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Future Foods: A Manifesto for Research Priorities in Structural Design of Foods

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Abstract

A number of major challenges facing modern society are related to the food supply. As the global population grows, it will be critical to feed everyone without damaging the environment. Advances in biotechnology, nanotechnology, structural design, and artificial intelligence are providing farmers and food manufacturers will new tools to address these problems. More and more people are migrating from rural to urban environments, leading to a change in their dietary habits, especially increasing consumption of animal-based products and highly-processed foods. Animal-based foods lead to more greenhouse gas production, land use, water use, and pollution than plant-based ones. Moreover, many animal-based and highly-processed foods have adverse effects on human health and wellbeing. Consumers are therefore being encouraged to consume more plant-based foods, such as fruits, vegetables, cereals, and legumes. Many people, however, do not have the time, money, or inclination to prepare foods from fresh produce. Consequently, there is a need for the food industry to create a new generation of processed foods that are desirable, tasty, inexpensive, and convenient, but that are also healthy and sustainable. This article highlights some of the main food-related challenges faced by modern society and how scientists are developing innovative technologies to address them.

Keywords: future foods; nanotechnology; gene editing; genetic engineering; artificial intelligence

Introduction

It is an extremely exciting time to be a food scientist. Major scientific and technological advances are being made in a broad diversity of areas that are transforming the way we produce and consume foods [1]. These advances are being driven by academic, industrial, and government scientists trying to tackle some of the major food-related challenges facing modern society, as well as by farmers and consumers who produce and purchase foods. These challenges include feeding a growing global population without damaging the planet, tackling the rise of diet-related chronic diseases, and providing a diverse range of safe, tasty, and nutritious foods [2, 3]. For instance, the recent EAT-Lancet report outlines a global diet that will lead to improvements in the sustainability of the food supply, as well as in individual health [3]. One of the main recommendations of this report is to reduce the level of animal-based products consumed, and increase the level of plant-based ones consumed. As a result, more research is required to create high-quality, affordable, and sustainable plant-based alternatives to meat, fish, eggs, and milk. This article reviews the major food-related challenges being faced by modern society and how structural design principles can be used to help address them.

The Health of the People

The Problem

The quality and quantity of food we consume is critical to our health and wellbeing. However, both undernutrition and overnutrition are causing major health problems around the globe. The United Nations reports that there are still over 820 million people globally who suffer from hunger, while the World Health Organization estimates that there are nearly 2 billion people suffering from micronutrient deficiency (ourworldindata.org). Urgent efforts are therefore required to ensure that high-quality foods reach people suffering from hunger and malnutrition. Many of these problems are due to extreme poverty and local conflicts, which require political solutions. As will be seen later, however, some of these problems can be addressed throughout technological solutions. For instance, structural design principles can be employed to create nutritious foods that are enriched with bioavailable micronutrients, such as vitamins and minerals.

For the majority of world history, diseases associated with eating too little were a far greater problem than those associated with eating too much. Within the past decade or so, however, it has been reported that more people die due to diseases associated with overeating (such as obesity, heart disease, diabetes, and stroke) than those caused by undereating (malnutrition) (World Health Organization). Obesity and related diseases have increased dramatically over the past few decades in many developed countries, and are now also increasing rapidly in many developing countries as they adopt a more Westernized diet and lifestyle (**Figure 1**). This increase is reducing the quality of life of a large fraction of the population, as well as putting a strain on economies and health care systems. Indeed, the *Centers for Disease Control and Prevention* (CDC) in the US estimates that it costs an additional $1,400 to treat someone who is obese. Detailed information about the global burden from non-communicable diseases can be found at the website "Our World in Data" (https://ourworldindata.org/burden-of-disease). Clearly there is an urgent need to create a food supply that will address these problems.

Many diet-related health problems would be reduced if individuals consumed more plant-based whole foods, such as fruits, vegetables, legumes, and nuts, rather than processed foods. However, many people do not have the time, energy, resources, or inclination to prepare all of their meals from fresh ingredients. Instead, they prefer to consume pre-prepared processed foods that are affordable, convenient, and tasty. Indeed, it has been estimated that highly-processed foods contribute over 60% of the calories to diets in some developed countries [4]. There is therefore a need for a new generation of healthier and more sustainable processed foods that consumers can easily fit into their diets.

Potential Food Design Approaches

Tackling Malnutrition

As mentioned earlier, hunger and undernutrition are usually associated with extreme poverty and armed conflicts, which means that many of the solutions needed to tackle them depend on economic development and political action. Nevertheless, science and technology can play an important role in developing foods to tackle these problems. In particular, the technologies used to increase the efficiency and reduce the costs of food production mentioned later can play an important role, such as genetic engineering, nanotechnology, automation, and artificial intelligence. Moreover, the bioavailability of essential micronutrients, such as vitamins and minerals, can be enhanced by using encapsulation technologies and food matrix design approaches (see later).

Reducing Calorie Density

One of the major factors contributing to diet-related problems in developed countries is the overconsumption of calorie-dense foods, such as cookies, cakes, snacks, and breads, which are rich in digestible fats and carbohydrates [5-7]. There has therefore been growing interest in developing reduced-calorie versions of these foods so that consumers can still enjoy them, but experience fewer adverse health effects [8-10]. The development of these kinds of products relies on knowledge of the molecular/physicochemical basis of food quality and deliciousness [1, 11]. In particular, the way that specific food ingredients and structures contribute to the desirable appearance, aroma, taste, sound, and feel of foods is required. This knowledge can then be used to reformulate foods to reduce the levels of high-calorie ingredients (such as fat and starch), while maintaining their desirable sensory attributes. This is an important area that research scientists with expertise in structural design principles can contribute. A few selected examples of the kinds of approach that can be used to develop reduced-calorie foods are given here to highlight the science involved.

Digestible fats have twice the calorie density of digestible proteins and carbohydrates, which makes them an important target for the creation of reduced-calorie foods [8]. For this reason, many researchers have focused on the development of reduced-fat versions of common foods, like dressings, sauces, spreads, and baked goods. These products have to be designed to look, feel, and taste like the conventional versions, otherwise consumers will not purchase them and incorporate them into their diets. This aim can often be achieved using structural design principles to create food compositions and structures with the desired attributes. As an example, mayonnaise is an oil-in-water (O/W) emulsion that consists of a high concentration of oil droplets (typically > 70%) dispersed within a watery medium [12]. The desirable textural attributes of this kind of product, such as its spoonability, are the result of the fact that the fat droplets are packed so closely together that they cannot easily flow past each other when a force is applied. The fat content of this kind of product can be reduced using water-in-oil-in-water (W/O/W) emulsions. This kind of multiple emulsion can be designed to have a similar appearance, texture, and mouthfeel as a conventional mayonnaise but with a significantly lower fat and calorie content [13]. The fat content is reduced by incorporating small water droplets within the fat droplets (W/O), so that some of the fat is replaced by water (**Figure 2**). This technology has already been used commercially to successfully produce reduced-calorie mayonnaise products that look, feel, and taste like the conventional versions, which are available in Japan.

Structural design principles have also been utilized to create reduced-calorie versions of other categories of high-fat foods, such as butter and margarine. Conventional fatty spreads are water-in-oil (W/O) emulsions that contain small water droplets dispersed within a partially crystalline oily phase (**Figure 2**). The 3D-network of interlinked fat crystals in the oily phase leads to their semi-solid ("plastic") texture, which is an important quality attribute, *e.g.,* for their spreadability [14]. Spreadable foods can be produced using high internal phase emulsions (HIPEs) that have much lower fat contents than conventional butter and margarine [15, 16]. This type of O/W HIPE consists of a high level of water droplets (> 70%) dispersed within an oil phase (**Figure 1**). The semi-solid characteristics of this type of material are due to the fact that the water droplets are packed so tightly together. To the authors knowledge, there are currently no commercial applications of this technology, but it does have considerable potential. Nevertheless, further research is needed to establish whether HIPEs can be produced economically, whether they have the desired quality attributes, and whether they are sufficiently robust for food applications.

Various other structural design approaches can also be utilized to produce reduced-calorie foods by removing some or all of the fat or starch. For instance, fat droplet and starch granule mimetics are being developed using various food ingredients, including indigestible oil droplets, protein microparticles, biopolymer microgels, and gums (**Figure 3**). The potential commercial success of food products based on these approaches depends on their cost, processability, and performance compared to the high-calorie products they are designed to replace. The physiological and nutritional effects of these new ingredients and foods should also be established to ensure they do not have any potentially adverse consequences. For example, it will be crucial to ensure they are satiating to avoid overeating, and that they do not have any unintended gastrointestinal effects. For this reason, it may be important to replace the fat and starch with healthier alternatives, such as dietary fibers and proteins, which can produce the desired quality attributes, but also beneficial nutritional and physiological effects.

Reducing Food Intake

A major cause of the increase in diet-related chronic diseases in recent years is the increase in total calories consumed, which depends on calorie density, but also on the amount of food ingested. Consequently, decreasing the total amount of calorie-rich foods consumed would help to reduce obesity, diabetes, and other chronic diseases [17, 18]. There are major differences in the rate of calorie consumption for different food and beverage products depending on their calorie density and physicochemical properties [19]. For example, sugary fluid beverages that pass through the mouth quickly (such as fruit juices) have a much greater rate of calorie intake than sugary solid foods that pass through the mouth more slowly (such as raw fruits that need to be chewed before swallowing). Researchers are therefore trying to redesign foods so that they have lower calorie densities and remain inside the mouth for a longer period [20, 21]. Food architecture can be used to create structures inside foods that are more difficult to breakdown inside the mouth during chewing using healthier or lower-calorie ingredients such as proteins and dietary fibers [22, 23]. In particular, proteins and indigestible polysaccharides can be used to form semi-solid structures with textural characteristics that are sensorial desirable and that extend the time they spend in the mouth [24]. These foods should provide greater satiety and satiation to consumers, which should make them eat less, thereby consuming fewer calories.

Reducing Food Digestibility

An additional factor that could also be contributing to the recent rise in diet-related chronic diseases, such as obesity and diabetes, is the change in the way foods behave within the human gastrointestinal tract (GIT) due to intensive food processing (**Figure 5**) [5]. In prehistoric times, humans only had unprocessed or lightly-processed foods available to eat, such as fruits, vegetables, nuts, cereals, eggs, and animal flesh, which tended to be digested relatively slowly within the human body, thereby leading to slow nutrient absorption, and only a modest increase in nutrient blood levels. Our gastrointestinal tracts evolved highly efficient mechanical, chemical, and enzymatic methods to breakdown these relatively unprocessed foods so that the calories and micronutrients could be effectively absorbed and utilized. In modern times, most foods undergo intensive food manufacturing operations so that many of their natural structures are broken down, such as epidermis, internal tissues, cell walls, and organelles. Consequently, the starch granules and oil bodies, which are typically trapped inside these natural structures are exposed, released, or disrupted during food processing. As a consequence, they are digested and absorbed much more quickly inside the human gut, which causes rapid increases ("spikes") in the nutrients and their metabolites observed in the bloodstream after a meal. The most well-known example in this area is the spike in blood glucose levels after eating foods containing high levels of rapidly digestible starches (like white bread) [25], which has been linked to hormone dysregulation and an increased susceptibility to diabetes. In principle, spikes in blood lipids or other food constituents could also have adverse effects on our metabolisms and hormonal systems.

A considerable amount of research is therefore being carried out to determine the factors that influence the rate and extent of the digestion of macronutrients, such as starch, fat, and protein [26, 27]. These experiments are being carried out using both *in vitro* digestion models, as well as *in vivo* feeding studies with animals and humans [26, 28]. In future, it may be important to develop healthier alternatives to existing foods by reducing the rate of macronutrient digestion by changing food composition and structure. As an example, the rate of starch digestion can be reduced using a variety of strategies [29]. One approach is to redesign food manufacturing operations so that more of the structures natural present in foods remain intact so that they can protect the macronutrients from rapid digestion within the human gut [30]. Whole grain bread is an example of this "minimal processing" approach – by leaving some of the natural structures in cereals intact, the starch is digested and absorbed more slowly [30]. Another potential advantage of this kind of minimal processing approach is that less energy and resources are usually needed during the manufacturing operations, which has sustainability benefits. Processing operations can also be developed to increase the amount of slowly digestible or resistant starch that is present [31-34]. Indigestible polysaccharides can be included into foods to increase the viscosity or gel the gastrointestinal fluids within the human gut, which should reduce the ability of the digestive enzymes to reach and hydrolyze the starch [35, 36]. Indigestible polysaccharides can also retard starch digestion through a variety of other physicochemical mechanisms, *e.g.,* by binding to amylases or by forming protective coatings around starch granules [37, 38]. The action of amylases may also be inhibited by other components that can be included in foods, such as some plant polyphenols [39, 40]. The digestion of starch can also be inhibited by trapping it inside dietary fiber matrices within food products [41]. Many similar approaches have been used to retard the digestion of lipids within the GIT, including trapping the lipids in natural or designed indigestible or slowly-digestible structures, adding components that thicken or gel the gastrointestinal fluids, and adding components that bind to lipases [27]. If these products are going to be successful, it will be critical to determine whether they can be economically produced, are desirable to consumers, and behave as expected when people consume them.

It should be noted that extensive processing of foods does not always have adverse effects on their nutritional quality. In some cases, there are nutritional benefits from highly processing foods, such as an increased bioavailability of fat-soluble nutrients and nutraceuticals (like carotenoids). In this case, mechanical or thermal processing may breakdown the plant cell walls, which facilitates the release of the beneficial bioactive components within the human gut.

Increasing Micronutrient Bioavailability

Rather than reducing the level of food components that may have adverse health effects (such as fat, sugar, and salt), the nutritional value of processed foods can be improved by increasing the level of food components with potentially beneficial health effects (such as vitamins, minerals, dietary fibers, or nutraceuticals) [42, 43]. There are often challenges to simply incorporating these health-promoting ingredients into food and beverage products [44]. For instance, they may not be fully soluble in the food matrix, they may chemically degrade, they may introduce off-flavors, they may adversely affect food appearance or texture, or they may have a low bioavailability. Consequently, structural design approaches are often required to successfully incorporate them into foods. In this section, the focus will be on the incorporation of nutraceuticals into functional foods, since this is one of the most widely studied categories of bioactive ingredients [45, 46]. The term “nutraceutical” covers a broad range of food components that are claimed to exhibit health benefits above their normal nutritional attributes, including carotenoids, polyphenols, phytosterols, curcuminoids, and ω-3 fatty acids [47]. There are a number of challenges associated with trying to introduce some nutraceuticals into food and beverage products [48, 49]. Many nutraceuticals have poor solubility in aqueous media (such as carotenoids and curcuminoids), making it challenging to disperse them within some foods. Moreover, many nutraceuticals are chemically labile so that they degrade before the food is even consumed or have a poor bioavailability so that they are inefficiently absorbed by the human gut (such as curcumin). As a result, many nutraceuticals never reach the site of action in an active form where they can exhibit their beneficial effects within the body [48]. These challenges can often be overcome by utilizing colloidal delivery systems that enhance the water-dispersibility, chemical stability, and oral bioavailability of nutraceuticals [27, 50]. Some of the different kinds of colloidal delivery systems that have been created to increase the efficacy of nutraceuticals are highlighted in **Figure 4**, such as microemulsions, liposomes, emulsions, suspensions, and microgels [51, 52].

Colloidal particles with hydrophobic cores and hydrophilic shells are the most commonly used type of delivery system for the encapsulation of non-polar nutraceuticals [51]. The hydrophobic core enables non-polar nutraceuticals to be trapped inside, whereas the hydrophilic shell allows the nutraceutical-loaded particles to be dispersed into an aqueous medium. Colloidal delivery systems are assembled from common food-grade ingredients, such as proteins, fats, carbohydrates, phospholipids, and surfactants [53]. They are often designed to stay intact within food products, but then breakdown within a particular region of the human gut (such as the mouth, stomach, small intestine, or colon), where they release the encapsulated nutraceutical [51]. Delivery systems can also be fabricated so that they generate a microenvironment inside the human gastrointestinal tract that alters the metabolism, bioaccessibility, and absorption of the nutraceuticals, thereby increasing their overall bioavailability [48]. For example, emulsion-based delivery systems contain lipid particles that form mixed micelles when they are digested, which can solubilize non-polar nutraceuticals and carry them to the epithelium cells where they can be absorbed [54].

Overall, two different strategies have been developed to increase the bioavailability of nutraceuticals in foods:

- *Functional foods*: As just discussed, colloidal delivery systems are being designed to encapsulate, protect, and release nutraceuticals. The nutraceutical-loaded colloidal particles they contain are introduced into functional foods or beverages to nutritionally enhance them.
- *Excipient foods:* An alternative strategy that has recently been developed to boost nutraceutical bioavailability is to use "excipient foods". This type of food does not contain any nutraceuticals, but it increases the bioavailability of the nutraceuticals in other foods that it is consumed with [55, 56]. As an example, an excipient food could be a cream that is served with fruit, a dressing that is poured on a salad, or a cooking sauce that is mixed with vegetables. Without the excipient food, the nutraceuticals in the fruits or vegetables would have a relatively low bioavailability, but with the excipient food they would have a relatively high bioavailability. The potential of excipient foods is best

illustrated with a specific example. In our laboratory, we have used a simulated gastrointestinal model to demonstrate that ingesting carrots with an excipient emulsion containing very fine digestible lipid droplets (a model sauce) greatly enhances carotenoid bioaccessibility [57] (**Figure 5**). The origin of this effect was attributed to the rapid digestion of the lipid droplets within the small intestine, which led to the formation of mixed micelles that could solubilize the carotenoids released from the carrots. We have also shown that the carotenoids in other types of fruits and vegetables, such as mangoes, peppers, and tomatoes, can also be increased using this approach [58-60]. Excipient foods have to be designed according to the nature of the nutraceuticals and foods they are consumed with. For instance, the concentration, composition, and dimensions of the lipid droplets must be optimized, and other components may also be included in the formulation, such as antioxidants (to inhibit oxidation), enzyme inhibitors (to reduce metabolism), or permeation enhancers (to promote absorption), depending on the properties of the nutraceuticals [56].

The development of colloidal delivery systems for nutraceuticals is a rapidly expanding field. In the future, it will be important to ensure that they can be created economically using acceptable food-based ingredients, that they can be incorporated into food products without adversely affecting their quality attributes or safety, and that they are actually effective. In particular, it should be noted that there may actually be adverse effects associated with increasing the bioavailability of some substances. For instance, studies have shown that increasing the uptake of vitamin E can promote cancer in smokers [61]. Consequently, manufacturers of nutraceutical-fortified products must carefully assess their products to ensure that they do not have any unforeseen adverse health effects.

Controlling Gut Health

Another strategy for increasing the health benefits of the human diet is to create foods that modulate the composition of the gut microbiome [62, 63]. Numerous studies have shown that the health and wellbeing of humans is highly dependent on the nature of the microorganisms living in their colons [64]. Certain types of gut microbiomes have been linked to good health, whereas others have been linked to illness. Consequently, there is great interest within the food industry in utilizing diet as a means of modulating the gut microbiome and therefore improving human health and wellbeing. This can be achieved by fortifying foods with either probiotics or prebiotics [65]. Probiotics are living microorganisms that are meant to reach the colon and promote the establishment of a healthy gut microbiome, whereas prebiotics are food components that stimulate the growth of the "good" microbes already living in the colon. A major challenge associated with delivering probiotic bacteria using foods and beverages is that they are often killed as they travel through the human gut, which may be due to high acidity levels, the presence of bile salts, enzyme activity, or changing oxygen levels. Colloidal delivery systems, as well as other encapsulation technologies, are being developed to protect probiotics in foods and within the upper gastrointestinal tract, but then release them in the colon [66, 67]. For instance, biopolymer microgels have been developed to encapsulate and protect probiotics. These microgels are made from dietary fibers so that they are resistant to degradation in the upper GIT, but are degraded by colonic bacteria when they enter the colon, thereby releasing the probiotics [68]. Recent research has shown that the internal pH of microgels can be controlled by incorporating insoluble antacids inside them [69], which enhances the stability of the probiotics within the gastric juices [70].

Despite the great potential for improving human health by manipulating the composition of the gut microbiota, there is still relatively little hard evidence that probiotics can actually improve the health of individuals whose gut microbiota is not already compromised [71]. For this reason, there is clearly a need for more systematic research in this area [72].

Personalized Nutrition

An emerging area where structural design principles may be particularly useful is in the development of functional foods for personalized (or precision) nutrition [73]. Personalized nutrition is based on the concept that foods should be tailored to the particular dietary requirements of an individual based on their specific genetic profile, metabolism, microbiome, and lifestyle [74, 75]. Consequently, an older person with diabetes requires a different diet than a younger person with hypertension. This field has grown rapidly in recent years due to major advances in genomics, analytical instrumentation, biosensors, computation, and data analysis [1]. These advances have enabled scientists to measure the many different kinds of molecules and microbes present within foods, as well as within biological samples collected from animals and humans (such as blood, saliva, urine, and feces). For instance, scientists can now measure changes in metabolite and microbiome profiles in response to different foods or diets for individuals with known genetic profiles. This information can then be used to formulate links between diet, genetics, metabolism, lifestyle, and health [74]. In principle, a diet can then be formulated that tailors to the particular nutritional requirements of each individual.

Functional foods and beverages formulated for personalized nutrition will therefore require particular combinations of nutrients, nutraceuticals, prebiotics, and probiotics [76-78]. These bioactive agents often require different kinds of delivery systems to disperse and stabilize them, as well as to ensure they are bioavailable. Some of the encapsulation systems mentioned in the previous section may therefore be required to formulate this type of food, either individually or in combination. For instance, hydrophobic vitamins (such as vitamin A, D, and E) or nutraceuticals (such as carotenoids or curcuminoids) may need to be encapsulated within hydrophobic colloidal particles (such as emulsions or nanoemulsions) to increase their dispersibility, stability, and bioavailability. All the hydrophobic bioactive substances may be packed into one type of delivery system, or it may be more advantageous to pack them into different delivery systems that are then combined together.

Food for the Elderly

There are major demographics changes occurring in many countries around the world. In particular, there is an increase in the fraction of the population that is elderly (66 or older) in many countries [79]. Older adults often have food and nutrition requirements that are different from younger people, which means that specially designed functional foods and beverages are required [79]. For instance, older adults often have problems with chewing and digestion, and so it is important to use structural design principles to create foods that can be chewed and digested more rapidly, while still maintaining their desirable quality attributes. There is often a reduction in flavor perception with age, and so it may be important to increase the levels of taste and aroma molecules within foods designed for the elderly, or to control the rate at which these molecules are released from the food matrix and reach the aroma and taste receptors. The elderly often have specific nutritional requirements, such as increased needs for bioavailable forms of calcium and protein to prevent bone or muscle loss. They are also more susceptible to chronic diseases such as diabetes, hypertension, heart disease, cancer, cognitive decline, and reduced eye health. Consequently, they may benefit from consuming foods that are fortified with nutraceuticals known to protect or treat these kinds of conditions. The level of physical activity often decreases with age, which means that the total daily calorie requirements are reduced. Consequently, there is a need for tasty and nutritious foods that have lower calorie densities. There is therefore considerable scope for the utilization of structural design principles to create a new generation of foods that target the specific needs of an aging population.

The Health of the Planet

The Problem

The United Nations predicts that the global population will continue to grow over the next few decades, reaching almost 10 billion by 2050. Moreover, people around the world are becoming wealthier and are moving from rural to urban environments, which is leading to a change in their dietary habits. In particular, many people are adopting a more Westernized diet, which contains a higher percentage of meat and other animal-based products. The production of foods using animals is usually less efficient than the production of foods directly from plants [2, 80]. Typically, there is more land use, water use, greenhouse gas production, and pollution associated with animal-based foods than plant-based ones[3]. Consequently, a major challenge of the modern food and agriculture industry is to produce enough high-quality food to feed everyone without irreversibly damaging our planet. This challenge will require considerable alterations in the types and quantities of foods people consume. To achieve this goal many food scientists are working to develop plant-based foods to replace animal-based ones (see later). In addition, the Food and Agriculture Organization (FAO) of the United Nations estimates that almost a third of the food currently produced is either lost or wasted during production, distribution, and utilization (www.fao.org). Effective strategies are therefore also needed to reduce this waste and to convert any waste streams that are created into valuable products [81].

Potential Food Design Approaches

In this section, a number of modern technologies that are being developed to address some of the problems associated with feeding a healthy diet to a growing global population are given as examples.

Genetic engineering

Genetic engineering involves designing the structure of foods at the molecular level – inside the nucleus of a cell. This technology has enormous potential to improve the future food supply, particularly newly developed methods such as CRISPR that enable more precise gene editing [82-84]. The genes of plants, animals, and microbes used to produce foods can be altered to increase yields, enhance resilience, reduce waste, and enhance nutritional profiles. A major hurdle to the use of this powerful technology is negative consumer perception [85], particularly in Europe, despite the fact that extensive studies have shown that approved genetically engineered foods do not promote significant environmental or health problems [86]. Nevertheless, there are an increasing number of genetically engineered foods being introduced into the market, particularly in the US [1]. From, a structural design point of view, an increased utilization of genetic engineering may lead to new or improved ingredients that can be used to construct foods. For instance, genetic engineering is being used to increase the level and modulate the fatty acid profile of the oils in soybeans and other commodity crops [87], which may require reformulations in the composition or structure of foods containing these ingredients. For instance, it may be necessary to utilize antioxidant strategies if the level of polyunsaturated fatty acids is increased.

Nanotechnology

Nanotechnology also has great potential to improve the future food supply by manipulating the structures of foods at a miniscule level [88, 89]. Indeed, it involves controlling the properties of materials at the nanoscale (typically 1-100 nm) to obtain improved or novel functional attributes. When the dimensions of materials are made very small they often behave in a way that is different from that of their conventional (larger) counterparts. Nanotechnology has been used to create nano-pesticides and nano-fertilizers that are more effective than the conventional versions [90]. The very small size of nanoparticles means that they can penetrate through plant-cell walls and into the interior of plants where they can have their beneficial effects. The availability of more effective pesticides and fertilizers could improve yields, reduce losses, and reduce pollution. Nanoparticles can also be used as tiny sensors to provide information about the health status or maturity of plants or the soil they are grow in[91]. In this case, the farmer would know precisely when to water, treat, or harvest plants, which could again improve efficiency and reduce waste. Nanofibers are being employed to create more effective water filters, which is linked to their high surface area and small pore size [1] These nano-filters may help to reduce pollution, minimize industrial waste, and generate more fresh water. Of course, it is important to ensure that any nanoparticles applied within food and agriculture are safe to the environment and to human health [92].

Artificial Intelligence, Robots, and Sensors

The efficiency of food production can be greatly increased by developing more detailed knowledge throughout the food chain (from farm to fork), as well as being able to rapidly act on this information [1]. Sensors are being developed that provide detailed information about the properties of foods and their environments. For instance, the health status and maturity of individual plants, as well as the soil they grow in, can be measured throughout their lifecycle allowing them to be treated with water, pesticides, and fertilizers only when needed, and allowing them to be cultivated at exactly the right time. This is in contrast to conventional methods where all the plants in a field are typically treated the same way, regardless of their individual health status or maturity. Sensors have also been developed to provide information about the environmental conditions that foods experience during their transport and storage (such as temperature, humidity, pressure, and mechanical forces), which enables these conditions to be optimized to reduce food waste and improve food quality. The information provided by these sensors is being integrated into comprehensive databases (such as "blockchain") to generate detailed information about the factors impacting food quality. Moreover, machine learning and artificial intelligence algorithms are being used to identify the major factors impacting product quality. Robots are being developed to plant, manage, cultivate, and process agricultural crops, thereby improving the efficiency of the process. Taken together these new technologies are enabling higher quality and more nutritious foods to be produced, while reducing waste, and decreasing energy costs associated with transport and storage.

Cellular Agriculture

Cellular agriculture is a rapidly advancing biotechnology that is being utilized to create more environmentally friendly and sustainable forms of food [93, 94]. Cultured meat, also known as clean meat, is being cultivated from animal cells within industrial bioreactors [95]. This form of meat has a number of advantages over conventional meat. It does not involve the rearing of animals for slaughter, thereby causing has less ethical problems. Moreover, cultured meat is more sustainable because it generates fewer greenhouse gases, causes less pollution, and uses less water and land than conventional meat [80, 96]. Typically, a few cells from a live animal are collected and then placed into a bioreactor that is operated under conditions (*e.g.,* nutrient levels, growth factors, oxygen, light, and temperature) that are optimized to encourage cell growth [97]. Under the right conditions, the cells form structures that can be collected and turned into meat-like products. Currently, most of the food companies working in this area are focusing on the development of processed meat products, like sausages, nuggets and burgers, because they are simpler to create than whole meats, such as beef steaks or turkey breasts. Because cultured meat is created from animal cells it has many of the same quality and nutritional attributes as conventional meat. A number of companies claim to be ready to bring these products to market in the near future.

Cellular agriculture can also be used to produce nutrient-rich edible microorganisms that are grown in fermentation tanks, including certain types of bacteria, algae, and fungi [98]. For instance, meat-like products are being created from a micro-fungus (*fusarium venenatum*) that grows into filamentous structures that resemble the fibrous structures found in animal tissue [99, 100]. Indeed, this microorganism is the basis of the meat-free products sold under the tradename Quorn™. A variety of other microorganisms are also being investigated for their potential to be consumed as alternative protein sources. Instead of being used as a nutrient source themselves, microorganisms are also being used to secrete food ingredients, which can then be incorporated into foods. As an example, specific microbial species (often yeast) are being utilized to generate egg, milk, and meat proteins [1, 94]. This process involves inserting a gene that produces the desired protein (*e.g.,* β-lactoglobulin) into the DNA of the microorganism [101]. During fermentation, the desired protein is expressed by the microorganism, which can then be collected and purified. These proteins can then be utilized as food ingredients to formulate food products. A number of food companies are already using this technology to produce milk, egg, and meat proteins. From a structural design perspective, the new proteins and other ingredients produced by these cellular agriculture techniques may be used as novel building blocks to create foods with new or improved properties. In future, it will be important that these processes can be economically scaled-up so that these novel ingredients become commercially viable. In addition, it will be important to test the safety of any new ingredients produced by these processes to ensure that they are safe for general consumption. In some cases, it will also be important to overcome negative consumer perceptions of genetically engineered foods.

Alternative Protein Sources

One of the most successful applications of structural design principles in the food industry recently has been the introduction of plant-based alternatives to meat and fish products. The plant-based burgers marketed by companies such as *Impossible Foods* and *Beyond Meat* are remarkable examples of successful food science and technology. These companies have managed to create plant-based products that look, feel, smell, taste, and even sound like beef burgers, which required a detailed understanding of food chemistry, physics, engineering, and sensory science. These products are already being sold in supermarkets, restaurants, and fast food stores. Life cycle analysis has shown that these products have a much lower impact on the environment than the equivalent animal-based products, including substantial decreases in greenhouse gas emissions, land use, water use, and pollution [102]. However, some of these products have similar or even worse nutritional profiles than real meat products. Consequently, more work is required to make plant-based products that taste good, are good for the environment, but are also good for our health. At present, most of the products are designed to simulate processed meat products, such as burgers, nuggets, and sausages since it is easier to mimic their properties. In the future, research will be required to develop a better understanding of how food composition and structure impact the physicochemical, sensory, and nutritional properties of meat products that are more difficult to simulate, such as beef steaks and chicken breasts. Structural design approaches can then be used to create plant-based alternatives that mimic their properties.

Other sources of protein are also being investigated for their potential to replace animal-based products in our diets [103, 104]. In particular, many edible insects are a valuable source of both macronutrients and micronutrients. Despite being consumed by over 2 billion people around the world already, many consumers in developed countries such as the USA and Europe find the idea of eating bugs disgusting. Consequently, it will be important for the food industry to create insect-based foods that look and taste good, and to educate consumers about their potential health and environmental benefits. The application of structural design principles will be essential in the formulation of good tasting foods from whole insects or specific insect components. For instance, it may be possible to use insects as a valuable source of functional food ingredients, such as emulsifiers, gelling agents, or thickeners.

Conclusions

Important technological innovations are being made that are transforming the way we produce and consume foods [1]. These innovations are being made by a diverse range of scientists who are using advanced technologies to address the serious food-related challenges facing modern society, including feeding a growing global population without damaging the planet, combating diet-related chronic diseases, and improving the safety, variety, and quality of foods available [2, 3]. During the past century, the food industry has been highly successful in producing a broad diversity of affordable and convenient high-quality foods, but they have often ignored the health and environmental impacts of their products. In future, it will be important to use the best of modern science and technology to address these issues. This will require traditional food scientists to think more creatively, as well as for scientists in other fields to bring their unique perspectives and expertise to bear on these important problems, such as biotechnologists, computer scientists, genetic engineers, nutritionists, nanotechnologists, medical professionals, and psychologists.

It will also be important that any new technologies are employed wisely. In particular, it is important to include all stakeholders in the food supply chain, including farmers, manufacturers, regulators, and consumers, in the development and implementation of these technologies. This will involve carefully considering the social, environmental, and economic issues associated with their application. In particular, the potential health and environmental impacts of a new generation of structurally designed foods should be carefully scrutinized on a case-by-case basis so as to ensure that they do not have any unintended consequences on individual or global health.

As stated in the beginning of this article, it is an exciting time to be a food scientist and there are many critical challenges that need to be addressed. Advances are being made in a broad range of diverse areas, including artificial intelligence, data analysis, robotics, genetics, biotechnology, nanotechnology, sensory science, and physiology, which are likely to dramatically change the way we produce, store, process, transport, and consume foods in the future.

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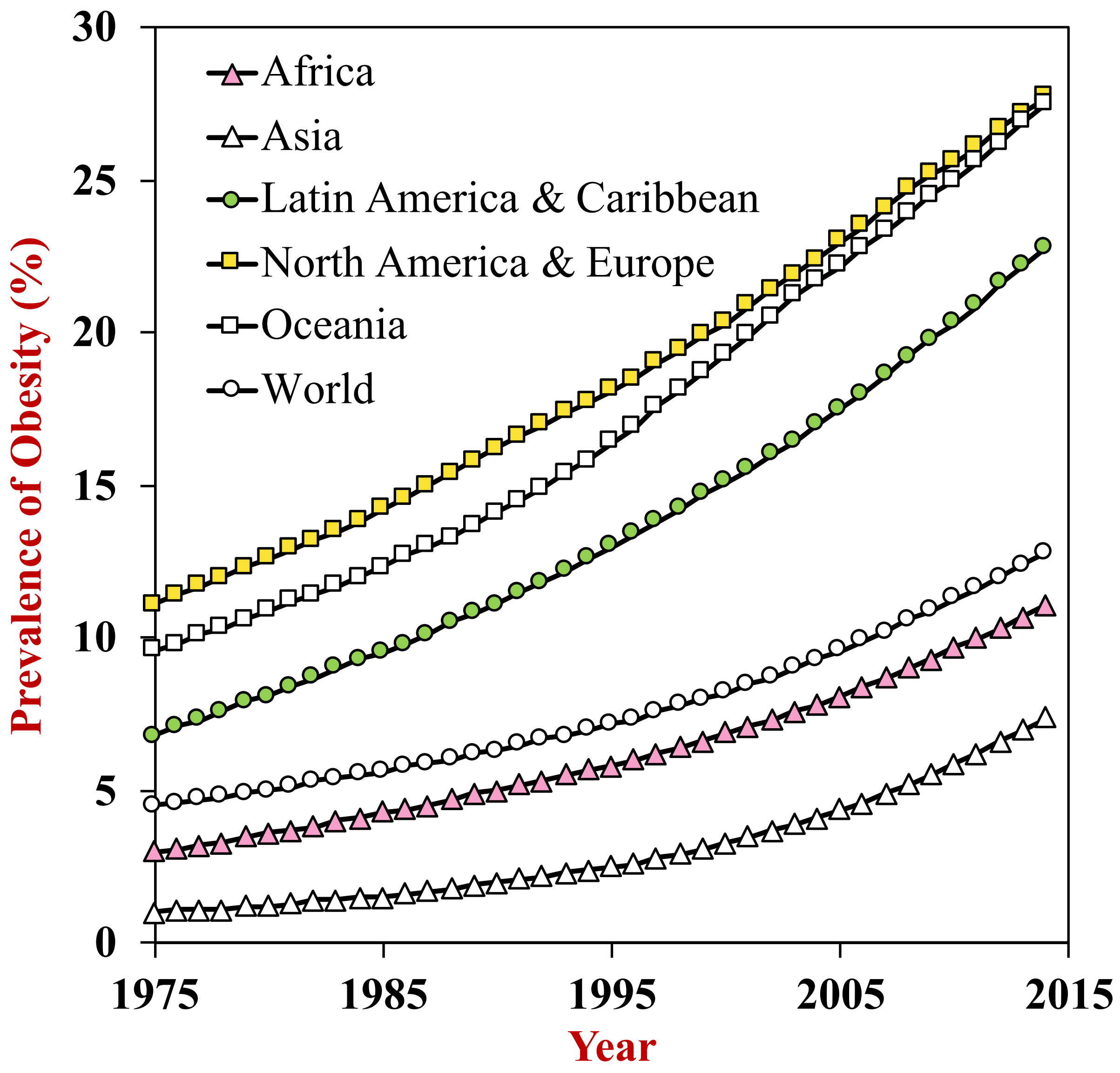


Figure 1. Prevalence of obesity in adults (18+ years old) as a percentage of population (FAO (2017)). Data taken from ourworldindata.org.

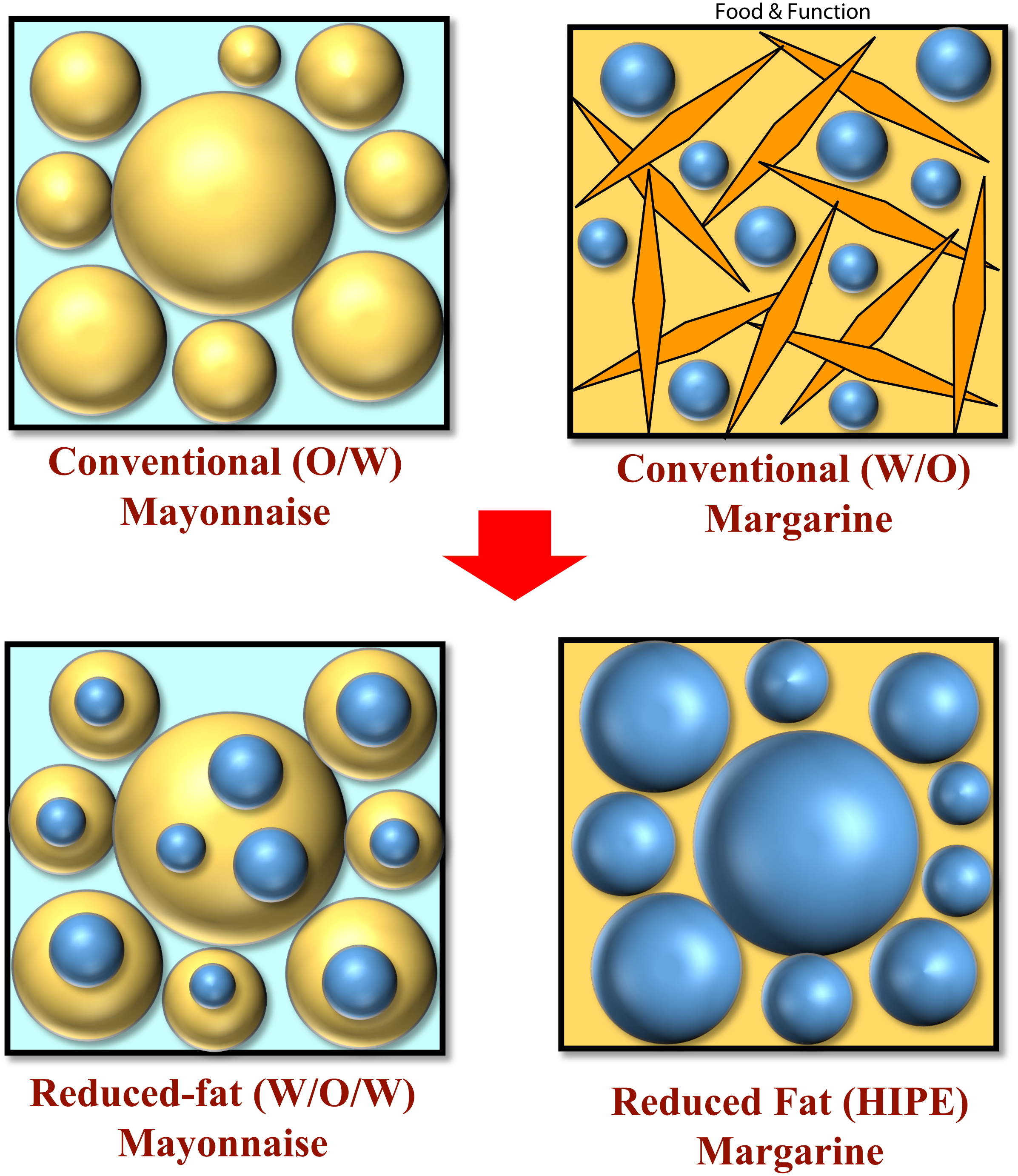


Figure 2. Schematic of conventional high-fat mayonnaise and margarine products and structurally designed reduced-fat versions.

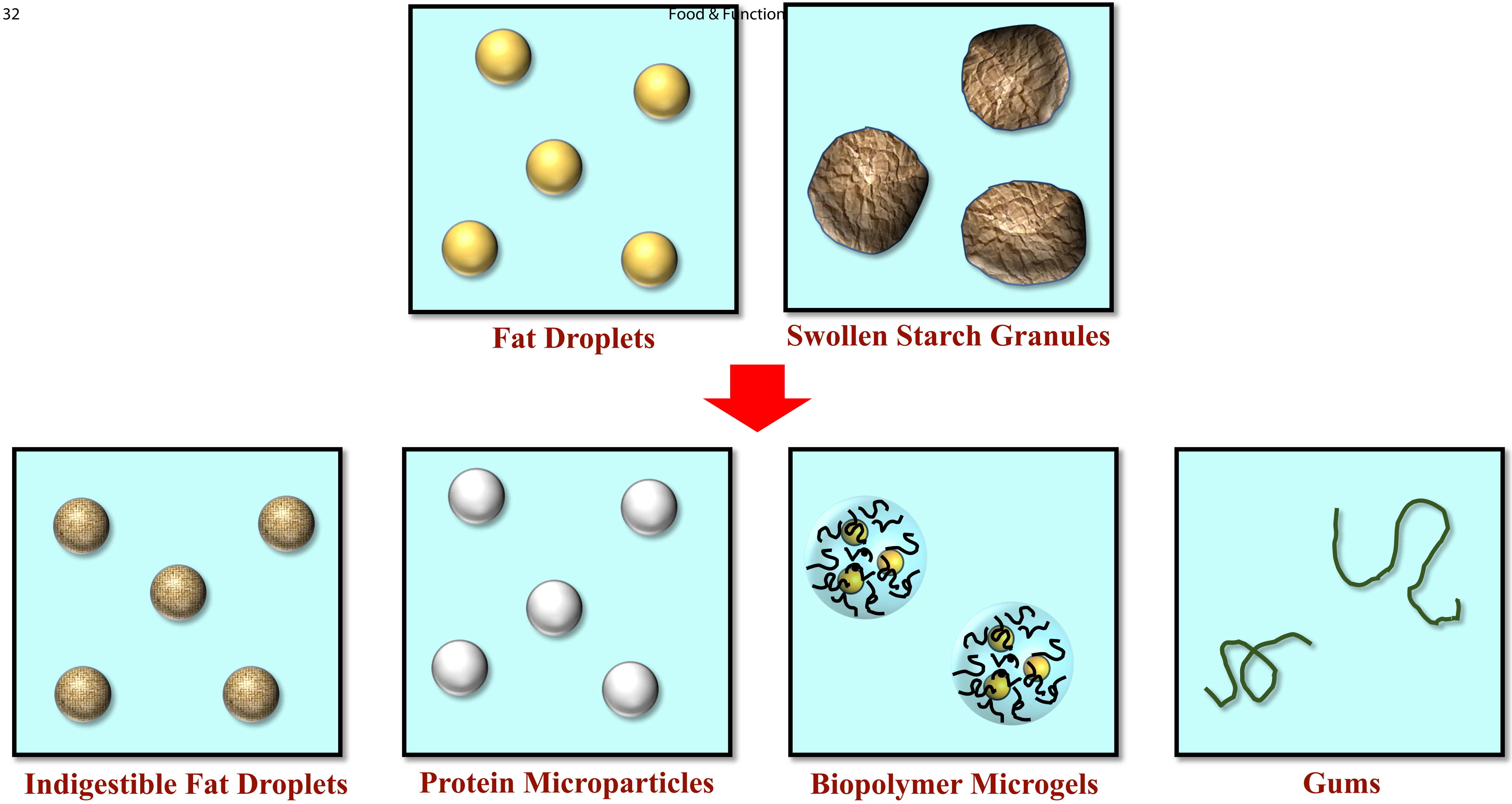


Figure 3. Schematic representation of fat droplets and starch granules and some of the strategies that can be used to mimic their properties in foods.

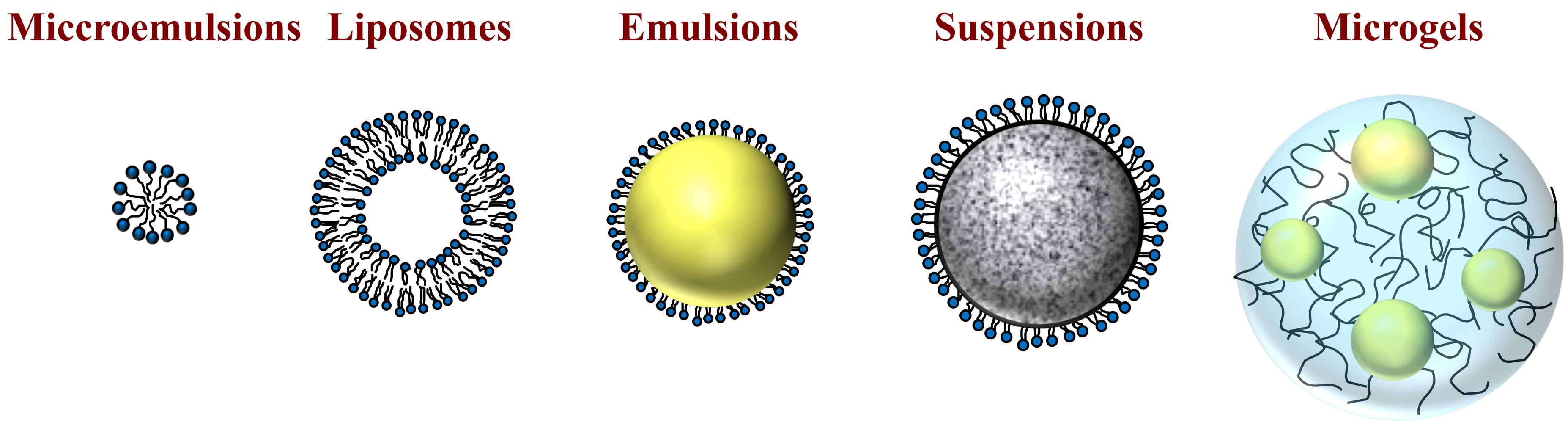


Figure 4: Examples of colloidal delivery systems that can be used to encapsulate, protect, and deliver nutraceuticals in foods and beverages. Emulsions contain fluid droplets, whereas suspensions contain solid particles.

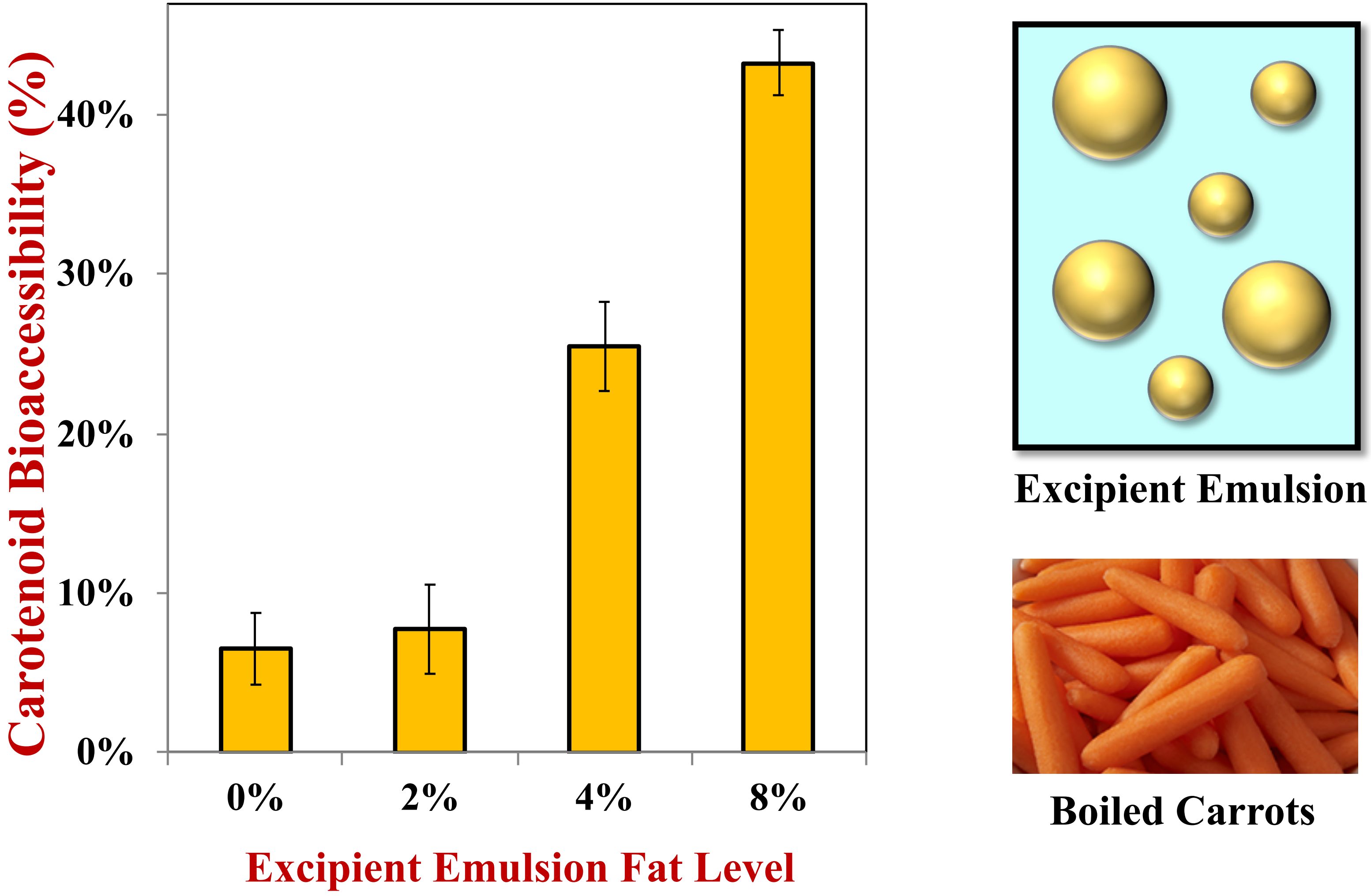
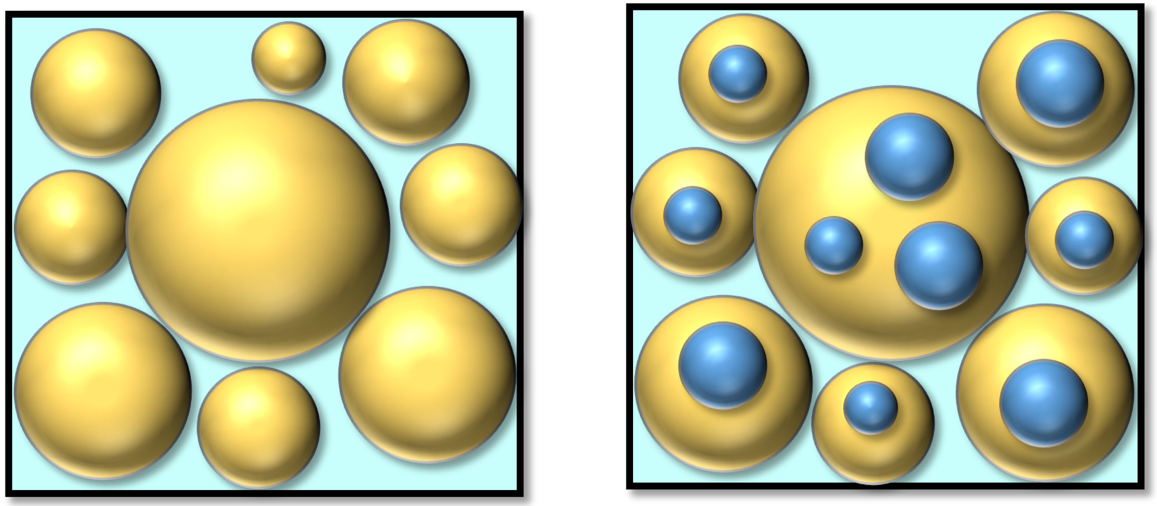


Figure 5: Carotenoid bioaccessibility (β-carotene) in boiled carrots is increased substantially when they are consumed with an excipient emulsion (From Zhang et al 2016).



Conventional (O/W) Mayonnaise

Reduced-fat (W/O/W) Mayonnaise