Food structure engineering for nutrition, health and wellness

Stefan F. M. Kaufmann\textsuperscript{a*}, Stefan Palzer\textsuperscript{b}

\textsuperscript{a}Nestlé Research Center, Nestec Ltd., Vers-chez-les-Blanc, P.O. Box 44, 1000 Lausanne 26, Switzerland
\textsuperscript{b}Nestlé Product Technology Centre for Confectionery, Nestec York Ltd., P.O. Box 204 / Haxby Road, York YO91 1XY, U.K.

Abstract

Many of today's food products addressing specific nutritional, health and wellness needs of human and animal consumers are often very complex structures. Consequently, it is of utmost importance in food engineering research to develop a detailed understanding of the time-dependent transient changes in all of the structural aspects of food matrices from raw material harvesting, to product processing, to the point of breakdown during shelf-life, consumption and final digestion. Food structural understanding and control needs to be mastered on a broad range of length scales including: the molecular, supra-molecular, micro- and macro-structural level. At the same time, the mechanical, physical and chemical properties of the food need to be considered. Only in this manner can a tailor-made build-up and controlled breakdown of food products be achieved, and subsequently, can specific nutritional, physical and sensorial properties be engineered. Reducing fat and sugar content in order to reduce the energy density of food requires a particular micro- and macro-structural design in order to compensate for resultant sensorial changes. Specific structures can improve the stability and bioavailability (ultimately bioefficacy) of bioactive compounds and probiotics. Improving the nutritional profile of food by increasing the overall content of (plant) proteins, dietary fibres or whole grains can be achieved by certain means of structuring. Specific health care products exhibiting a particular rheological behaviour at very high protein content, for example, can only be realised by targeted modification of their supra-molecular structure. Finally, food microstructures can be designed in such a way that their modulated digestion behaviour triggers different physiological responses.

1. Introduction

Their exists an increasing demand by global consumers for healthier and more nutritious food products that are both addressing specific health needs and sustainably produced according to high ethical standards.
standards. As for many consumers, healthy eating is linked to natural products and a growing demand for these products is observed, particularly in Europe and North America. In order to improve the quality of lives of consumers in developing countries, highly nutritious products are needed that are relevant and that can be offered at an affordable price. It goes without saying, that pleasure should – of course – never be compromised. Food, unlike supplements and pharmaceutical products, is not only consumed for nourishment or specific health purposes, but also for the enjoyment of its taste, flavour, texture and colour.

Depending on the product category and the targeted consumer health concerns, certain nutritional, health and wellness aspects can be linked to different product attributes like low energy density, high content of whole grains / fibres and proteins, or the addition of micronutrients and bioactive compounds. However, the corresponding products often show sensorial defects or a limited physical and/or chemical stability compared to the “standard” products. Some of these issues can be solved by an appropriate design of the matrix structure of the targeted food product. However, it must always be ensured that the composition and processing of foods are carefully balanced to ensure the optimal nutritional properties [1].

Parallel to the structural design, the future oral breakdown of foods must be taken into account. Texture results from a dynamic process in which texture attributes are continuously analysed by the oral sensory system during mastication. It can be shown that for each food a so-called “texture pathway” can be built based on the dynamics of texture perception during food consumption [2].

Finally, the digestion behaviour of food structures can be modulated, and thus, different physiological responses can be triggered.

2. Designing complex food structures with tailored properties

2.1. Energy density / salt reduction

In order to address severe global public health concerns like obesity (overnutrition), the reduction of the volumetric energy density of a targeted food product can be achieved by either increasing its air and water content or by decreasing its sugar and fat content.

Air or other gases dispersed in the form of small bubbles act as structural elements in many liquid, semi-liquid and solid foods including: ready-to-drink beverages, mousses and other chilled or frozen desserts, chocolate and extruded breakfast cereals. Gelatin gels, for example, may be aerated applying ultrasound. This dispersed air provides an additional phase within gel-type foods and potentially accommodates new textural and functional demands [3].

An increasing amount of water can be bound in a food matrix through emulsion or gel structuring. Water-in-oil-in-water (W/O/W) double emulsions show much potential in the formulation of fat-reduced products such as mayonnaise or dressings. Food biopolymers like proteins and polysaccharides have been successfully incorporated into the internal and external aqueous phases of this type of double emulsions in order to improve the stability and yield of model systems [4].

Such disperse systems need to be effectively stabilized by surface active molecules like biopolymers (e.g. proteins) or by solid particles situated at the interface. Today, relatively little research is directed at answering the question about what happens when both surface active polymers and particles are present together [5].

In order to compensate for sensorial changes a particular micro- and macro-structural design is required. The structure of emulsions and foams needs to be adapted in such a way that the final rheological properties (mainly responsible for the mouthfeel) and the release characteristics of flavours match the original product.
When reducing the sugar content of products, their perceived sweetness can be replaced by natural non-caloric sweeteners. For instance, steviol glycoside extracts (i.e., from the leaves of Stevia rebaudiana) are approximately 350 times sweeter than sugar and have become more and more available as a natural and healthy sugar alternative. The physicochemical impact of sugar in products, however, needs to be replaced by a combination of bulking agents to compensate for the loss in matrix structure (or simply volume). This complex task involves the detailed understanding of each bulking agent’s contribution to the structure build-up and the related impact on certain sensorial properties.

Low temperature frozen low-fat ice cream is an example of an energy-density-reduced food in which the combination of a significant change in the recipe (decreased fat content; adjusted stabilisation) and an additional processing step (twin screw extrusion) leads to a texture that is perceived to be creamier compared to an ice cream produced conventionally (see Figure 1). The additional high shear forces (i.e., exceeding the ones in conventional scraped surface heat exchangers by approximately 3 orders of magnitude) applied to the complex multiphase system of ice cream result in a reduction of air bubble and ice crystal sizes while increasing the functionality of the destabilised fat droplets [6]. The enhanced fat destabilisation, which is increased dependant on the type of emulsifiers used, is promoting the fat structuring and thus ultimately improving the overall stability and the meltdown behaviour [7].

Fig. 1. Generation of microstructure for fat-reduced ice cream. Reprinted from [10] with permission from Elsevier.
That these structural changes have a significant impact on quality characteristics can be proven by the measurement of the rheological properties of the product. Sensorial studies have demonstrated, for example, a close correlation between loss moduli $G''$ measured in an oscillatory thermo-rheometry test and typical quality parameters like scoop ability and creaminess [8].

Another potential way to provide fat-reduced textures is the use of microparticulated proteins or hydrocolloid structures that mimic full-fat food properties.

Further ideas about engineering approaches to fight obesity are summarised in [9].

Similar to sugar and fat, elevated salt intake is a major concern for public health authorities and its reduction has become a major initiative within the packaged food industry in recent years. Salt release and perception is very much influenced by changes in the food matrix. A recent study provided evidence for the important role of structure and texture on salt mobility and perception, but also the interaction between fat and salt in model dairy products [11]. In addition to these concerns, it must not be forgotten that a reduced salt content can also heavily influence food preservation and thus food safety, which is beyond the scope of this review.

2.2. Stabilisation and bioavailability of bioactive compounds / encapsulation of aroma compounds

Enriching food products with vitamins, minerals or bioactive plant compounds requires the homogeneous dispersion or dissolution of the active substances in their respective food matrix. Furthermore, their active constituents have to be stabilised as they are often susceptible to oxidation and/or other degradative reactions. Generally, bioactives need to be protected against oxygen and light as well as being physically separated from potential reaction partners such as iron. Further, uncontrolled release or reduced bioavailability must be prevented.

Several encapsulation systems based on protective carbohydrate structures for the dissolution and stabilisation of such substances in solid matrices are available and generally well mastered [10]. A far more challenging task is the targeted delivery of active ingredients in a fluid aqueous phase [11]. A major issue are the different solubility characteristics exhibited by the bioactive molecules in different matrices. Additionally, encapsulation techniques for hydrophilic components differ considerably from systems targeting the delivery of lipophilic components. Figure 2 shows some encapsulation / delivery systems for hydrophilic and lipophilic bioactive molecules and micronutrients developed by the food industry and suppliers.

Food industry can benefit from the pharmaceutical industry in regards to the selection of appropriate delivery systems and strategies for the inclusion of bioactives in food products. The molecular dispersion of a drug, just as a bioactive compound used in food, is a prerequisite for its absorption across biological membranes. After eating (i.e., “oral administration” in pharmaceutical terms), this dictates, that the active substance must first dissolve within the gastrointestinal tract before partitioning into and then across the enterocyte [12]. Colloidal structures that may even be formed during the digestive process (like in the case of lipids) have the potential to prevent precipitation and enhance absorption. Enhancing solubilisation in the intestinal milieu is one way to enhance the bioavailability of bioactives with poor water solubility.
Encapsulation techniques can also be used to prevent the loss of aroma compounds that can affect flavour intensity, and thus, positively impact food quality and perception. Therefore, the physicochemical characteristics of volatile compounds and their interaction with the food matrix need to be considered. As an example, the encapsulation of bioactive compounds with edible films not only allows for the control of flavour loss, but also is a technique for controlled flavour release of aroma compounds with time [13]. This controlled-release effect can be used to either maintain a certain quality of the food product over shelf-life and consumption or to provide a special flavour experience for the consumer (e.g. a flavour burst upon chewing the food).

2.3. Improved nutritional profile / nutritional application addressing special healthcare needs

Improving the general nutritional profile of food can be achieved by increasing the overall content of (plant) proteins, dietary fibres or whole grains; however, the inclusion of these types of ingredients often requires specific ways of food structuring and consequently, the adjustment of process conditions during food production.

The consumption of whole grain cereals, fruits and vegetables, for example, represents the most common and natural source of dietary fibres. Unfortunately, whole grain derived fibres are the most difficult to incorporate into products without compromising on the final texture and taste of the product [14]. A typical example is the negative effect of the incorporation of wheat bran in extruded cereal products. The addition of bran significantly changes the physicochemical properties of the starch like the glass transition temperature, melting temperature and sorption isotherm. As a consequence of these changes, expansion properties are considerably reduced [15]. A study focussing on the influence of wholegrain flours from different origins (wheat, rye, triticale, barley, tritordeum) on the production of cakes showed similar results and found significant correlations between water absorption and specific volume, symmetry and firmness [16].

Food structures composed of natural, and thus, less purified raw materials are often physically and chemically less stable. Nevertheless, their stability can also be improved by means of structuring. Protective layers can be applied [17], natural stabilising components can be added to the recipes and the supramolecular structure of single ingredients can be changed through physical processing.

Increasing the protein content of foods is normally accompanied by a rise in viscosity. Conversely, the controlled unfolding and aggregation of protein macromolecules can be used for targeted structuring that can lead to a reduction of this negative effect. Depending on the pH, temperature and the presence of ions,
the macromolecular proteins can adopt different shapes and structures such as fibrils, spherical micro-gels, micro-particles, and fractal aggregates of gels [18]. Another example of how mixtures of whey protein micro-gels and soluble aggregates can be used as building blocks to control rheology and structure can be found in [19]. [20] reviews the use of β-lactoglobulin and whey protein isolate aggregates in cold-set gels, foams and emulsions as key structuring elements.

In most cases, the quality of food is defined by sensorial characteristics and consumer-driven preference. Then again, there are also nutritional applications addressing specific health care needs. Patients suffering from neurogenic dysphagia, the medical term for the symptom of difficulty in swallowing, are known to be at high risk of respiratory and nutritional complications. Increasing the bolus viscosity greatly improves the swallowing function [21]. Quality of life can be tremendously improved, if the flow behaviour of normal foods can be modified by adding certain viscosity-modifying supplements. This requires profound understanding of the swallowing process (e.g. controlling mechanisms, determination criteria of bolus swallowing) as well as rheological understanding of individual ingredients and their relation to the “food processing” in the mouth [22, 23]. Health care products that are normally very nutrient dense and / or exhibit a particular rheological behaviour during manufacturing and/or consumption can only be designed by targeted modification of their supra-molecular structure.

2.4. Modulated digestion

Finally, food microstructures can be designed in such a way that their modulated digestion behaviour triggers different physiological responses – a research area that is getting more and more attention within the food industry as in vitro models become more sophisticated.

Proteins are reported to be the most satiating of all macronutrients, but not all proteins are alike. Some are digested and absorbed rapidly, while others may impact metabolism and glucose control. [24] compares, for example, the effects of various protein sources (whey, casein, soy) on energy metabolism, satiety and glucose control in humans. It was shown that protein-rich meals promote greater energy expenditure than carbohydrate-rich meals of equal caloric content. These findings confirm the assumption that increased protein content in the diet can promote weight control. Colloidal interactions (like those with proteolytic enzymes and physiological surfactants in the gastrointestinal tract) play a key role in protein digestion and need to be well understood in order to produce food with optimum nutrition for the consumer [25].

The nutritional quality of starch strongly depends on the processing and the physicochemical state of the starch. Slowly digestible starch (SDS), such as native maize starch, offers the advantage of a slow increase in postprandial blood glucose levels and sustained blood glucose levels over time when compared to rapidly digestible starch with its fast increase, peak and subsequent decline [26]. This more constant supply of energy during digestion might influence satiety, physical and mental performance and can have implications for diabetes management [27].

The ability to regulate lipid uptake is seen as beneficial in several areas like improved nutrition, especially for young and elderly, or the reduction of disease risk. Emulsions systems with increased structural complexity are seen as a mechanism by which lipid uptake may be controlled [28, 29]. As already mentioned in [12], lipid digestion and the resulting colloidal structures can be designed to elicit particular physiological properties such as the targeted delivery of bioactives.

3. Conclusion

Most food products are structurally complex. It can be concluded that during the development of products addressing specific nutritional, health and wellness needs, the structure of the food matrix, and consequently, product processing needs to be adapted. A detailed understanding of the time-dependent transient changes in all of the structural aspects of food matrices from raw material harvesting, to product
processing, to the point of breakdown during shelf-life, consumption and final digestion needs to be developed. Furthermore, at each point in time within this cycle there exists a broad range of length scales ranging from the molecular, supra-molecular, to the micro- and macro-structural level determining the mechanical, physical and chemical properties of food structures. Only in this manner a tailor-made build-up and controlled breakdown of food products can be achieved, and the specific nutritional, physical and sensorial properties engineered.

Examples given in this review showed that a targeted structuring of processed food can partially compensate for the elimination of fat and sugar from foods (i.e., in turn addressing overnutrition) or to enable a higher content of ingredients with an improved nutritional profile (e.g. whole grains / dietary fibres or high nutrient dense foods addressing moderate undernutrition). Furthermore, structuring of the food matrix is an important tool to improve the stability of healthier formulations and the bioavailability of bioactive compounds. Finally, food microstructures can be designed in such a way that their modulated digestion behaviour triggers different physiological responses.

References


Presented at ICEF11 (May 22-26, 2011 – Athens, Greece) as paper FPE323.