. Advances in biotechnology are enabling food and ingredient companies to use different kinds of microbes (such as yeast and bacteria) to synthesize proteins and other high-value food ingredients (Figure 4). Typically, the microbes are kept in a fermentation tank under optimized conditions that stimulate their growth and multiplication, such as temperature, oxygen, light, pH, and nutrient levels. The microbes may excrete the proteins, or they may be disrupted to release the proteins, which can then be isolated and purified. Modern biotechnology approaches can be used to engineer microbes to produce a wide range of food proteins from animal, plant, or microbial sources. This approach is being used to create milk, egg, and meat proteins that have never been in an animal. Fermentation approaches can also be used to grow whole microorganisms that can be used as protein-rich alternatives to animal products, such as the filamentous microfungi (*Fusarium venenatum*) used in Quorn products.

3. Food architecture: Structural design of novel foods

The physicochemical properties, sensory attributes, and gastrointestinal fate of foods ultimately depend on the type, organization, and interactions of the ingredients they contain. For this reason, there has been growing attention on controlling the structural organization of the ingredients within foods to obtain the required sensorial and nutritional attributes (Figure 4). The concept of food architecture refers to the rational design of foods from the bottom up (McClements 2020b). Food ingredients and processing operations are carefully controlled to create structures that provide specific desirable attributes, such as appearances, textures, flavor profiles, mouthfeels, or digestion rates. In this section, a few examples of food design approaches that are being developed to improve the healthiness or sustainability of foods are given for different macronutrients.

3.1. Proteins

In a recent meta-analysis, researchers summarized the relationship between the intake of total proteins, animal proteins, or plant proteins and mortality (Naghshi et al. 2020). This analysis involved 715,128 participants, and included 113,039 cases of death (16,429 from cardiovascular diseases and 22,303 from cancer). The results of this meta-analysis suggest that consumption of plant rather than animal proteins resulted in a lower risk of all-cause mortality and death due to cardiovascular diseases, which is attributed to the ability of plant proteins to lower heart metabolic risk factors, including blood lipids, lipoproteins, and blood pressure, as well as improved blood sugar regulation. This study suggests that it would be beneficial to replace animal proteins with plant ones to improve human health and wellbeing.

As a result, the food industry is creating a range of high-quality plant-based analogs of traditional animal products, such as meat, fish, eggs, and dairy products (Samard and Ryu 2019). Many plant proteins exhibit a broad spectrum of functional attributes that can be utilized to create the structures and properties required to simulate those found in animal products, such as thickening, gelling, binding, emulsifying, and water holding properties (Schreuders et al. 2019). The food industry has already been highly successful in creating high-quality processed meat analogs from plant proteins, such as burgers, sausages, and nuggets (Ismail, Hwang, and Joo 2020). However, further research is still required to accurately simulate the structures and properties of whole muscle tissues, such as beef steaks, pork

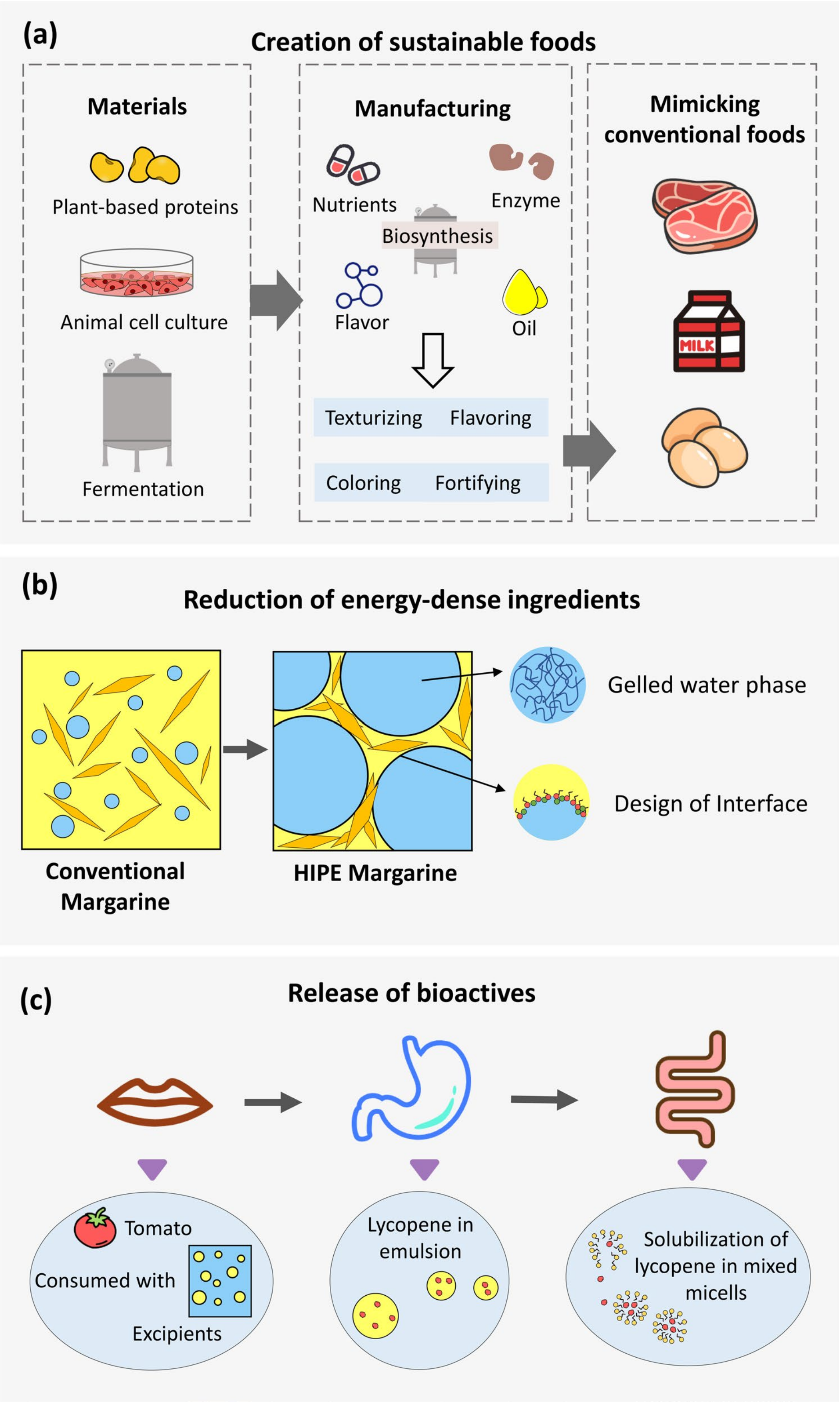

Figure 4. New directions in food processing in the future. (a) Creating sustainable foods. Alternative food ingredients may include synthetic flavoring substances, fats, nutrients, enzymes, etc. from plant proteins, cultured meat, and microbial synthetic proteins, through the organization, coloring, adding flavor and other technology processing, to obtain a variety of animal food substitutes. (b) Reducing calorie intake. The new butter can reduce the proportion of oil phase by constructing water-in-oil high internal phase emulsion, and control the stability and texture of the system by designing the structure of water phase, oil phase and interface. (c) Promoting the release of functional factors. Co-ingestion of tomato and excipient helps to dissolve and transport fat-soluble functional components such as lycopene in the body, thus facilitating its absorption by the body.

chops, chicken breasts, and fish fillets (McClements and Grossmann 2021b). Researchers are therefore employing food architecture approaches to create a new generation of plant-based foods that look, feel, and taste like animal-based ones. Moreover, they are focusing on improving the health profile of these products by reducing fat, sugar, and salt levels, as well as fortifying them with vitamins, minerals, and nutraceuticals. The creation of affordable, convenient, delicious, healthy and sustainable products requires the careful selection of ingredients and structuring techniques (Kyriakopoulou, Dekkers, and van der Goot 2019). In some cases, novel strategies have to be developed to create the ingredients required to formulate these products. For instance, hemoglobin produced by microbiological fermentation has been used to produce meat-like colors and flavors in plant-based meat analogs (Jin et al. 2018; Yang and Zhang 2019). Similarly, Impossible Foods has used soybean leghemoglobin extracted from transgenic yeast to create meat-like colors and flavors in their plant-based burgers (https://impossiblefoods.com/burger). Compared with real beef hamburgers, it has been reported that these plant-based burgers have substantial environmental benefits, as they require 96% less land to produce and emit 89% less greenhouse gasses.

3.1.1. Structuring of proteins in foods

Meat-like structures can be created from plant proteins using a variety of processing methods, including extrusion, spinning, and shearing (Ismail, Hwang, and Joo 2020).

1. *Extrusion*: Extrusion is currently the most commonly used processing method for the production of plant-based meat products. It consists of a series of unit operations, including mixing, heating, shearing, forming, and cutting (Maurya and Said 2014). Initially, the raw materials (such as proteins and/or polysaccharides) are mixed together and hydrated. They are then fed into the extruder where they are forced through a series of screws under high shears, pressures and temperatures, which mixes, denatures, and aggregates them. Finally, they are forced through a small orifice with a well-defined shape (the die). They may then be cut into the required shape using a machine blade. As the biopolymer blend is squeezed through the die head, the materials form fibrous structures due to the orientational forces they experience. According to the level of water added, extrusion can be categorized as either low- or high-moisture extrusion. Typically, it is easier to produce meat-like fibrous structures from plant proteins using high-moisture extrusion (He et al. 2020).
2. *Shearing*: The shear cell technology is finding increase use for the creation of fibrous meat-like structures from plant proteins (Maurya and Said 2014). This approach is not widely used for the commercial production of plant-based foods at present, but it has lower energy requirements than extrusion, which may be advantageous for some applications. This process is typically carried out by shearing and gelling biopolymer blends in a cone-shaped or concentric cylinder cell (Maurya and Said 2014). The concentric ("Couette") cell consists of two nested cylinders, of which the outer cylinder is typically stationary and the inner one rotates at a constant speed. The biopolymers (proteins and/or polysaccharides) used as raw materials are mixed with water and then placed in the concentric cylinder cell. The biopolymer blend is then subject to controlled processing conditions by rotating the cylinder at a fixed speed, temperature, and processing time. This leads to the formation of a semi-solid material with a fibrous internal structure due to the combined influence of the directional shear forces and heating (Krintiras et al. 2016). In particular, heating causes the protein molecules to unfold and aggregate with each other, thereby locking the fibrous structures into place.
3. *Spinning*: Spinning methods are mainly based on changes in the solubility of proteins in different solutions. In wet spinning, plants proteins and binding agents are first dissolved in a dilute alkali solution to form a "spinning solution," which is then extruded through porous plates or nozzles into an acidic salt solution (Obata, Taniguchi, and Yamato 1976). This leads to the formation of fibrous structures that are then locked into place due to the strong attraction between the proteins and binding agents under acidic conditions. Electrospinning methods are also being explored for their potential to form fibrous structures that might be incorporated into meat analog products. In this case, a mixture of biopolymers and other ingredients is dissolved in water and then placed in a syringe. A high voltage is then applied between the tip of the syringe and a collection plate. This causes the biopolymer solution to be pulled out of the syringe and form a thin stream. The water is evaporated from this thin stream as it moves through the air, which leads to the formation of solidified biopolymer-rich nanoscale or microscale fibers. Only certain kinds of biopolymer solutions are suitable for electrospinning: they should have high solubility, viscosity, electrical conductivity, and surface tension.

At present, the large-scale commercial production of plant-based meat products is usually carried out using extrusion. In comparison, shear cell and spinning technologies are still largely at the experimental stages of development (He et al. 2020). It should also be noted that soft matter physics principles can be utilized to create meat-like structures from plant proteins, often in combination with plant polysaccharides (McClements and Grossmann 2021a). For instance, fibrous structures can be formed by inducing phase separation of biopolymer mixtures through thermodynamic incompatibility or coacervation mechanisms, followed by shearing (to form fibers) and gelling (to fix their structure).

3.1.2. Biotechnological production of alternative proteins

Advances in biotechnology are also be utilized to create protein-rich foods that are alternatives to traditional

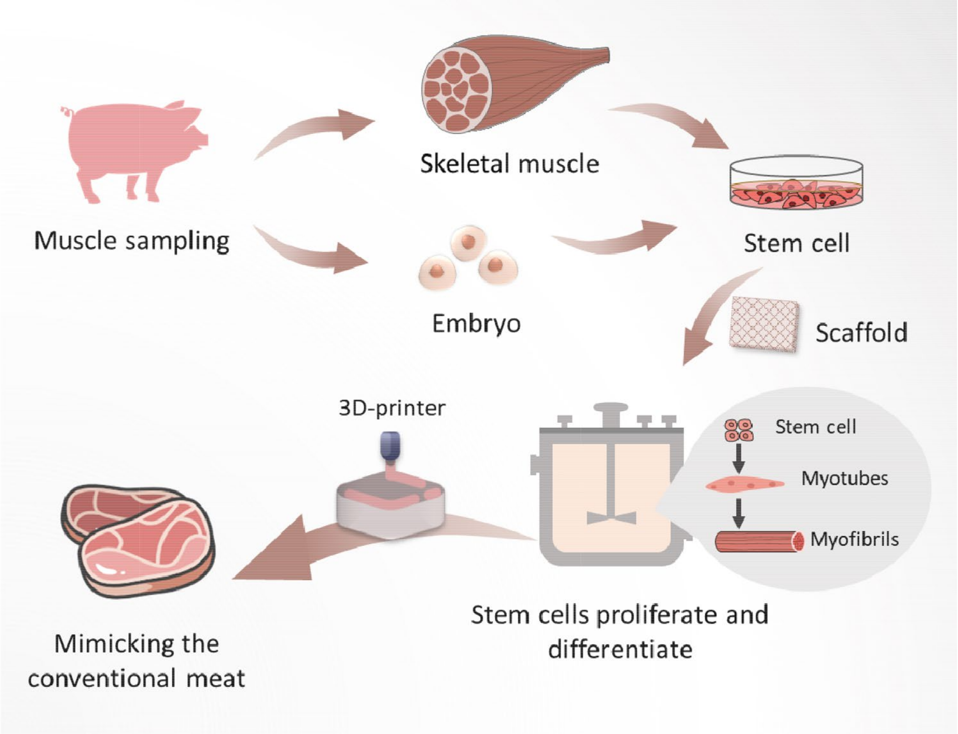

Figure 5. Production of meat using cell culture methods.

animal-derived foods. Cultured meat, also referred to clean meat, cell-based meat or cultivated meat, involves producing animal muscle tissues using stem cells that are grown in bioreactors (Zhang et al. 2020). These stem cells can be extracted from living animals without the need to slaughter them. The rise of cultured meat technology is mainly a result of progress in stem cell biology (e.g., the inductive multipotential stem cells) and tissue engineering (e.g., in vitro skeletal muscle transplant) that were initially applied into medicine (Rubio, Xiang, and Kaplan 2020). Professor Mark Post from the Netherlands used muscle stem cells to create edible cultured meat products (burgers) at the laboratory scale (Post 2014). The production of cultivated meat has some advantages over other kinds of alternative proteins: it more closely resembles real meat; it does not contain some of the allergens and antinutritional factors found in plant proteins. It also has advantages over conventional meat: it has a lower environmental footprint; no animals need to be slaughtered; and its nutritional profile can be improved. In particular, it is possible to improve the healthiness of these products by growing adipose tissue cells that contain more polyunsaturated fatty acids and less saturated fatty acids than conventional meat (Ismail, Hwang, and Joo 2020). As shown in Figure 5, multipotential stem cells are typically extracted from the somatic stem cells or embryos of live animals, and then cultured in bioreactors under optimized conditions for tissue growth (e.g., nutrient levels, growth factors, oxygen, light, pH, and temperature). The cells grow and proliferate until reaching the required concentration and are induced to differentiate into muscle cells. These cells then combine into muscular tubes, which under appropriate conditions, further grow into skeletal muscles (Tuomisto 2019). Typically, some kind of mechanical support is required in the bioreactors to ensure that the correct structures are formed. Biomaterials are often used as extracellular matrices in the final tissues formed (Wolf et al. 2015). At present, it is difficult to create products that accurately simulate the delicate structures found in whole muscle meats, such as beef steaks, chicken breasts or pork chops, but they can be successfully used to produce minced meat products, like burgers or sausages (Bhat, Kumar, and Fayaz 2015).

At present, this technology is only suitable for the small-scale production of cultivated meat. There are still several challenges that need to be overcome before the large-scale commercial production of cell-based meat can be achieved. Further work is required to identify low-cost nutrient media, as well as to optimize the growing conditions in large-scale bioreactors to increase yields and reduce costs (Tuomisto 2019). In addition, more affordable and consumer-friendly alternatives to bovine fetal serum are required as a growth medium. Moreover, more work is still required to convert the muscle tissues produced using cell-based methods into food products with meat-like looks, textures, and tastes (Ng and Kurisawa 2021). Improvements in the sensory attributes of these products will be important for increasing their market acceptance (Zhang et al. 2020).

Additive manufacturing (3D-printing) technologies have been employed to create cultivated meat products with more realistic structures and properties (Zhang et al. 2020). 3D printers can be used to assemble muscle cells, fat cells, and scaffolds that support cell growth and proliferation. By controlling the type and location of the different cells and other ingredients, a 3D printer can create products with meat-like appearances and textures (Handral et al. 2022).

Modern biotechnology can also be used to create alternative proteins through cellular agriculture processes, where microbial cells are used as foods or to produce food ingredients. Fermentation has been used throughout human history to create a range of familiar food products, including beer, bread, cheese, yogurt, and fish sauce. However, it can also be utilized to create new kinds of foods and food ingredients. Some fungi can produce mycelia that have fibrous structures similar to those found in meat products. One of the most successful commercial meat substitutes produced from microbial fermentation is Quorn™, which is a mycoprotein produced by the microfungi *Fusarium venenatum,* that is used as a substitute product for chicken, meat balls and minced meat (Rubio, Xiang, and Kaplan 2020). Airprotein (www.airprotein.com) is another innovative food company that has used microbial fermentation (hydrogenotrophs) to produce protein-rich (≈80%) powders using the air (CO_2, O_2, and N_2) water and minerals as raw materials. This product has a similar amino acid profile as real meat and is rich in vitamin B_{12}, which is normally lacking from plant-based diets. It has been utilized to create simulated meat products.

Microbes can also be utilized to secrete proteins and other high-value functional ingredients that can be used to produce the next generation of alternatives to animal products. Perfect Day uses microbial fermentation to produce milk proteins (such as caseins and whey proteins) that can be utilized to create animal-free dairy products. This process involves inserting DNA fragments that code for specific proteins into yeast cells, which then express these proteins during fermentation. The proteins can then be collected, purified, and utilized as functional ingredients. This approach does not involve the rearing or killing of any animals, and has a much lower environmental footprint than the production of animal foods (Takefuji 2021). The molecules produced using cellular agriculture processes can be utilized as specialized functional ingredients in food products, such as flavors, colors, enzymes, gelling agents, thickeners, and emulsifiers (Voigt 2020).

3.2. Carbohydrates

The overconsumption of foods containing high levels of sugars or rapidly digestible starch (RDS) has been linked to the increase in diet-related chronic diseases such as obesity and diabetes. These types of foods include bread, cookies, crackers, cakes, confectionery, noodles, white rice, and potatoes, which make up an appreciable fraction of the calories in many people's diets. After consumption, RDS is rapidly digested into glucose, which is then rapidly absorbed into the bloodstream causing hyperglycemia. As a result, insulin is secreted, which simulates the uptake of glucose by the body and leads to hypoglycemia. Over time, these increases and decreases in blood glucose levels lead to insulin resistance and type II diabetes, thereby increasing the propensity to become obese (Birt et al. 2013). For this reason, there has been interest in developing a new generation of processed foods that does not lead to large fluctuations in glucose blood levels, thereby helping to prevent diabetes and obesity.

3.2.1. Resistant starch

The physical form of ingested starch has a large impact on its digestion rate. Resistant starch refers to starch that is not hydrolyzed by digestive enzymes in the upper gastrointestinal tract (GIT), but is fermented by bacteria in the colon, leading to the production of short-chain fatty acids (SCFAs) (Ashwar et al. 2016). These metabolites have been linked to a number of important biological activities, including prevention of colon cancer, blood sugar control, intestinal flora modulation, reduction of blood cholesterol levels, and alteration of macronutrient metabolism. Resistant starch comes in a variety of forms that are able to limit the ability of digestive enzymes to access and hydrolyze the starch molecules. For instance, it may be starch trapped within plant cells and tissues, raw starch granules, or retrograded starch (Ashwar et al. 2016). There have therefore been attempts to control food processing operations so as to increase the levels of resistant starch present in foods, e.g., by leaving cellular structures intact, avoiding starch gelatinization, or promoting retrogradation (McClements 2020a). For instance, the mechanical forces, pressures, temperatures, and times used during processing may be optimized. It is important, however, that the final products still have the desirable physicochemical and sensory attributes, otherwise consumers will not find them desirable. Resistant starch is often formed using extrusion processes that disrupt the original structure of the starch molecules and cause them to assemble into densely-packed structures that are resistant to enzymatic hydrolysis (Birt et al. 2013). Resistant starch can also be created by chemical modification of natural starch. For instance, starch can be modified using esterification, etherification, or crosslinking reactions that increase its resistance to hydrolysis by amylase (Tian et al. 2019). Alternatively, starch can be co-ingested with other food components that interfere with the activity of amylase, such as lipids, polyphenols, and dietary fibers (Tian et al. 2019). Nevertheless, it is important to ensure that this does not promote any unintended adverse health effects.

3.2.2. Low-sugar foods

Food researchers are also creating foods containing reduced levels of sugars (such as glucose, fructose, and sucrose) so as to reduce their potential to promote diabetes and obesity. One of the most effective strategies is to utilize non-nutritive sweeteners. Polyols like xylitol and sucralose can provide sweetness to foods without having some of the disadvantages of sugars. For instance, polyols typically have a lower calorie content, cause lower increases in blood sugar levels, and do not cause tooth decay (Edwards et al. 2016). Some unusual natural sugars (like allulose) also have lower calorie contents than conventional sugars and are therefore finding increasing utilization in foods. Artificial high-intensity sweeteners (like saccharine, aspartame, and sucralose), which can be utilized at much lower levels than conventional sugars, are also used in some food products. However, there is increasing resistance to the utilization of these artificial sweeteners in foods and beverages because of consumer demands for clean labels. Moreover, the flavor profile, duration, and aftertaste of these artificial sweeteners are different from that of real sugars, which some consumers do not find acceptable. For these reasons, there had been interest in the identification of natural high-intensity natural sweeteners that have desirable flavor profiles, such as Stevia (Gaudette and Pickering 2013).

Sugars are added to some foods to reduce their bitterness. The level of sugars in these kinds of foods can therefore be reduced by adding ingredients that block the perception of bitter tastes. As an example, MycoTechnology (USA) produced ClearTaste™ from the mycelia of mushrooms that are bitter blockers that can be used to reduce the bitterness and astringency of foods, thereby reducing the amount of sugar that needs to be added (Soni and Langan 2018).

3.3. Lipids

Over the past few years, the food industry has been reformulating many of its products to reduce their fat content and alter their fat profile due to consumer concerns about the effects of excessive intake of total fats, trans-fats and saturated fats on chronic diseases like obesity and heart disease. Conversely, they have been trying to increase the levels of healthy fats (such as polyunsaturated omega-3 oils) in their products due to their perceived health benefits. In this section, we highlight some strategies that have been introduced to improve the lipid profile of foods with the objective of making them healthier.

3.3.1. Fat replacers

Simply reducing the fat content of foods tends to have adverse effects on their quality attributes and sensory acceptance. For this reason, there has been interest in the identification of fat replacers that can decrease the total fat content of foods, as well as simulating their desirable physicochemical properties and sensory attributes, such as appearance, texture, mouthfeel, and flavor profile (Chen et al. 2020). Fat replacers can be divided into two main categories: fat substitutes and fat mimetics. Fat substitutes have similar physicochemical characteristics as conventional fats (i.e., they are hydrophobic liquids) and so they can be used to replace fats on an approximately one-to-one basis. For instance, Olestra™ was developed by the Procter and Gamble Company as a fat substitute and approved for use in the USA in 1996. It is a sucrose fatty acid polyester that consists of a sucrose molecule in the center with numerous fatty acid chains covalently attached to the hydroxyl groups. Consequently, it has a hydrophobic exterior and is insoluble in water. The lipase molecules in the human gut cannot hydrolyze the ester bonds holding the fatty acids to the sucrose because of steric hindrance effects. Consequently, Olestra simply passes through the upper gastrointestinal tract and into the colon, which means that it has a low calorie content. However, it can have undesirable health effects such as diarrhea, anal leakage, and inhibition of oil-soluble vitamin absorption. Fat mimetics are usually biopolymers (proteins and/or polysaccharides) that are able to simulate the appearance, texture and/or mouthfeel of fats (Peng and Yao 2017). Microspheres produced from milk proteins can be used as effective fat substitutes because they have similar dimensions and surface characteristics as the fat globules in dairy products (Kew et al. 2020). For this reason, they have been incorporated into dairy products such as cheese, yogurt, and ice cream as fat mimetics. Simplesse® (Singer, Yamamoto, Latella, 1988) is a commercial fat mimetic produced by NutraSweet. Globular milk proteins unfold and aggregate when heated and sheared under appropriate pH conditions, leading to the formation of protein microspheres with similar diameters (5 µm) and charges as milk protein-coated fat droplets (Kew et al. 2020). These protein microspheres can therefore create some of the desirable lubricant sensations normally provided by fat droplets.

Natural or modified starches can also be used as fat substitutes, as some starch-based particles have similar sizes and shapes as fat droplets. In particular, they provide physiochemical properties such as thickening, gelling, and water holding that are associated with fatty-like sensory properties in foods. Typically, modified starches are more commonly used in the food industry than natural starches, because the latter type has a tendency to break down when exposed to common processing conditions, such as acidic pH, heating, and freezing (Chen et al. 2020). The thickening and lubricating properties that fats often bring to foods can sometimes be simulated by adding dietary fibers, such as pectin, locust bean gum, guar gum, and xanthan gum. Nevertheless, most fat mimetics are unable to solubilize hydrophobic flavors or vitamins, which can have adverse effects on the flavor profile and nutritional content of reduced-fat foods (McClements 2019).

3.3.2. Structural design of lipids

In addition to the replacement of fats by other food ingredients, structural design principles can also be used to decrease the total fat content of foods. Many lipid-based foods, including salad dressing, mayonnaise, milk, cream, sauces, margarine, and butter, mainly exist in an emulsified form. Butter and margarine are water-in-oil (W/O) emulsions that typically contain around 20% of water in the form of small droplets dispersed in 80% of fat in the form of a partially-crystalline 3D network of aggregated fat crystals (Norton, Moore, and Fryer 2007). This fatty matrix contributes to the semi-solid (plastic) mechanical properties of these foods. Researchers are investigating the possibility of using water-in-oil (W/O) high-internal-phase emulsions (HIPEs) as a means to create reduced-fat versions of these products (Lee et al. 2019). W/O HIPEs consist of a high concentration (> 74%) of water droplets that are so tightly packed together that they give the final product some solid-like characteristics, therefore partly mimicking the texture provided by fat crystal networks in conventional products. Traditionally, W/O HIPEs are prepared using relatively high concentrations of oil-soluble surfactants (such as PGPR), which causes challenges because of cost, flavor, and toxicity issues (Zhu et al. 2019). Hence, there is considerable interest in identifying more label-friendly emulsifiers to stabilize these systems. Abbaspourrad and coworkers successfully developed a stable

W/O HIPE containing 20% oil and 80% water by gelling the oil and water phases with beeswax and carrageenan, respectively (Lee et al. 2019). In this case, glyceryl monooleate (GMO) was used as an emulsifier that could form a fat crystal network around the water droplets.

Multiple (double) emulsions can also be used to reduce the fat content of fatty food products. In particular, water-in-oil-in-water emulsions (W/O/W) can be used to reduce the fat content of traditional oil-in-water emulsions (O/W), while maintaining their desirable physicochemical properties. In this case, some of the fat inside the oil droplets is replaced by water droplets. For instance, this approach has been used to create mayonnaise-like products with fat contents as low as 36%, which is about 40% lower than conventional mayonnaise, while still keeping a similar appearance, texture, and flavor profile (Yildirim, Sumnu, and Sahin 2016). Structural design principles have also been used to create gastric-stable emulsions, which can delay gastric emptying thereby prolonging the feeling of fullness, which may reduce the overall intake of high-calorie foods (Norton, Moore, and Fryer 2007).

3.3.3. Gene editing

Altering the lipid profile of foods through genetic engineering of plants has also been explored as a means of improving their nutritional profile. Some of these products have already been developed and tested and are now commercially available. For instance, a high-oleic soybean oil isolated from genetically engineered plants that is claimed to be healthier for the heart has been marketed by Calyxt in the USA (Voigt 2020). Two saturated fatty acid enzyme genes in the soybean genome were inactivated using genetic engineering, thereby decreasing the production of linoleic acid and increasing the production of oleic acids. Since this type of soybean oil was produced from gene editing without the introduction of any foreign genes, it is not considered to be a transgenic product in the USA.

3.4. Functional foods

Food scientists have recently focused on the development of functional foods that are specifically designed to improve human health by decreasing the risks of certain chronic diseases and/or curing them (Šamec, Urlić, and Salopek-Sondi 2019). In addition, they are carrying out systematic research on the natural food products (such as berries, spices, tea, and coffee) that are claimed to act as "superfoods" that exhibit particularly strong health benefits when consumed at sufficiently high levels.

3.4.1. Fortified foods

The nutritional value of foods can be improved by fortifying them with specific nutrients (e.g., omega 3 oils, proteins, vitamins, and minerals) and nutraceuticals (e.g., carotenoids, polyphenols, and phytosterols). For instance, milks have been fortified with vitamin D, orange juice has been fortified with calcium, yogurts have been fortified with probiotics, and breakfast cereals have been enriched with omega-3 fatty acids, vitamins, and minerals (Salvia-Trujillo, Martín-Belloso, and McClements 2016). However, direct addition of the nutrients and nutraceuticals into the food matrix is often challenging due to their poor solubility, stability, and bioavailability characteristics. These challenges can often be overcome using well-designed colloidal delivery systems that encapsulate, protect, and control the release of the bioactives. In particular, food-grade nanoparticles have proved especially effective for this purpose, including nano-emulsions, nano-gels, nano-liposomes, nano-microcapsules, and nano-fibers (McClements 2020a). For instance, a hydrophobic bioactive agent can be trapped inside the hydrophobic core of a nanoparticle that has a hydrophilic shell. The presence of this shell means that the hydrophobic bioactive can easily be dispersed in water. The composition and properties of the core and shell can be designed to protect the bioactives from chemical degradation. Moreover, they can be designed to release the bioactives at a specific location with the human gut in a bioavailable form, thereby increasing their efficacy. Selection of appropriate materials to form the core and shell of food-grade nanoparticles is essential to ensure that they function properly (Saifullah et al. 2019). It should be noted that nanomaterials are not new to the food industry. They are naturally present in many commonly consumed foods, such as the casein micelles in milk, the oil bodies in nuts and seeds, and the lipoproteins in eggs. Nanoparticles may even be formed unintentionally in traditional foods during routine food processing operations, such as homogenization, grinding, or cooking (McClements 2019). The utilization of nanoparticles to encapsulate and protect nutrients and nutraceuticals is likely to remain an important area of food research in the future.

3.4.2. Superfoods

In general, the term superfood is used to describe foods containing high levels of nutrients or bioactive phytochemicals believed to promote human health and wellbeing (Taulavuori et al. 2013). Many foods are claimed to exhibit health benefits because they contain high levels of bioactive components, such as lycopene in tomatoes, omega-3 fatty acids in fish, and polyphenols in tea, coffee and berries. In vitro and in vivo studies have often demonstrated the potential health benefits of these bioactive components when consumed regularly at sufficiently high levels (Bigliardi and Galati 2013). Consequently, there has been great interest in encouraging increased consumption of these "superfoods" or in using them as ingredients in other foods. For instance, the bioactive compounds in a superfood can be isolated and used as nutraceuticals for the production of functional foods. When designing these foods it is important to account for food matrix effects on the bioavailability and pharmacokinetics of the bioactive components, as this can impact their gastrointestinal fate (Van den Driessche, Plat, and Mensink 2018). It should be noted, however, that the scientific evidence to support the beneficial health effects of consuming most superfoods is weak or non-existent. Indeed, no generally accepted definition for this term currently exists and there is certainly a need for more rigorous clinical studies on their efficacy and safety, as well as for a stronger regulatory framework (Liu et al. 2021).

3.4.3. Excipient foods

Many of the health-promoting bioactive components found in natural foods (such as fruits, vegetables, and cereals) have a relatively low bioavailability because of their poor solubility, stability, and absorption in the gastrointestinal tract. As a result, they do not fully exhibit their beneficial health effects. Recently, there has been interest in the development of excipient foods that can increase the bioavailability of bioactive components in foods that they are consumed with (Salvia-Trujillo, Martín-Belloso, and McClements 2016). Excipient foods are not bioactive themselves, but they create an environment within the gastrointestinal tract that increases the bioavailability of the bioactive components ingested with them (McClements et al. 2015). Oil-in-water emulsions and nanoemulsions are commonly used as excipient foods because of their unique compositions and structures. They can contain hydrophobic, hydrophilic and amphiphilic functional ingredients, and their oil droplet sizes can be controlled. Excipient nanoemulsions have recently been reported to increase carotenoid uptake from tomatoes by creating mixed micelles in the small intestine that solubilize, protect, and transport the carotenoids to the epithelium cells where they can be absorbed (Nemli et al. 2021) (Figure 4c). They have also been reported to improve the oral bioavailability of carotenoids in spinach by delaying gastric emptying and forming mixed micelles (Yao et al. 2021).

4. Eco-friendly food packaging

4.1. Development trends

Traditionally, food packaging has been developed to protect foods from environmental stresses, increase their safety, extend their shelf lives, and minimize waste (Han et al. 2018). Petroleum-based plastics are often utilized for this purpose. However, there has been growing concern about the negative impacts of the production and disposal of plastics on the environment (da Cruz et al. 2014). In addition, the large amounts of food waste associated with the modern food industry have become a major concern (Raak et al. 2017). For this reason, food scientists are focusing on the design of new types of biodegradable, smart, and active packaging materials to address these issues (Poyatos-Racionero et al. 2018). Figure 6 highlights the importance of this area by showing the change in the number of publications on functional and sustainable packaging materials over the past 20 years.

4.2. Functional food packaging

Food packaging materials are normally designed to have good optical, mechanical, and barrier properties. More recently, there has been interest in extending their functionality to provide additional protections to food ("active packaging") or to provide information about food properties during storage ("smart packaging") (Figure 7). This new generation of functional food packaging is likely to play an important role in food storage, preservation, and quality monitoring in the future.

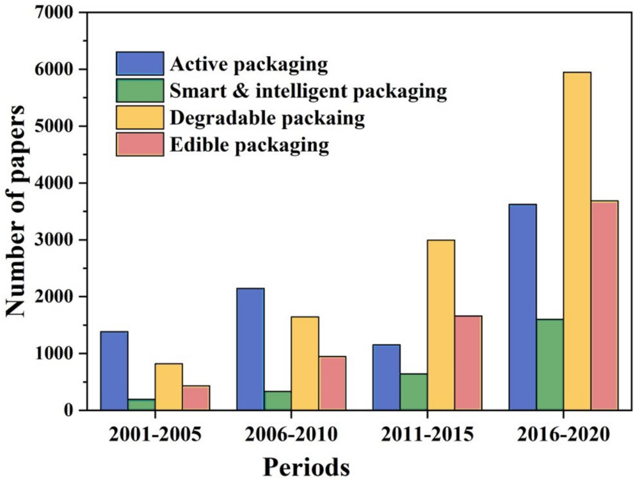

Figure 6. Trends in the number of publications on some functional packaging and sustainable packaging from 2001 to 2020.

4.2.1. Active packaging

Food deterioration is usually caused by either microbial growth or chemical degradation. Consequently, there has been interest in developing active food packaging materials containing antimicrobials and/or antioxidants that can retard these process and thereby extend the shelf life of foods (Biji et al. 2015). Active packaging typically contains food-grade antimicrobials or antioxidants that either remain in the film or are slowly released into the food. The antioxidants and antimicrobials used for this purpose may be synthetic or natural ingredients (Huang et al. 2019). However, there is increasing interest in the utilization of natural preservatives due to consumer concerns about the impacts of synthetic ones on human health and the environment.

Synthetic preservatives are artificially synthesized substances that exhibit antibacterial and/or antioxidant ability, which may be inorganic or organic. Inorganic synthetic preservatives are often nanoscale particles comprised of inorganic metals or metallic oxides (Rawashdeh and Haik 2009), such as those made from silver, copper oxide, titanium dioxide, zinc oxide, and graphene (Azeredo et al. 2019). These inorganic nanomaterials exhibit their antimicrobial activities through a variety of mechanisms, including generation of free radicals and interaction with key biochemical components, such as bacterial cell membranes, DNA, enzymes, proteins and organelles (Azeredo et al. 2019; Slavin et al. 2017). However, the widespread use of inorganic nanoparticles is limited because of their high costs, potential toxicity, and poor label friendliness

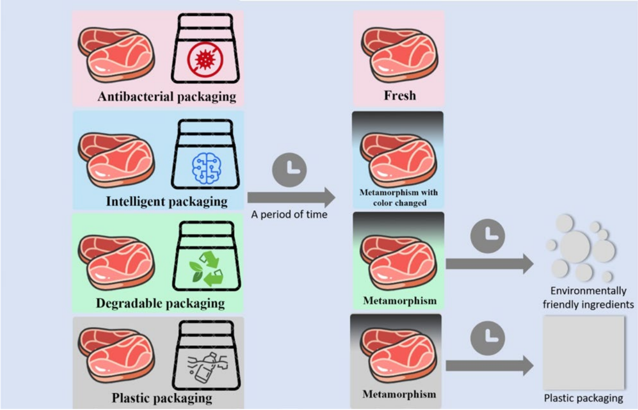

Figure 7. Comparison of active, smart, degradable and plastic packaging materials.

(Echegoyen and Nerín 2013; Zorraquín-Peña et al. 2020). Organic synthetic preservatives include various aldehydes, phenolic compounds, and quaternary ammonium salts. These substances can also exhibit antibacterial activity by disrupting microbial cell walls and interacting with key biochemical components (Friedman et al. 2017), thereby disrupting critical biochemical pathways (Saidin et al. 2021). Organic synthetic preservatives tend to have a broader spectrum of antibacterial activity and are less expensive than inorganic ones. Nevertheless, they are still limited by their relatively low stability, potential toxicity, and poor label friendliness. Hence, there has been great interest in identifying natural preservatives to replace synthetic ones.

Natural antibacterial agents can be extracted from animals, plants, or microbes: animal-derived substances include chitosan, proteins, peptides, and amino acids; plant-derived substances include essential oils, phytochemicals, and polysaccharides; and microbe-derived substances include microbial metabolites (Lucera et al. 2012). The incorporation of natural preservatives into packaging materials has been shown to be effective at increasing their antioxidant and antibacterial activity (Aloui et al. 2021). Nevertheless, further research is required to develop effective, robust, and economically viable packaging materials containing natural preservatives (Ahmed et al. 2020).

Moreover, the incorporation of preservatives into packaging materials may alter their optical, mechanical, and barrier properties, which should be taken into account during the development of these systems. Ideally, the preservatives should either enhance or not impact the desirable functional attributes of the packaging materials they are incorporated into.

4.2.2. Intelligent and smart packaging

An intelligent packaging material can convey information about the properties of a food through the utilization of indicators and/or sensing devices that are embedded within it or located on its surface. This type of packaging material can provide valuable information about the safety, quality, or maturity of a product throughout the supply chain, including production, transportation, storage, and utilization. The indicators and sensors carried by intelligent packaging systems mainly include time-temperature indicators, gas detectors, freshness and/or maturity indicators, and radiofrequency identification (RFID) systems (Kerry, O'Grady, and Hogan 2006; Prasad and Kochhar 2014). Through a combination of detection, tracking, recording and transmission, intelligent packaging systems convey important information that helps food producers, distributions, and consumers judge the status of a product (Ghaani et al. 2016). As a result, this can lead to increases in food quality, improvements in food safety, extensions in shelf life, and reductions in waste. Intelligent packaging materials can be categorized based on their underlying operating principles as indicator, sensor, or RFID packaging (Vanderroost et al. 2014). Indicator packaging materials rely on an observable change that is related to alterations in the key properties of food, such as a change in color of the packaging material when the temperature, pH, or freshness of the food changes. Compared to other types of packaging, the indicator type is relatively simple, low-cost and convenient, but the sensors used are often unstable to environmental stresses (such as heat, light, or moisture) (Biji et al. 2015; Roy and Rhim 2020). Sensor packaging materials rely on the utilization of sensors embedded in or on the film that transform some change in food properties into a signal that can be detected and recorded. Some of the most common sensors used are gas sensors, biosensors, printed electronics, chemical sensors, and electronic noses (Biji et al. 2015). Sensor packaging materials can provide food producers, distributors, and consumers with more detailed information about food properties, but they are typically more expensive and cannot be incorporated into all forms of packaging. RFID systems rely on wireless sensors for the identification of food and for data collection. They mainly consist of a combination of a label and a suitable reader. Important information about food properties (such as origin, date of production, transportation route, etc.) can be stored on the label, which can then be used by producers, distributors or consumers to make informed decisions (Todorovic, Neag, and Lazarevic 2014). RFID is particularly suitable for the management and optimization of food supply chains (Sarac, Absi, and Dauzère-Pérès 2010). It is especially useful for tracing purposes when there are food poisoning outbreaks or food recalls.

Smart packaging materials monitor changes in food products and/or the environment using sensors and then make appropriate responses to these changes through a feedback mechanism (Kuswandi et al. 2011). Thus, intelligent packaging is only designed to monitor foods, whereas smart packaging is designed to both monitor foods and to change them (if required) (Vanderroost et al. 2014) To some extent, smart packaging is, therefore, a combination of intelligent and active packaging. For instance, if a sensor detects the presence of microbial contamination in a food, then it can respond by releasing antimicrobial agents.

4.3. Sustainable food packaging

As mentioned earlier, petroleum-based packaging materials are widely used in the food industry because of their relatively low costs, good optical, mechanical and barrier properties, robustness, and heat-sealing ability. However, it is difficult to recycle or dispose of these materials, which causes environmental damage (Wohner et al. 2020). In addition, pollution caused by inadequate disposal of petroleum-based packaging materials may have adverse effects on human health (Yates et al. 2021). Thus, many researchers are attempting to develop more sustainable packaging materials as environmentally-friendly alternatives to petroleum-based ones.

4.3.1. Degradable packaging

Degradable materials are decomposed by natural environmental conditions, leading to the formation of safe organic products that do not cause pollution (Othman 2014). Degradable materials can be classified by the degradation mechanism as photodegradable, biodegradable, or photodegradable/biodegradable materials. The most commonly used degradable materials in food packaging include starch, polylactic acid, polyvinyl alcohol, polycaprolactone, and celluloses.

Degradable nanomaterials, such as those derived from cellulose and chitin, are particularly suitable for constructing this type of packaging material due to their low costs, high abundance, and excellent functional attributes(Bhargava et al. 2020). Cellulose-based nanomaterials include cellulose nanofibers (CNF) and cellulose nanocrystals (CNC). CNCs are produced by mechanical treatments, acid hydrolysis, and/or enzyme hydrolysis (Stelte and Sanadi 2009; Hubbe et al. 2008). These nanoparticles have large surface areas and many surface hydroxy groups, which can be modified to endow additional functional attributes (Moon et al. 2011). The incorporation of cellulose nanocomposites has been shown to improve the mechanical and barrier properties of degradable packaging materials (He et al. 2020; Zhang et al. 2020). These effects can mainly be attributed to the high mechanical strength and restriction to diffusion processes that cellulose nanoparticles provide when they are uniformly dispersed throughout a packaging matrix (Abdollahi et al. 2013).

4.3.2. Edible packaging

Edible packaging materials are usually prepared from biodegradable food-grade macromolecules, such as proteins, polysaccharides, and/or lipids (Mohamed, El-Sakhawy, and El-Sakhawy 2020). In some cases, these macromolecules can be assembled into coatings or films that have the mechanical, barrier, and optical properties required to protect foods. The functional performance of edible packaging may also have to be improved by incorporating other functional ingredients (Dhall 2013). This is often necessary due to the limitations inherent in using food macromolecules alone. For instance, polysaccharide- and protein-based films have high mechanical strength and oxygen blocking ability, but limited water vapor blocking ability (Petkoska et al. 2021). Conversely, lipid-based films have good water vapor permeability and moisture-stability properties, but poor mechanical strength. For this reason, biopolymers and lipids are often combined together to create composite edible packaging materials with improved properties (Talegaonkar et al. 2017).

Active, intelligent, and smart versions of edible packaging materials can also be created to increase their functional performance. Typically, biopolymers are used to form the matrix and then sensors or active ingredients are incorporated using blending, pressing, layer-by-layer, or electrostatic spinning methods (Chen et al. 2021). Nevertheless, further research is still required to create economic and robust edible packaging materials that can be produced commercially at sufficiently large scales.

5. Precision nutrition and customized food production

Different individuals have different nutritional requirements depending on their genetics, metabolisms, microbiomes, lifestyle preferences, and phenome (McClements 2019). It is therefore likely that nutritional recommendations will be increasingly given at the individual rather than the population level. Precision or personalized nutrition relies on the availability of advanced analytical technologies to affordably and rapidly provide detailed data about the genetics, epi-genetics, metabolomes, microbiomes, and phenomes of individuals (Figure 8). Advanced computational methods are then required to store and analyze this data so as to find connections between an individual's data, health, lifestyle, and diet. This knowledge can then be used to design a specific diet and lifestyle to ensure that an individual remains healthy.

5.1. Nutrition demand and digestive and metabolic differences

Different countries around the world have developed dietary guidelines based on the characteristics of their populations. These guidelines are based on the general principles of nutrition combined with knowledge of the nutritional needs of the particular population. Though dietary guidelines present reasonable guidance for the general population and specific groups, regional diversity and the complexity of the human body make the dietary guidelines different among regions (Figure 9, Sino-US differences in dietary guidelines). Moreover, dietary guidelines cannot match the needs of every individual or achieve the goals of precision nutrition guidance. Consequently, more research is required to develop the analytical instrumentation, databases, and computation models to develop more personalized nutritional advice.

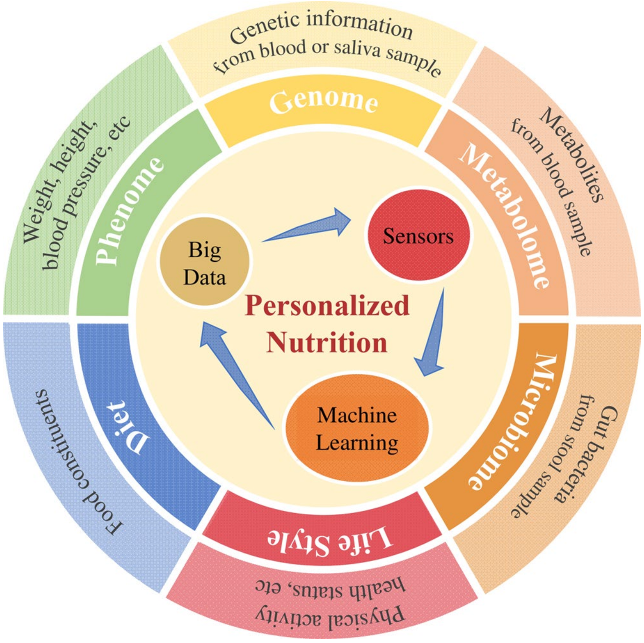

Figure 8. Personalized nutrition involves several aspects, including the genome, metabolome, microbiome, life style, diet, and phenome (McClements 2019).

Differences in development phase, physiology, and health status result in differences in the nutrients and calories different individuals require. For instance, teenagers are at a critical growth stage and require more energy, water, carbohydrates, minerals, creatine, and vitamins than adults to meet their growth needs. Moreover, the nutritional requirements of pregnant women are significantly different from those who are not pregnant. For example, pregnant women are recommended to increase their intake of seafood, dairy products, and iron-fortified functional foods. Many elderly people suffer from bone and muscle aging, which means that they should consume foods containing higher levels of bioavailable calcium and proteins. Elderly people who are prone to cardiovascular diseases should consume more foods that are low in saturated fats and high in polyunsaturated fats (Sacks et al. 2017). Moreover, the physical activity of people often drops as people age and so they may require foods that have a lower calorie density to avoid becoming overweight or obese. Conversely, people working in extreme conditions, such as military personnel, firefighters, and athletes, require nutrient-dense foods that are high in calories (Pasiakos 2020).

Differences in gastrointestinal physiology among individuals may also mean that they require foods with different nutrient profiles or digestibility. The gastrointestinal tract harbors about 100 trillion microbes, including bacteria, fungi, viruses, and protozoa (Sender, Fuchs, and Milo 2016). The intestinal flora is symbiotic with the human body and plays a vital role in maintaining normal metabolic functions and human health. The composition and functions of the intestinal flora vary greatly between people, which may be a result of genetic differences, as well as external factors (Vandeputte 2020). For instance, the intestinal tract of an obese person has lower proportions of *Bacteroidetes* and higher proportions of *Actinobacteria*. Diet is one of the most important external factors affecting the composition and function of the intestinal flora and can be most easily altered or controlled (Sonnenburg et al. 2016). Ingested foods are partially digested and absorbed in the upper gastrointestinal tract, but a fraction of the undigested material reaches the colon and acts as a substrate for intestinal microbes. As a result, the intestinal microflora plays an important role in the digestion and absorption of foods, as well as influencing their health effects on the human body. Differences in national diet have an important impact on the microflora of populations. For instance, the intestinal tracts of Japanese people contain a unique microbial strain that can secrete alga metabolic enzymes, which is because they regularly consume seaweed (Hehemann et al. 2010). This research highlights that dietary interventions can directly act on intestinal microflora and impact its composition and function, thereby altering human health. In the future, more research is required to better understand the complex links between diet, the gut microbiome, and human health. This knowledge can then be used to create diets that will enhance human health and wellbeing.

5.2. Nutriomics and individualized food design

Nutriomics is the study of the interactions between the human diet and genes and their effects on human health

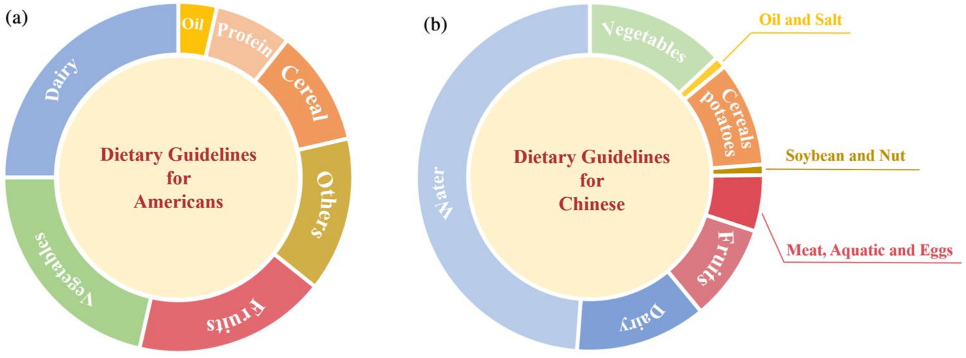

Figure 9. Dietary guidelines for (a) Americans; (b) Chinese.

at the molecular and population levels. This knowledge can then be used to create dietary intervention schemes and health care measures based on analysis of individual genome structures and characteristics. This science includes nutritional genomics, transcriptomics, proteomics, metabolomics, and systems biology (Van Ommen and Stierum, 2002). Early nutriomics research was mostly explorative and aimed to determine new nutrimental and dietary mechanisms by applying transcriptomics or proteomics techniques. Changes in the transcriptome or proteome reflect changes in inflammation and oxidative stress pathways, as well as alterations in metabolism, which can provide valuable information about how specific foods impact human health. Advanced metabolomic methods are increasingly being applied into nutrition research, since metabolites are the actual products of dietary intake and metabolism, and thus can be utilized to more precisely evaluate the biochemical and physiological pathways of biomarkers produced by diets (exogenous) or diseases (endogenous). Metabolomics can also be used to prove the effectiveness of metabolic biomarkers and evaluate food intake, and plays a critical role in studying the relationship between food intake and health/disease (Brennan and de Roos 2021). Food metabolism is a complex process, and the ingested foods introduce new metabolites into the body, which then undergo complex metabolic reactions in various biochemical pathways. In addition, the ingested foods alter the composition and function of the colonic microflora, which also has important health implications. Rådjursöga et al. (2019) found after intake of breakfast cereals, it caused increases in the serum concentrations of proline, tyrosine and N-acetylated amino acids in adults, but after eating ham and eggs, the serum concentrations of creatine, methanol and isoleucine increased. Measurements of appropriate biomarkers allow scientists to rapidly identify metabolic dysfunctions and undesirable health conditions. Lu et al. (2017) reported that lipid peroxidation metabolites may be good biomarkers to differentiate stable angina pectoris and myocardial infarction. Furthermore, metabolomics has been used to provide an assessment of the potential biological ages of individuals (Ordovas and Berciano 2020). With the presence of chronic diseases, biological age is older than the actual age, and the difference between the two ages is related to risks of disease and death.

The application of dietetics and nutriomics into research on *in vivo* dietary interventions has indicated that ingested bioactive ingredients affect the transcriptome, proteome, metabolome, and gut microbiotas. Detection of changes in biomarkers during the early stage of diseases can help to provide information about how diets prevent or delay the development of chronic diseases. In the future, it is likely that advanced omics tools will become increasingly important in the development of precision nutrition.

5.3. Food sensory perception differences

Customers are increasingly taking food nutrition and health into account when making dietary choices. However, any newly designed foods must still be desirable, affordable and convenient, otherwise people will not consume them. Individuals vary considerably in their food preferences depending on their genetics and life history. Consequently, it is important for food manufacturers to understand the key factors affecting consumer choices so they can design healthier and more sustainable foods that people will incorporate into their diet. Food flavor and preference depend on the integration of information coming from different human senses, including sight, sound, taste, aroma, and touch, as well as previous experiences and associations. Researchers are currently trying to identify the relationships amongst food composition and structure, the physiological structures and pathways linked to sensation, individual differences in sensory organs, brain patterns after food ingestion, sensor perception, and the emotional feedback of consumers (Torrico et al. 2021). The sensory perception of foods is a rapidly advancing science due to the availability of new analytical tools and theories. For instance, the identity of many taste receptors has already been established, as well as the neuron structures related to the five primary tastes (sweet, sour, bitter, salty, savory) (Zhang et al. 2019).

A number of factors contribute to individual differences in the sensory perception of foods. First, genetic differences decide the sensitivity of individuals to different flavors e.g., some people are super tasters, normal tasters or non-tasters of bitterness depending on the combination of alleles they have (Bartoshuk 2000). Secondly, environment, age, gender, income, physiological state, health status and other factors influence the sensory perception of different individuals (Weenen et al. 2019; Henkin, Levy, and Fordyce 2013). Overall, this highlights the importance of accounting for personalized sensory attributes, as well as personalized nutritional needs, when formulating the next generation of foods.

The textural properties and mouthfeel of foods during eating are also important parts of the sensory perception of foods and directly affect food preference and acceptance (Prakash, Tan, and Chen 2013). Consequently, there have been great efforts in understanding and controlling the factors that influence the texture and oral processing of foods using *in vitro* mechanical methods, as well as *in vivo* sensory methods (Upadhyay and Chen 2019). In particular, oral processing utilizes a combination of material science, sensory science, and physiology to understand the behavior of foods inside the mouth during mastication and how this is perceived by consumers as mouthfeel. During oral processing, solid foods are mixed with saliva, broken down, moved around the mouth, and coat the tongue, cheeks, and palette. The bolus formed elicits sensory responses by interacting with nerve endings in the oral mucosa that then send signals to the brain that are interpreted as taste and texture (Steele 2018; Simon et al. 2006; Ishihara et al. 2013). Saliva volume and composition, oral temperature, tongue morphology, and chewing parameters all affect the sensory perception of foods. Researchers are developing new analytical methods to simulate the conditions in the mouth, such as oral tribology (Upadhyay and Chen 2019), which can provide valuable insights into the key properties of foods that impact sensory perception. This knowledge can then be used to design delicious foods with novel or improved sensory attributes, or to create foods that are designed for individuals with health problems that interfere with normal sensory perception (Collins and Bercik 2009; Peppas et al. 2021).

6. Conclusions and prospects

The modern world is faced with numerous challenges associated with the food supply chain, including global population growth, climate change, biodiversity loss, pollution, waste, growing diet-related chronic diseases, and food safety issues. It is critical to produce safe, nutritious, and sustainable foods without damaging the environment. Moreover, these foods must be designed to meet people's growing aspirations for a better life.

There are many advances in modern science and technology that are being employed to create a new generation of healthier and more sustainable foods. Alternative protein sources are being developed to replace protein-rich animal-derived foods like meat, fish, eggs, and milk, including proteins obtained from plants, insects, microbes, and cell cultures. Advances in sensing, robotics, and artificial intelligence are being used in agriculture, food distribution, and food processing operations to make them more efficient, reduce waste, and decrease the dependence on manual labor. Genetic engineering is being utilized to improve the yield and nutritional quality of agricultural crops, to reduce waste, and to increase their resilience to climate change. Additive manufacturing (3D printing) is being utilized to create personalized foods with sensory attributes and nutritional profiles tailored to individual needs. Food architecture and nanotechnology are being used to improve the healthiness of foods by removing ingredients known to promote chronic diseases (such as fats, sugars, and salts) or fortifying them with ingredients known to promote health (such as vitamins, minerals, and nutraceuticals), while still ensuring desirable food quality, affordability, and convenience. Biodegradable, active, smart, and intelligent packaging materials are being developed to reduce the negative environmental impact of traditional plastic-based packaging, as well as to improve food quality, safety, and sustainability. Precision nutrition is utilizing the latest advances in analytical instrumentation (omics) and computational tools (big data and artificial intelligence) to better understand the links between foods, individuals, and health. This knowledge is then being used to design foods to meet the specific nutritional requirements of each person, which will lead to improved health and wellbeing.

It is clear that modern science is transforming the food supply. It will be important to ensure that these new technologies are carefully tested before being implemented so as to assess and reduce any potential risks. Moreover, it will be important for food companies to be transparent about the principles behind these new technologies, as well as their potential risks and benefits, so that consumers can make informed choices and regulators can develop appropriate legal frameworks. It is certainly an exciting time to be a food scientist. The discipline is rapidly changing and the authors believe that there will be many more innovations that can potentially improve the food supply and ensure that all the people on the planet have access to an affordable, healthy and sustainable diet.

Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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