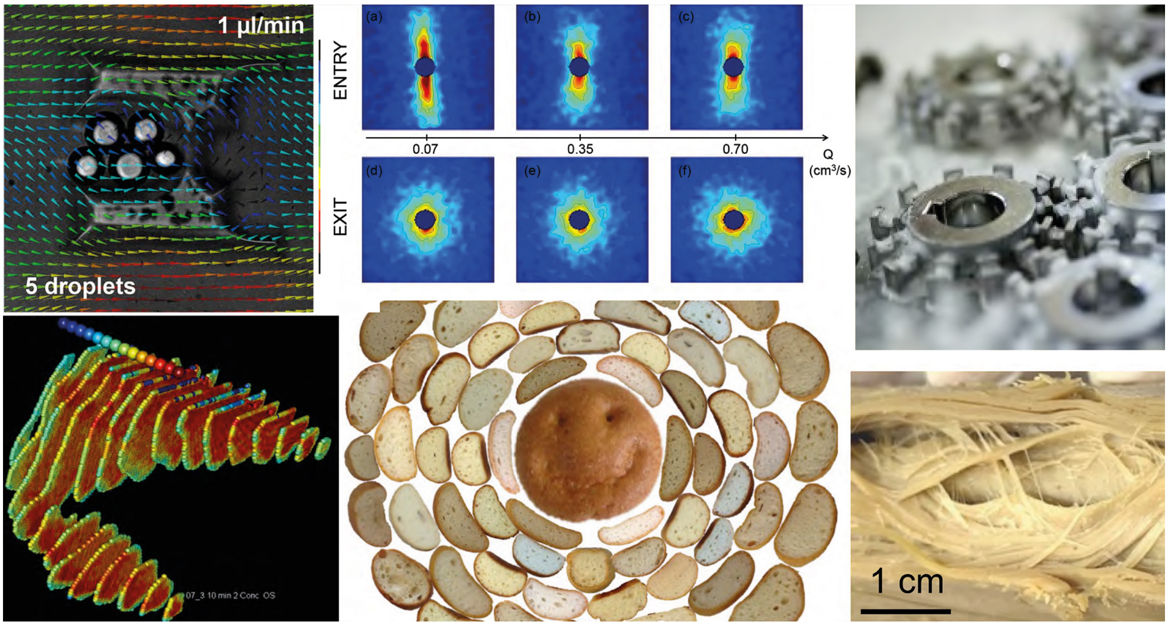

◂ FIG. 1: Clockwise from the top left: Microfluidic digestion chip with flow field, small-angle neutron scattering images of oriented fibers, rotor-stator mixing geometries, fiber structure of meat analogues, gluten-free bread made from different pulses, magnetic resonance image of emulsion creaming in human stomach (All image by the corresponding author and coworkers).

EDIBLE SOFT MATTER

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Food is essential to life but also sees a catalog of demands which include feeding mankind without damaging the planet, tackling the rise of diet-related diseases, and providing tasty, healthy and nutritious foods. Understanding, designing and producing innovative food requires a fundamental knowledge of the functional properties of raw food materials and how these food ingredients interact to form complex multiscale, multicomponent materials. Here we show how soft matter science can be applied to edible materials and thus guide food design and production.

Origin of the food that we eat today

Food has accompanied mankind since our species first emerged, and came along initially in the form of whole fruits, grains, vegetables as well as meat, fish and eggs. Food was eaten raw and as a first processing step beyond cutting, cooking was introduced approximately 700'000 years ago [1]. Over time naturally occurring fermentation was domesticated and grinding and later milling were most probably the first food processing unit operations [2]. All these processes change the nutrient profile and/or the accessibility of nutrients by a controlled breakdown of the native food structure that might only partly be digestible by the human body [3,4]. Mankind has long been able to generate food products that do not exist in nature, *e.g.* bread, by simple processing steps. These processing steps also allowed mankind to separate farming and food production so that larger communities could be fed and the development of cities and states were fostered.

It took until the end of the 19th century to recognize that the overall appearance of the diverse forms of food is caused by only three main building blocks, so-called macronutrients, which compose all food: proteins, carbohydrates (sugars, polysaccharides), and fats and oils. Minerals and trace elements may be embedded already in the macronutrients (*e.g.* sulfur in proteins) or are part of the entire food matrix (*e.g.* flavor molecules, enzymes, and other chemical compounds). With proteins, carbohydrates, and fats as main ingredients, food ●●●

● ● ● manufacturing and food industries had their own 'Lego® bricks' to compose new food that nature was not providing. Along with improved preservation methods and large-scale farming securing a supply chain of standardized food raw materials, a huge number of processed foods became available in the first half of the 20th century. However, these food products still adhere to the composition of the original food, but manufacturers realized that further processing was possible. For example, the main ingredient of an apple are polysaccharides and sugars. Processed apple sauce, perceived by some as somewhat too sour, could to be sweetened by adding sugar, a macronutrient already present in the raw apple. Similarly, canned condensed milk or yoghurt can be thickened or otherwise structured by the addition of milk protein powder, a macronutrient already presents in raw milk. In this way, food was composed and preserved by adding or removing the three main building blocks without manipulating the overall 'recipe' of the raw material.

Macronutrient-based food manufacturing and processing used the same unit operations (milling, sieving, mixing, kneading, aeration, …) as used in domestic kitchens. The colloidal and soft matter approach was not utilized in this 'unit operations' perspective, *i.e.* molecular interaction, aggregation, phase separation at length scales below typically 1 μm was not considered in food production. This approach drastically changed in the mid 1970's when, driven by societal and industrial trends as well as general concerns on food safety and food security for an increasing population, the Federal Drug and Food Administration allowed manufacturers to go beyond the classical macronutrient-based food design concept, especially to add ingredients that were not part of the original recipe [5]. Yoghurt is an almost perfect example as milk fat could be removed to achieve a low-fat product and on the other hand polysaccharides were added to compensate for the rheology, structure, and mouthfeel of the missing milk fat. Polysaccharides such as guar gum, locust bean gum, or starch are not part of the original yoghurt recipe, which only uses milk and specific bacteria. This means that any food ingredient can be used to design food with specific properties or to fortify a food matrix with micronutrients such as minerals, vitamins, flavonoids or omega-3 fatty acids to enhance nutrition and health benefits. As a result, the food industry now uses ingredients that we do not find in our kitchens.

Food becomes edible soft matter

By eliminating the borders between the macronutrients and introducing micronutrients, not only the food industry received a whole new set of 'Lego® bricks', but also food colloids and edible soft matter science was born. Here the analogies of the building block for food and soft matter, *e.g.* for polymers and polysaccharides, colloidal particles and globular proteins, or surfactants and lipids opened an entirely new view on food [6 - 8]. This view into the soft matter domain became necessary to understand colloidal interaction leading to aggregation, phase separation, and depletion, which in turn determine the stability and structure and thus taste, mouth feel and nutritional profile of the novel food we eat. For example, the interaction of charged polysaccharides like pectin or carrageenan with protein determine the stability of "Ready-To-Drink" cacao or low-fat milk-based products. However, the edible soft matter approach comes with challenges. Food is a multi-scale, multi-component, multi-aggregated material and food scientists must deal with this complexity in a holistic way, *e.g.* by taking into account interactions amongst several ingredients [9]. In addition, some ingredients are complex by nature, such as acacia gum, a highly ramified polysaccharide, or gluten, a highly polydisperse protein mixtures comprising giant aggregates.

Physiological guided food design

Almost all food we eat can be viewed as a storage container full of nutrients, dietary fibers, and flavors. This can be an apple or egg picked or collected in the wild or a loaf of bread, cheese, or meat alternative manufactured by various man-made processes. Here, colloidal and soft matter laws are used to design food structures, first for preservation and storage and, second for releasing the nutritional compounds when breaking the structure, *i.e.* eating and digesting the food. Food only becomes food when we break down the storage structure. One example for an evolutionary developed storage container serving a clear-cut physiological purpose is breast milk. Milk can be viewed as a food colloid evolved to deliver nutrients (fats, sugars and whey proteins) and act as reservoir for the controlled release of calcium. In the gastric environment the fat globules, milk sugars and whey proteins are rapidly digested by gastric juices while the second fraction of the milk proteins, caseins, coagulate enzymatically in the stomach, which prolongs their digestion time, thus enabling casein to act as a storage container for calcium. Calcium is used primarily for bone growth and cannot be taken up rapidly in the gastro-intestinal track. The controlled release of calcium from the slowly digested casein gel now guarantees a match of release and uptake rate. This perfect storage and delivery system acts as a physiological guided design proposal for edible soft matter made from alternative raw materials.

Advanced techniques for food science and engineering

Techniques that allow the study of the structure and dynamics of food materials and processes are usually not specific to food systems. However, within the full gamut of soft matter techniques, a range of them was found to be of particular benefit such as confocal microscopy, Diffusing Wave Spectroscopy (DWS), Atomic Force microscopy (AFM), tomography, rheology and microfluidics. Confocal microscopy is used to visualize complex structural evolution in food systems such as protein dispersions and how those structures change under the application of a flow using a rheo-confocal set-up. X-ray tomography is now widely used to image systems in three dimensions and under transient conditions as during bread baking. DWS is an extension of classical dynamic light scattering to sufficiently turbid media such as emulsions and other colloidal dispersions. The same formalism is used in microrheology to retrieve the rheological properties of a food system. AFM gives access to insights into the question of the colloidal forces ensuring lubricated flow in concentrated dispersions such as chocolate or can probe interactions between droplets and bubbles. Bulk rheology, interfacial rheology as well as tribology contribute to the understanding of flow structuring, emulsion stability and food saliva interaction. Microfluidic methods benefit from very rapid development in food sciences since the early 2000, allowing the study of the formation of complex food structures under well-controlled conditions *e.g.* for nutrient encapsulation purposes, the adsorption of surface stabilizing structures under flow, or the stability of interfaces or the controlled swelling of double-emulsions designed for low-fat mayonnaise texture control. However, major challenges exist for experimental characterization of edible soft matter: (i) Heterogeneities in structure and dynamics for which more advanced approaches are developed to investigate them *e.g.* by space-resolved DLS or scanning SAXS, (ii) Sample environment to cope with pressure and humidity but also to address physiological environment during food uptake and digestion, and (iii) Techniques to study fast structural changes in *e.g.* rheology.

Current areas of focus

Protein transition

Food production contributes significantly to the greenhouse gases emission [10, 11]. Moving away from animal-based proteins to plant-based proteins is one major approach to reduce the environmental burden of the food and agriculture sector. The protein transition is challenging as most food products and production methods are based on water-soluble animal-based proteins, while plant proteins are only partially water-soluble. This is a food scientist's dilemma but also constitutes a chance for the edible soft matter approach to adapt processes and products with non-water-soluble plant proteins. The clear goal is to deliver the same functionality in 'green' plant-based products as in classical products.

Acknowledging the complexity

Traditional foods, even if they have undergone processing, have a rather short ingredients list. Moving food production from kitchen to industrial level along with increasing shelf life and safety requirements partly ballooned the number of ingredients and processing steps demanding standardization of the raw materials. Designing robust production methods acknowledging the complexity of food raw materials and their colloidal interactions, could facilitate wholesome ingredients-based foods and more sustainable processing approaches.

Texture and Perception

Texture as well as human sensory perception can be understood as a complex interplay between the multiscale structural and mechanical properties of a food product. Linking food structure and perception is a quite "old" problem introduced with the concept of psychorheology, which links instrumental to sensory data such as mouthfeel, creaminess, chewiness, or richness [12]. Soft matter science is undoubtedly the best adapted scientific field to unveil this interplay but also to tailor the intricate structure-function relationship in foods.

Ultra-processed foods

There is much current concern about the link between health and ultra-processed foods that include many ingredients not found in the traditional kitchen. The soft matter approach has contributed significantly to the growth of such foods. If their link to negative public health outcomes is confirmed, soft matter science should also have a key role to play in shortening the ingredients list (using fewer 'Lego blocks') and in designing healthier textures that, *e.g.* encourage 'slow eating'. ■

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