Food Eng Rev (2016) 8:91–115
DOI 10.1007/s12393-015-9125-z

REVIEW ARTICLE

Food Engineering at Multiple Scales: Case Studies, Challenges and the Future—A European Perspective

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Received: 23 October 2014 / Accepted: 26 May 2015 / Published online: 3 June 2015

Abstract A selection of Food Engineering research including food structure engineering, novel emulsification processes, liquid and dry fractionation, Food Engineering challenges and research with comments on European Food Engineering education is covered. Food structure engineering is discussed by using structure formation in freezing and dehydration processes as examples for mixing of water as powder and encapsulation and protection of sensitive active components. Furthermore, a strength parameter is defined for the quantification of material properties in dehydration and storage. Methods to produce uniform emulsion droplets in membrane emulsification are presented as well as the use of whey protein fibrils in layer-by-layer interface engineering for encapsulates. Emulsion particles may also be produced to act as multiple reactors for food applications. Future Food Engineering must provide solutions for sustainable food systems and provide technologies allowing energy and water efficiency as well as waste recycling. Dry fractionation provides a novel solution for an energy and water saving separation process applicable to protein purification. Magnetic separation of particles advances protein recovery from wastewater streams. Food Engineering research is moving toward manufacturing of tailor-made foods, sustainable use of resources and research at disciplinary interfaces. Modern food engineers contribute to innovations in food processing methods and utilization of structure–property relationships and reverse engineering principles for systematic use of information of consumer needs to process innovation. Food structure engineering, emulsion engineering, micro- and nanotechnologies, and sustainability of food processing are examples of significant areas of Food Engineering research and innovation. These areas will contribute to future Food Engineering and novel food processes to be adapted by the

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food industry, including process and product development to achieve improvements in public health and quality of life. Food Engineering skills and real industry problem solving as part of academic programs must show increasing visibility besides emphasized training in communication and other soft skills.

Keywords Food Engineering · Emulsion engineering · Dehydration · Fractionation · Membrane separation · Novel processing · Education · Sustainability

Introduction

Food Engineering, as reviewed by Heldman and Lund [1] and Brady and Labuza [2], has made significant contributions to food manufacturing and preservation which have enabled the modern supply of high-quality, nutritious and safe foods. The development of industrial food manufacturing required a deep and systematic understanding of microbial growth in foods and recognition of the importance of thermal kinetics in thermal processing to food safety. Furthermore, food engineers developed systematic methods for the innovative use of pH, temperature and water activity, a_w, to control and reduce food spoilage. Food Engineering, including engineering of manufacturing processes and food packaging, use of raw materials, formulation of food products and enhanced shelf life of foods, has provided the industry with understanding of the development needs of foods that have met consumer expectations of quality and convenience [1, 2].

Among many definitions of Food Engineering [1], the European Academy of Food Engineering (EAFE) defines that "Food Engineering covers the study, modeling and design of ingredients and foods at all scales using technological innovations and engineering principles in the development, manufacturing, use and understanding of existing and emerging food processes, food packaging and food materials from food production to digestion and satiation enabling development and design, production, and availability of sustainable, safe, nutritious, healthy, appealing and affordable supply of high-quality ingredients and foods." A shorter definition of modern Food Engineering is also considered as *Science, Innovation, and Engineering for Diet and Well-Being*. The EAFE was established as a subgroup of the European Federation of Food Science and Technology (EFFoST) in 2012. EAFE was established to form a Collegium of Food Engineers and Technologists for effective networking and advancement of education, research and publicity of Food Engineering and technology in Europe. EAFE emphasizes the role of Food Engineering in food safety and supply, nutrition, diet and public health as the often forgotten but underpinning discipline for innovations, production and availability of a safe and healthy supply of foods.

The modern food supply relies largely on sophisticated food production and traceability, innovations in food formulation, processing, packaging, storage and distribution which guarantee quality and safety and ultimately the delivery of nutrients for human health and well-being. There is a wide and multidisciplinary global Food Engineering landscape contributing to the future food supply for the rapidly increasing global population. Important developments and innovations include thermal and nonthermal processing technologies that provide food safety with minimal changes in food quality and adaptation of innovative emulsification and food structuring processes that use materials science principles in process and product development [3]. Food materials science and structure–property relationships have become important areas in the overall understanding of food freezing [4] and emulsification technologies as well as food solids behavior in dehydration and food powders [5, 6]. On the other hand, significant developments and solutions are introduced to more sustainable food production and processing, energy saving and waste reduction.

The first section of this review discusses structure–property relationships and novel emulsification and fractionation processes. The formulation and structure engineering are discussed in relation to dehydration, while emulsion engineering and the production of emulsified systems with nanoscale dispersed components are shown to provide an opportunity to manufacture complex stabilization and delivery systems for bioactive components or to use single particles as individual "nanoreactors" to reduce temperature and concentration gradients. Emulsions with monodispersed particles can be produced using a microchip known as edge-based droplet generation (EDGE) emulsification method [7, 8]. The EDGE technology and use of protein fibrils to produce layer-by-layer droplet interfaces are introduced as novel approaches to produce monodispersed stable particles. A modification of the cross-flow conditions for membrane processes is also introduced to reduce concentration polarization and allow fractionation of particles in microfiltration [9, 10]. The second section of this review covers an overview of energy and water use in the food industry and the possibilities of new technologies and processes for achieving a more sustainable food production system. Concentrated and dry fractionation technologies are discussed to reduce water and energy uses in separation processes. Subsequently, other important academic contributions and future needs of Food Engineering are analyzed, and finally, an overview of Food Engineering education is provided.

Food Structure and Particles

Food Structure Engineering

Food structure engineering can be defined as innovative and intelligent formulation, processing and use of food materials aiming at the applications of knowledge and understanding of food systems to enhance their physicochemical or microbial stability, processability, sensory performance and nutrient delivery. Such principles can be schematically expressed by process–structure–property relationships, which indicate the interplay of the areas of (i) process engineering typically addressing the description of process–structure functions and (ii) materials science specifically considering structure–property functions [11]. Food structure engineering extends from intelligent use of food ingredients aiming at formulations enhancing physicochemical stabilization of nonequilibrium states to form appealing sensory and textural characteristics and protection of nutrients in such structures [12–14] and to control food manufacturing and processing parameters for the use of temperature, pressure, pH, hydrogen bonding, hydrophobicity, water content, electric charge, solubility and time among other parameters and their combination to maximize desired product characteristics with minimum losses of nutrients [3, 5, 14]. With appropriate packaging technologies and controlled distribution chains, such structure-engineered foods can provide attractive shelf life and nutrient delivery. The design and engineering of food structures for satiety and satisfaction in digestion have opened up an extensive new research area leading to formulation of food structures with optimal rheological, controlled release, bioavailability and overall digestion properties for the human gastric system [15–19]. We highlight the role of food solids as determinants of the success of structure formation in food processing and how structure formation may be affected by key processing parameters.

Food Processing and Food Structure

The modern food industry produces both traditional and novel structures with high consumer appeal. The science and engineering of food structure emphasize scientific understanding of food materials. It should not be confused with "molecular gastronomy" which refers to a "scientific look at cooking" methodology of producing culinary art in a gastronomic surrounding using tools made available by modern technologies [20].

Innovative structures are typical of confectionary, and they satisfy human senses besides being edible. Some traditional examples include meringues which are produced by using a concentrated and viscous mix of protein and sugars. The proteins act as surface active components at the air interface, while slow dehydration under temperature-controlled flow allows the continuous phase of sugars to vitrify into crispy membranes. The membranes are physically noncrystalline solids and structure-carrying glasses providing stability against flow under gravity [21]. A similar type structure is formed in freeze-drying of foods. Freeze-drying is based on sublimation of ice to retain a freeze-concentrated glass structure around voids left by the ice crystals [22]. The freeze-drying process can be seen as one of the first food structure engineering processes that gained popularity in 1960s as it removed water at low temperatures with microentrapment and high retention of volatile flavor and aroma components. Furthermore, freeze-drying was one of the first processes accepted by the food industry to emphasize convenience to consumers. Extrusion processes and particularly the high-temperature short time (HTST) extrusion process were adapted to food materials from the plastic industry. The process emphasizes the glass-forming characteristics of carbohydrates at low water contents and temperatures, while viscous flow required for structure formation can be achieved as a result of thermal and water plasticization above the glass transition of the solids [21]. The recognition of the underlying materials science principles was described successfully by state diagrams for dehydration, extrusion and freezing [4, 5, 23, 24].

Much data are available for food dehydration processes, extrusion and freezing showing critical parameters for extending the shelf life of food solids for several years. Most of the dehydrated and frozen foods show stability achieved by converting at least some of the solids to a noncrystalline solid state, i.e., temperature and water content are controlled to keep the materials stable [4, 5]. Theories of water activity as a mobility-controlling factor were complemented by information on the glass transition of particular food components at various levels of water plasticization [2, 5]. The effects of the glass transition on oxidation, nonenzymatic browning reactions, enzymatic reactions, structural collapse and component crystallization have shown that glass transition affects and often explains the occurrence of such reactions although may not be sufficient as such to explain temperature dependence of deteriorative changes in foods [24].

Freeze-drying and spray-drying have provided excellent examples of structure formation in dehydration processes. Freezing is the fundamental step of structure formation in freeze-drying as the sublimation step should maintain the solid structure of the maximally freeze-concentrated solids. The stability of the material during the freeze-drying is determined by the onset temperature of ice melting, T_m', while the solids after dehydration must be stored below the glass transition temperature, T_g, of the main components to reduce viscous flow. The glass-forming solutes often entrap or encapsulate dispersed particles, which is the basis of their long-term stabilization. Spray-drying relies on the rapid solidification of glass-forming solids in concentrates which also entrap dispersed components but allow phase separation, e.g., diffusion and self-assembly of proteins toward the air–particle interface. A typical example of glass-forming sugars and dispersed oil particles in spray-dried solids is shown in Fig. 1.

The effect of glass former on the particle structure and properties after spray-drying is not well known. We expect that the flow characteristics or "strength" of the glass formers and their interaction with other solids contribute to powder characteristics. We have introduced a Williams–Landel–Ferry (WLF) model [5] analysis of solids flow characteristics in mixes of sugars and polymeric food components. The WLF model (Eq. 1) constants C_1 and C_2 can be derived using experimental relaxation times, τ, with the assumption of $\tau_g = 100$ s at the onset temperature of the calorimetric glass transition, T_g. A decrease in the number of logarithmic decades for flow, e.g., to result in stickiness, can be defined as the critical parameter, d_s, of Eq. 2 and a corresponding $T–T_g$ is given as the strength of the solids, S. A comparison of noncrystalline trehalose-whey protein (WPI) solids at various trehalose-WPI ratios is shown in Fig. 2.

$$\log\frac{\tau}{\tau_g} = \frac{-C_1\left(T - T_g\right)}{C_2 + \left(T - T_g\right)} \quad (1)$$

$$S = \frac{d_s C_2}{-C_1 - d_s} \quad (2)$$

The above examples are using information of the noncrystalline state of food materials in a systematic manner to guide structure formation in food processing as well as for stability control of resultant products. Such structures can be used to include dispersed phases and their stabilization using various methods as described in other sections of the present article.

A novel approach to implement structured water into food systems has been based on so-called *water powder* produced by spray freezing of particles composed of water with oligo- or polysaccharides and/or proteins. Such particles making up water powder become stabilized by the solids components which form (i) a glassy surface layer and (ii) an internal glassy lamellar structure separating unfrozen water and ice crystal domains. The surface layer and the lamellar particle core areas exhibit different freezing kinetics and form two glassy structural building blocks. The surface layer (i) consists of a kinetically entrapped-water glass, containing an unfrozen water fraction that may recrystallize, whereas the lamellar core (ii) is formed of vitrified, maximally freeze-concentrated solutes of the watery fluid system and ice crystals (Fig. 3).

Water powder particles are stable during cold storage at about 2–3 °C below the glass transition temperature of the maximally freeze-concentrated solutes, $T_g{}'$, of the glassy layer structures. Such storage conditions may typically be found over the range −35 to −6 °C using appropriate oligo-/polysaccharide/protein mixtures. As demonstrated by Windhab [26], such water powders considerably facilitate formation of homogeneous mixtures of small fractions of water into other powders when cold-mixed and then heated for melting. This novel process supports an energy-

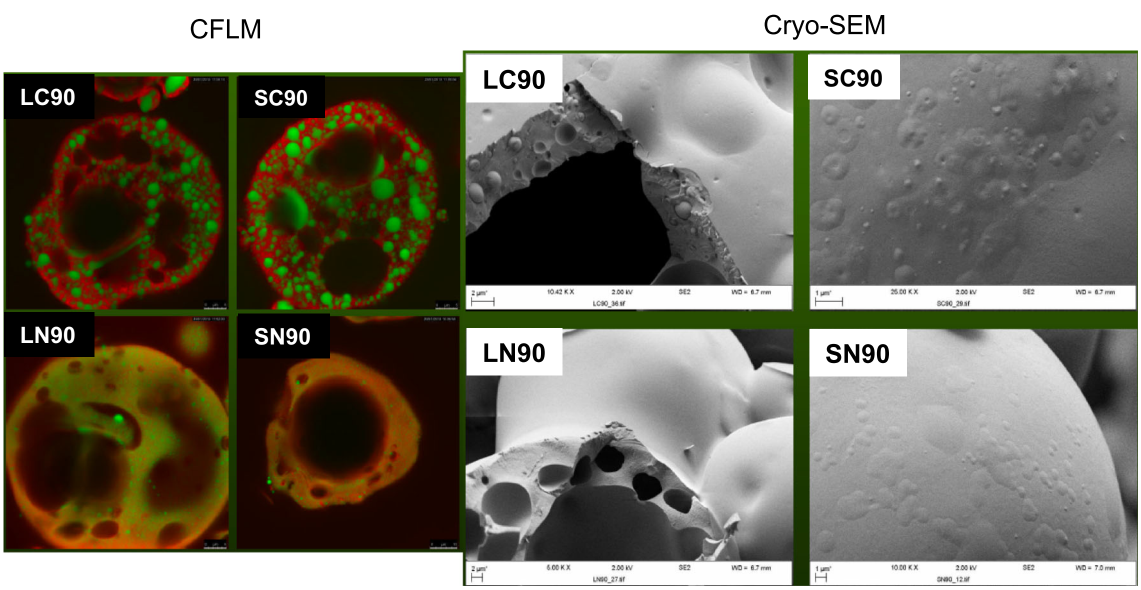


Fig. 1 Spray-dried particles of conventional (LC and SC) and nanoemulsions (LN and SN) in confocal (CFLM, *left*) and scanning electron microscopy (cryo-SEM, *right*) images. The significant difference in encapsulated core oil particle size (*green*), protein (*red*) and particle nanostructure (dispersed oil within solids) is obvious. Glass formers used were lactose (LC and LN) and sucrose (SC and SN). (Courtesy of Patrick Maher and Mark Auty, Moorepark Food Research Centre, Fermoy, Ireland) (Color figure online)

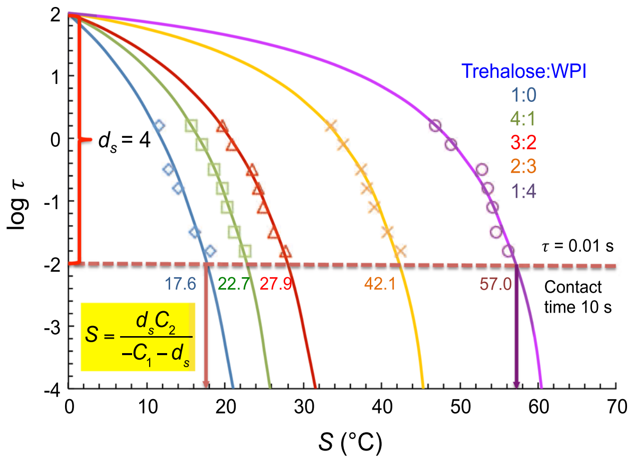


Fig. 2 Strength parameters, S, at $d_s = 4$ decreasing the structural relaxation time, τ, as measured using dynamic mechanical analysis (DMA) to $\tau = 0.01$ s. Such decrease in τ is known to result in particle stickiness and aggregation at a contact time of 10 s (Color figure online)

efficient production of sinter-based or agglomerated food products, but the process has a wide applicability and is not restricted to food manufacturing.

Precision Production of Emulsions for Precision Applications

Milk and dairy products, desserts, mayonnaises, sauces, spreads, but also creams and lotions for pharmaceutical and cosmetic formulations, paints, agrochemical products and bitumen are well-known dispersed systems. The inner structures of such dispersions are often natural in the nano- and sub-micrometer scale, and their multiple phase structures are characterized by a high interfacial area. In engineering of such structures, it is useful to define miniemulsions as those that have droplets in the submicron scale, while nanoemulsion droplets have a radius smaller than <100 nm. Both miniemulsions and nanoemulsions are used in formulations for functional foods, cosmetics or drugs, particularly when active components are encapsulated for their stabilization and enhanced bioavailability. In intermediate products, miniemulsion droplets may be designed to serve as "nanoreactors" for the production of synthetic polymers (miniemulsion polymerization), especially when monomers show a low solubility in the continuous phase or nanoparticles have to be encapsulated (core–shell particles). Examples for applications were summarized by Köhler and Schuchmann [27]. Mini- and nanoemulsions have to be stabilized not only by emulsifiers and stabilizers against flocculation and coalescence, but also by osmotic agents to prevent Ostwald ripening [28].

Principles of Emulsion Structure Engineering and Design

In designing products that meet specific customer needs, we have to understand the influence of inner structures on characteristic product properties. This relationship was called property function by Rumpf [29] and is often referred to as structure–property function. The inner structure of an emulsion-based material is mainly influenced by the production process and processing parameters, a relationship called process function [30] or process–structure relationship (Fig. 4). Precision production in applications requires processes that allow for a robust control of emulsion droplet size and structure. Structural

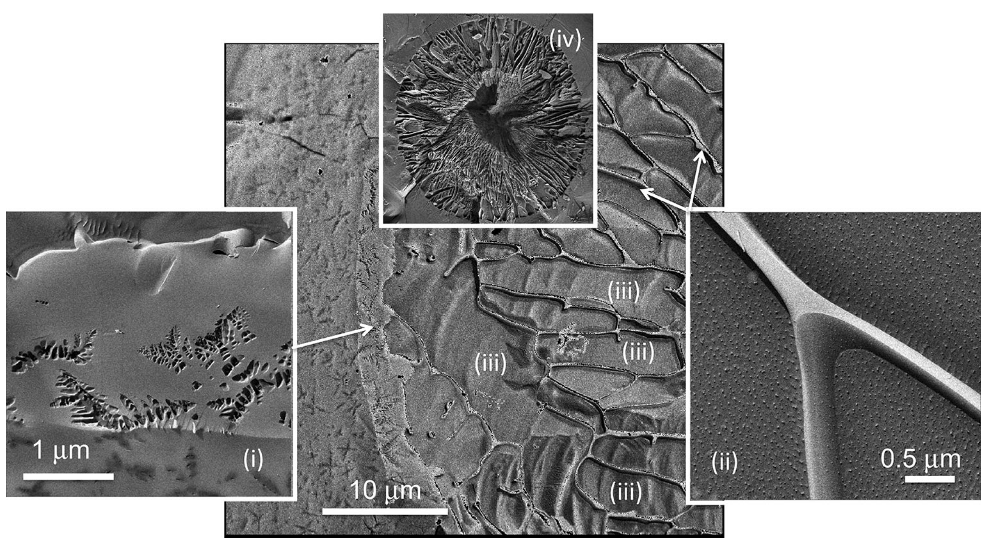


Fig. 3 Spray-frozen water powder particles with a glassy shell and an internal lamella structure: (*i*) kinetically entrapped-water glassy surface layer; (*ii*) maximally freeze-concentrated, glassy internal lamellae surrounding (*iii*) ice crystals; (*iv*) central cut through the particle. All images were produced by cryo-SEM and partial sublimation [25]

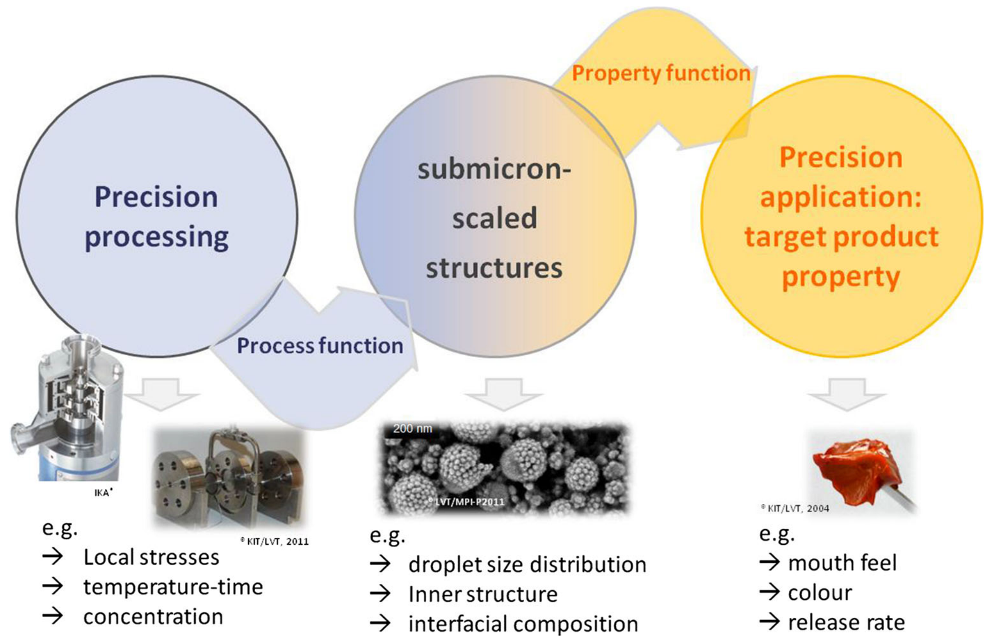


Fig. 4 Basic principles of product design applied to emulsion-based materials

units of the materials become responsible for product properties and have a scale of several nano- to micrometers. Manufacturing of the systems requires the development of processes which enable the control of process parameters at the nanometer scale.

Emulsion Structures by Precise Processing

The control of process parameters within manufacturing equipment on a submicron scale is illustrated here by using the high-pressure homogenization process as an example. High-pressure homogenizers are common in the food industry, especially when submicron-scaled emulsion droplets have to be produced [31]. High-pressure homogenization systems in the dairy industry are used for hourly production of several thousands of tons of dairy liquids. Emulsion droplets are disrupted in a specific valve, being characterized by flow channels of up to >100 µm in length. In order to understand local flow conditions inside the valve, high-resolution analytical techniques and basic chemical engineering tools such as computer-based fluid dynamics are used. The latter solve the Navier–Stokes equations on a local level, using mathematical grids at a nanometer scale [32, 33]. Process simulation is a major challenge as droplets influence each other and local flow in droplet surroundings. In addition, cavitational effects often are found in homogenization devices (Fig. 5). Local flow velocities are analyzed by high-resolution optical analytics, such as µ-PIV.

The use of local flow velocities allows calculation of stresses acting on droplets, as shown in Fig. 6 for a single-phase flow through a spherical orifice of 200 µm diameter at 100 bar homogenization pressure [34]. Droplets deform and break when the capillary number exceeds a critical value [35, 36]. In high-pressure homogenization equipment, the critical capillary number is rapidly exceeded within a timeframe of µs. The process is almost instant and occurs in nonequilibrium conditions, as shown in detail by Bentley and Leal [37]. The calculation of droplet size distributions which result from a wide distribution of stresses is one of the main challenges to food and chemical process engineers in simulation of high-pressure homogenization systems.

Emulsion Droplets as Nanocapsules and Carrier Systems

In traditional food and emulsion-based products, fat is distributed as small droplets in order to improve emulsion stability and also palatability and digestibility. In addition, an appealing texture, creaminess and a pleasant mouthfeel are desired. Emulsion droplets may also serve as carriers for (bio-) active molecules. We have designed emulsions with multiple functions for the droplet phase: (i) solvent for the active molecules; (ii) stabilization of sensitive components against UV radiation, oxidation and other chemical reactions; (iii) suitability for uses with active molecules in products with a high consumer preference; (iv) transportation of active molecules through the intestinal tract and controlled release at a targeted site and rate. Multiple emulsions, such as water-in-oil-in-water systems (W/O/W), were found promising and investigated for the use as vehicles for the delivery of the active molecules [39, 40]. Active molecules were encapsulated in the inner aqueous

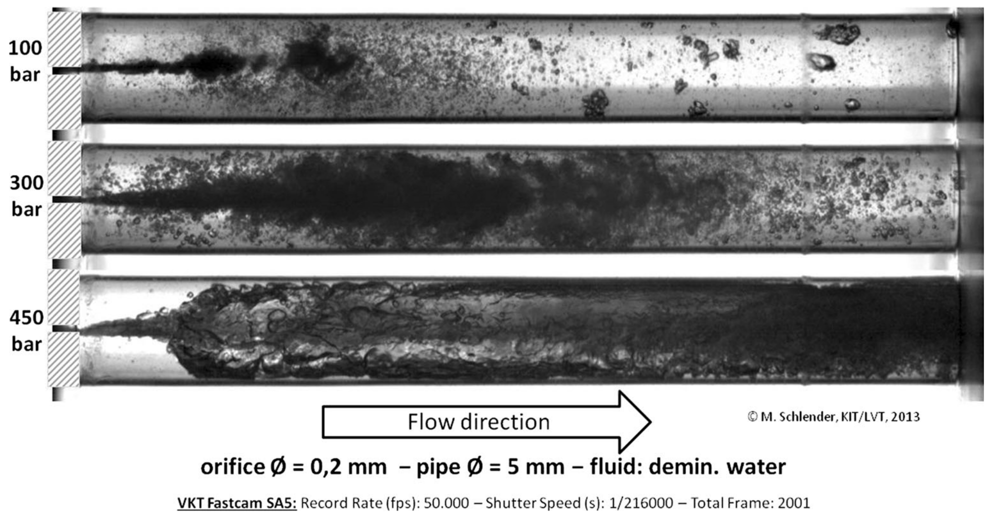


Fig. 5 Images of a cavitating fluid leaving a homogenization orifice at different homogenization pressure differences

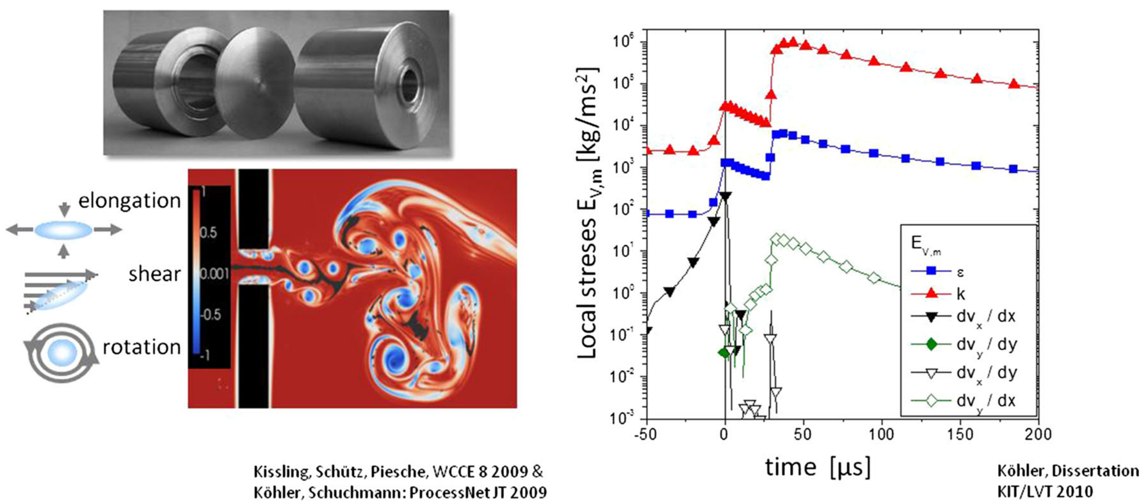


Fig. 6 Stresses acting on droplets flowing through a spherical high-pressure homogenization orifice, as depicted by the photograph: (*left*) graphical illustration (from direct numerical simulation) [38]; (*right*) local stresses on the middle axes as function of time: stresses resulting from local turbulent energy dissipation *e*, *k* as well as shear and elongational stresses in *x*- and *y*-direction. The fluid leaves the orifice at time $t = 0$ µs [31]

phase with diameters over the range of 50–1000 nm. Our investigations showed that active molecules were released by either coalescence of the inner core to the outer aqueous phase [41] or molecular transportation via the outer lipid phase [42]. The release rate was dependent on the size of the inner and outer phases, and the emulsifier system used (Fig. 7). In this case, "precision production" enabled a "precision application."

Emulsion Droplets as Nanoreactors and Templates

Solid nanoparticles in suspensions are conventionally produced in large reactors via precipitation as shown in Fig. 8 (left). The large reaction volume and broad distribution of local stresses result in local reaction conditions which are difficult to control. A precision production of nanoparticles of controlled chemical composition, size and structure may not be achieved in such traditional processes. Furthermore, there is a resultant limited product quality and need for a subsequent and intense downstream processing. Analysis of the process and resultant product characteristics show much difficulty. There is, however, a possibility to reduce the reaction volume (microsystem technology). We have designed systems with dimensions at the scale of 100 nm based on miniemulsion droplets serving as nanoreactors. In each droplet, a reaction takes place, e.g., precipitation of solid nanoparticles [45–47]. Nanoreactor systems showed several advantages: (i) well-defined reaction conditions, e.g., temperature; (ii) a limited surrounding volume; and (iii) precise concentration of reactants [48]. The reactor system was scaled up by increasing the

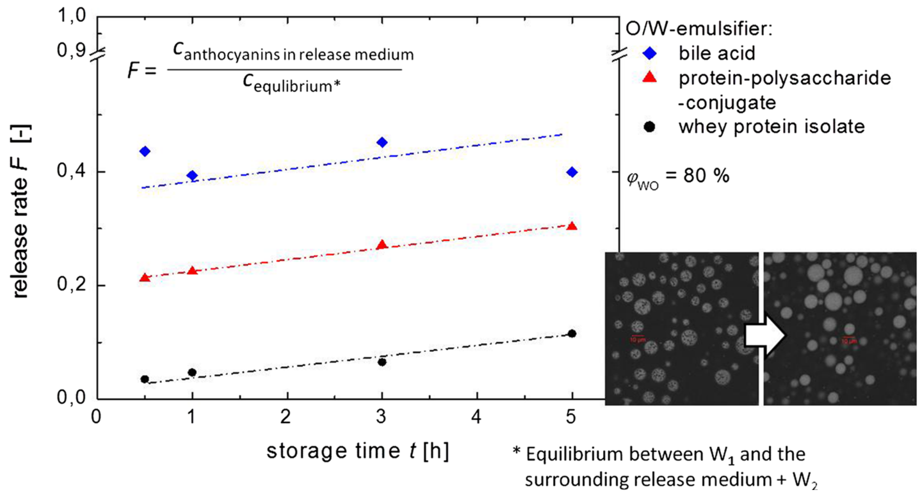


Fig. 7 Release of anthocyanins from W/O/W double emulsions: 80 % dispersed fraction in the inner emulsion (W/O) containing anthocyanins in the inner aqueous droplets. The inner emulsion was stabilized by O/W emulsifiers of different molecular structures influencing the primary release in double emulsion processing. Secondary release during storage was diffusion controlled and independent of the emulsifier used, but the secondary release was determined by the double emulsion structure parameters [43]. Photographic images of Guan et al. [44] are also shown

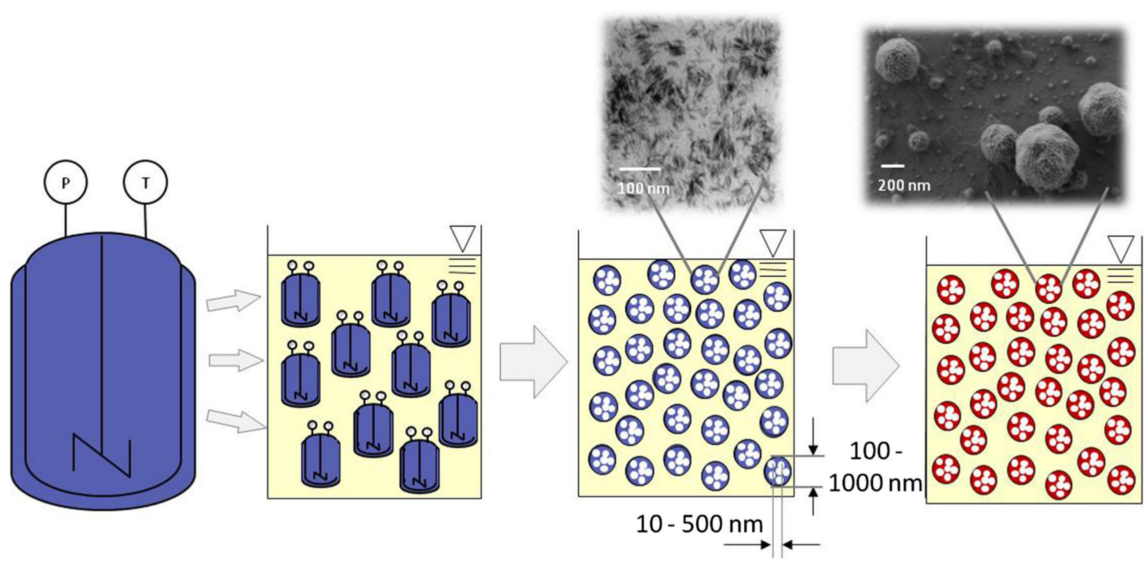


Fig. 8 A reactor (*left*) and imaginary nanoreactors. Miniemulsion droplets can be designed as nanoreactors to produce reactor templates, as described and photographed by Winkelmann [48] to show nanoparticles precipitated in emulsion droplets (*middle*). The core–shell nanoparticles were produced via miniemulsion polymerization and photographed by Hecht [52]

number of identical reactors, i.e., the number of droplets was increased (numbering-up) by increasing the emulsion volume. We obtained nanoparticles of precise size and chemical structure as shown in Fig. 8 (middle). When monomer droplets were filled with nanoparticles and polymerized (miniemulsion polymerization), the miniemulsion droplet became a template for the resultant core–shell nanoparticles (Fig. 8, right) [49]. Precision in structuring hybrid particles was highly dependent on the processing conditions for the miniemulsion production [50] and interactions between nanoparticles and surfactants [51].

Edge-based Droplet Generation

High-speed imaging has enabled visualization of the various mechanisms and enhanced the development of new processes for emulsification, encapsulation and separation. The scale-up of the novel technologies relies on understanding the nanometer scale and knowledge transfer to enable the scale-up of microtechnology for uses in industrial settings. One example is the edge-based droplet generation which provides a new emulsification method with substantial energy savings. Classic emulsification devices, such as high-pressure homogenizers and colloid mills, are typically using only 1–5 % of the supplied energy for droplets generation and up to 99 % of the energy is lost as heat [53]. It is also known that membrane emulsification provides a high efficiency as energy is used on the micrometer scale, i.e., at the scale of the droplets formation. A drawback of a membrane droplet generator is the pore size distribution of membranes which reduces monodispersity of the droplets. Therefore, other microstructured devices are developed, such as the EDGE technology developed at Wageningen University [8] and shown in Fig. 9.

The EDGE technology is based on guiding the oil through a channel onto a shallow area called plateau, as shown in Fig. 9. The height of the plateau is typically 1 µm, and the droplet size scales to 6–8 times of the plateau height. This implies that droplets with a diameter of 1 µm require a plateau of ~150 nm (which is currently technically feasible albeit at the lower-resolution limit). Upon reaching the end of the plateau, the oil expands into a deeper area, where the Laplace pressure difference leads to a spontaneous droplet formation. The spontaneous droplet formation implies that the cross-flow velocity of the continuous phase does not influence the droplet size, and even more importantly, the droplets generated are extremely monodispersed as indicated in the Fig. 9 (right).

The EDGE technology has been scaled up, albeit still on the microchip level, but using >100 plateaus in parallel. The droplet size is constant and depends on the height of the plateau, as was also confirmed through simulations by van Dijke et al. [7]. Our present studies concentrate on the parallelization of the EDGE technology with scaling-up toward industrial applications using food materials. More specifically, we are exploring metal surfaces and sieves, and also look at alternative designs as discussed by Nazir et al. [54]. We also investigate surface modification techniques to prevent changes in wettability resulting from adsorption of food components which are essential for continuous operation and cleaning [55, 56].

Tailored Multiple Emulsions for Multicomponent Encapsulation

With specifically developed microfluidic chips, multiple emulsion structures were developed such that a well-defined number of monodisperse sub-drops were incorporated into a drop of a next larger monodisperse size class as demonstrated in Fig. 10. However, such microfluidic approaches are not really suitable to be translated into industrial production scale by parallelization.

The scaling approach adapted by Windhab et al. [57] at ETH was based on dynamic membrane (DYMEM) devices using micro-engineered Controlled Pore Distance (CPD) membranes [57]. Their method overcame the limitation of conventional membrane emulsification by introducing an additional shear cross-flow field to the throughput flow direction across the membrane surface by rotating the membrane or using a rotating membrane placed with a defined gap distance to the membrane. A detailed quantitative description of the functional relationships between DYMEM emulsification process parameters and resulting drop size distribution had to be established. Additional consideration of microscopic interfacial and flow phenomena close to the membrane pore surface provided results that could be used to explain the relationships of process parameters and droplet sizes. Droplet detachment from various CPD membranes was studied. Well-defined laminar shear flow across a flat circular membrane was achieved by choosing a cone-plate arrangement of membrane and rotor with a narrow gap of 50–100 µm. That approach in the experimental setup enabled the investigators to use flat micro-engineered CPD membranes and observe the membrane surface during processing in close detail [58].

The micro-engineered membranes were used to study the impact of pore size, adjusted interpore distance, surface wetting properties and pore shape in detail. Micro-engineered membranes of (i) silicon and (ii) silicon nitride basis

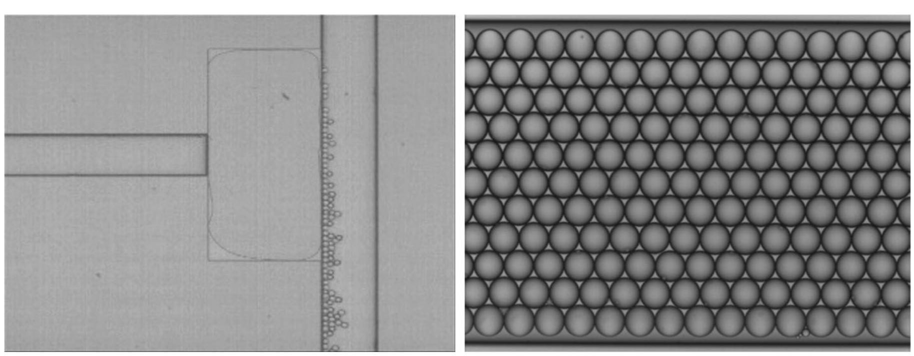


Fig. 9 EDGE emulsification principle: Top view of a microchip in which oil is fed from the left onto a shallow plateau, and where monodispersed droplets are formed when the oil reaches the deeper area in which monodispersed droplets are formed (*left*). Monodispersed droplets formed by the microfluidics (*right*) [8]. Reprinted with permission by John Wiley and Sons

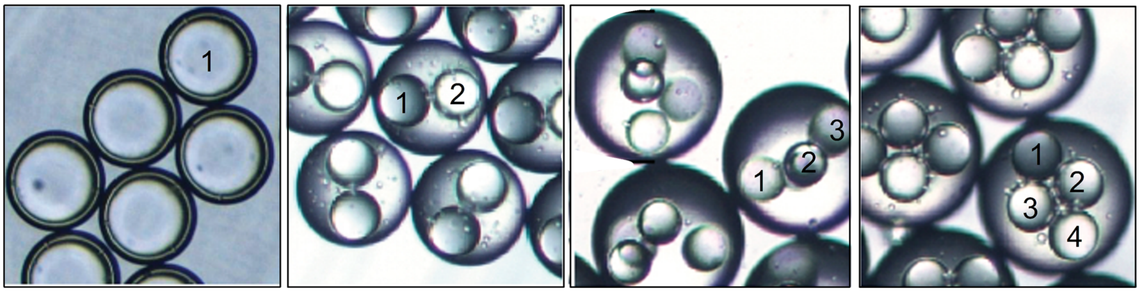


Fig. 10 Tailored multiple emulsion with several monodisperse drop size classes and distinct numbers of sub-drops produced by a specific microfluidics setup [57]

were developed with pore sizes down to 400 nm and with adjusted hydrophilic/hydrophobic surface characteristics. Systematic experimental work was supported by CFD simulations of the drop formation and detachment processes at the membrane surface under acting flow fields.

It was demonstrated that the generated emulsion drop mean size ($x_{50,3}$) scaled with the membrane wall shear stress, independently from the viscosity ratio of the disperse to the continuous fluid phases (Fig. 11). As long as the drop detachment followed a dripping mechanism, monodispersed droplet size distributions were approached [60].

Whey Protein Fibrils for Encapsulation

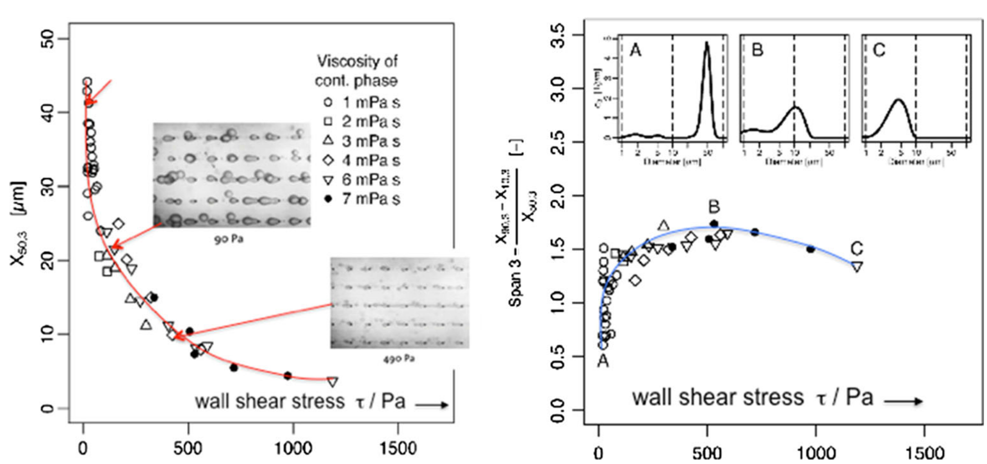
The classic dilemma of microcapsules is a need to have sturdy particles that resist stresses of various conditions while showing flexibility in reaching a target location to release their content. Our approach is to layer various encapsulation components in order to build a strong shell that can spontaneously disintegrate at a desired pH by neutralization of the component charges. Whey protein fibrils shown in Fig. 12 (left) were used as one of the encapsulation components, because they can be formed at low pH under shear, they are typically in the micrometer range in length, but in nanometer range in width [61], carry a charge, and are potential edible encapsulation components.

The rationale behind using the fibrils is that they have a much larger persistence length as molecules. Microcapsules made by layer-by-layer (LBL) adsorption using protein molecules are known to be physically highly unstable, even if as much as 50 layers are put onto each other. Besides the fibrils, an oppositely charged highly methylated pectin was used, and these two components were alternatingly deposited on template oil droplets. The resulting microcapsules are shown in Fig. 12 (right) [62]. The components interact through opposite charges, and upon reaching a required thickness (~100 nm), the encapsulation layer becomes mechanically very strong with a capability to dissolve only extremely slowly when exposed to acidic conditions. Such engineered microcapsules are interesting candidates for bioactives release and delivery in the lower part of the GI tract.

Membrane Separation and Fractionation

Knowledge of phenomena on the micrometer scale can be applied very effectively to membrane separation and even fractionation of molecular components that are closely

Fig. 11 Dynamic membrane drop formation performance using micro-engineered CPDN membrane [59]: drop mean diameter scaling with membrane surface shear stress (*left*); drop size distribution width expressed by span (O (hydrioil)/W (Polyglycol 35000 s) emulsion (*right*)



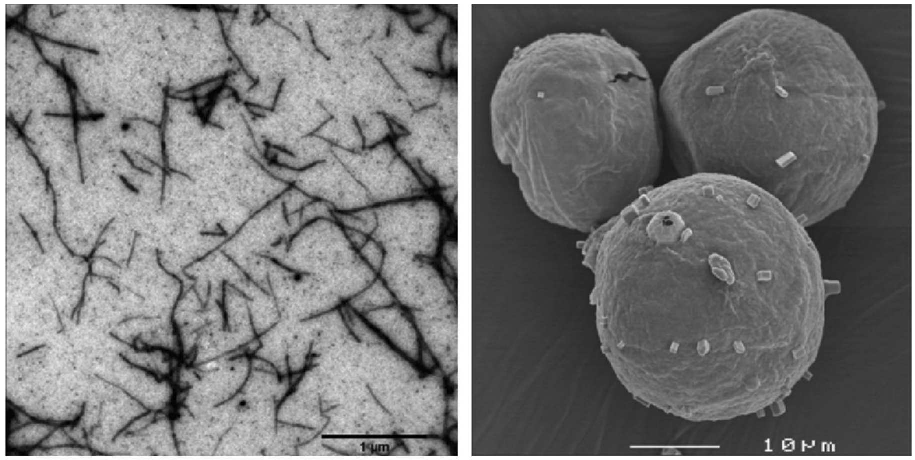


Fig. 12 Whey protein fibrils (*left*) produced at low pH (Reprinted with permission, Copyright American Chemical Society). Microcapsules (*right*) prepared by layer-by-layer adsorption of whey protein fibrils and pectin to achieve ability to resist low pH conditions [63]. (Reprinted with permission, Copyright American Chemical Society)

similar in size. During a membrane filtration process, liquid components are carried toward the membrane surface where some components are retained as their penetration is limited by the size of the pores. As a consequence, a concentrated layer of larger components builds on the membrane surface. Such concentration polarization reduces the efficiency and selectivity of separation, as illustrated in Fig. 13.

An intelligent use of particle interactions may induce particle migration away from the membrane which allows operation under very different conditions from those that are traditionally used in membrane filtration (Fig. 10). The shift principle forces particles to interact which results in shear-induced migration behavior. As a result, particles migrate to an area in which the shear is the lowest, i.e., particles migrate toward the center of the channel. Large particles have a higher diffusivity than smaller particles and those migrate predominantly at the center of the channel, while the small particles remain at the membrane or wall surface.

The shift principle membrane system was elegantly used by van Dinther et al. [9, 10] who developed a new design for membrane processes. Their membrane module consisted of a closed channel first stage where particles were allowed to migrate and a second stage containing a porous channel (membrane) with very large pores; typically, pores sizes were >5 times the size of the largest particles. The control of the cross-flow velocity and the transmembrane pressure allowed separation of various particle size fractions. The composition of each fraction was determined by the process conditions. The actual fluxes that were measured were typical of microfiltration, while most importantly no flux decrease and concentration polarization took place, and because of that the efficiency and the selectivity remained constant.

Sustainable Food Processing for the Future

The Energy and Environmental Impact of the Food Industry

The growth in global population and climate change by 2030 will increase food production needs by 50 %, energy demand by 45 % and water demand by 30 % [64]. Climate change and consequently food security is high on the agenda of many governments, including that of the UK [65]. Among the main priorities of the UK's "Food 2030" strategy [66] are to reduce the food system's resource use and greenhouse gas (GHG) emissions and to reduce, reuse and reprocess food

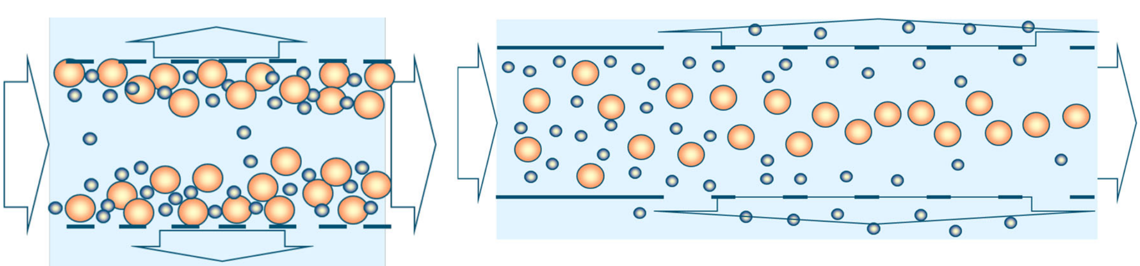


Fig. 13 Schematic representation of membrane filtration with concentration polarization (*left*) and the shift principle (*right*) which allows particles to move away from the membrane surface leading to improved filtration, and a process enabling molecular component fractionation

waste. Estimates for the USA indicate that energy savings of the order of 50 % are achievable in food chains by appropriate technology changes in food production, processing, packaging, transportation and consumption [67]. The environmental impact of the food and drink industry is so large because it is a major part of the economy of the EU.

In the UK, for example

- the food chain involves approximately 300,000 enterprises and employs 3.6 million people, constituting 13 % of national employment [66];
- food industry is the largest manufacturing sector, employing 500,000 people and contributing 80 billion GBP to the economy;
- food is the biggest consumer spending category at over 160 billion GBP, i.e., >20 % of UK consumer expenditure [68]

Annually, the UK food chain is also responsible for

- 160 Mt CO_2 emissions, 115 Mt CO_2 from UK food chain activity and the rest from imports [68].
- 15 Mt of food waste; most of which can be avoided or used as a resource into the food chain [69].
- 367 TWh use of energy [70] and approximately 18 % of total UK final energy use.
- 347–366 million m^3 use of water in 2010 with manufacturing use between 185 and 196 million m^3 [71], a 15–20 % reduction since 2007.

Energy usage and CO2 emissions across the food chain in the UK can be grouped into several areas:

- *Agriculture—energy* consumption in food production is between 10 and 20 GWh with an estimated energy saving potential of 20 % [70].
- *Processing*—food and drink manufacturing is responsible for more than 10 % (42 TWh) of industrial energy use and 13 $MtCO_2e$ emissions per year. About 68 % of the energy is used for process and space heating, 16 % is electrical energy used by motors, 8 % is electric heating, 6 % by refrigeration and the remainder by compressors [70].
- *Food transport*—transport is responsible for emissions from energy use of approximately 18.4 $MtCO_2e$ per year, of which nearly 6.0 $MtCO_2e$ is for food freight, more than 80 % of which is performed by Heavy Goods Vehicles [72].
- *Food retail*—food retailing in the UK is responsible for around 12.0 TWh, around 3 % of total electrical energy consumption [73]. Estimates for GHG emissions from retail operations vary between 6 and 9.5 $MtCO_2e$.
- *Food consumption*—energy use of food consumption in the home accounts for approximately 21 Mt CO_2 [66]. Of these, 3.8 Mt CO_2 is for private cars, 8.4 Mt CO_2 for refrigeration and 8.4 Mt CO_2 for cooking. The food service sector is estimated to be responsible for 5.3 Mt CO_2 emissions.
- *Food waste*—the food chain is responsible for around 15 Mt of food waste which accounts for more than 30 Mt CO_2 emissions [62].

As shown by the data above, there is a huge scope for reducing the energy and water usage—and thus the costs—of the industry. Reusing food waste has been well studied, and the literature is extensive [74, 75], with solutions proposed vary from pyrolysis [76] to anaerobic digestion [77]. More work needs to be done across the whole food chain [78], and the need is also to involve the consumer and to change consumer behavior [79]. Waste recycling may not be the most efficient solution; the need is to minimize it through process design and different manufacturing methods—some possible routes are outlined below.

Role of Food Engineering: New Processes and Products

To make the food chain sustainable will need significant new technologies and changes in manufacturer and consumer practices. Much of this will use methods that are common to other sectors—such as innovations in transport and energy usage [80]. The food system has to be treated as part of a whole, together with water and energy uses [81]—the wish to grow crop biofuels can obviously conflict with the need to grow food. Methodologies such as life cycle analysis, developed in other sectors, can be applied to food chain problems both at a whole [82] or part-sector [83] level.

Innovations in Food Engineering will, however, be needed to make food processing more energy efficient and minimize wastage. The food industry has a number of constraints that are not found in other industries. For example, heat is used both to ensure microbial destruction and to generate flavors and the texture of foods [84]—there are thus limits to the reductions in heat load that can be carried out without producing an unsafe or unattractive product.

Existing Processes: Optimize, Measure, Control

Energy can be saved at the processing plant level by optimizing and integrating processes and systems to reduce energy intensity. Commonly, a substantial safety threshold is added to ensure that the food does not cause a safety hazard—however, such overprocessing increases the waste in the system. A number of studies of the optimization of conventional processes have been made, for example, in thermal sterilization [85, 86]. An analysis of fryers has also shown that reduction in energy usage is possible [87, 88].

There are optimization needs for a good understanding of efficient process monitoring and control methods. These methods are often lacking—the need is to have systems that can be validated for online monitoring and process control. Process probes such as time–temperature indicators can be used to validate models [89] and to demonstrate process uniformity [90]. Such methods offer a chance of reducing the overprocessing given to foods while maintaining required product safety. Better understanding of how processes work and use of knowledge for improved process control will minimize waste through energy recovery and better use of by-products.

New Processes

Extensive research has been done on a range of novel food processes, in which preservation occurs through nonthermal means, such as high pressure and pulsed electric fields, or through heat generation, such as ohmic and microwave processes [91]. These processes either reduce microbial load without heat or give a more precise heat profile than conventional processing. In some cases, such as in high-pressure sterilization, the process is essentially thermal in that heat is generated when pressure is applied and absorbed on decompression [92]. All such processes deliver reduction in microbial load through nonthermal means or by a controlled heating pattern. A number of products are commercially available—the need is to generate an advantage to the consumer and economic viability. Suitable process indicators would also be valuable in process validation and control [93, 94].

Limited studies of the environmental impact of novel processes have been made [95], and it is possible that there are environmental advantages over conventional products. If, for example, shelf-stable foods could be manufactured to the same quality as fresh food or ready meals, the need for refrigerated transport and storage in the home would be reduced.

New Materials and Operating Methods

A highly hygienic manufacturing plant is critical in the food industry. Frequent cleaning is needed to ensure process sterility and to remove product residues. Both of these processes require energy and generate waste. A useful metric is the number of tonnes of water that is used in making a tonne of product—often this can be more than two or three. Much work has been done to look at fouling problems, and these processes are now reasonably well understood [96], although cleaning is less well characterized [97].

New coatings for process surfaces have been developed that can significantly reduce fouling and speed cleaning [98]. The new coating materials potentially offer a step-change reduction in waste and energy usage—however, they need to be made cost-effective and resistant to process conditions and cleaning chemicals [99]. Advances in surface technologies are such that it is likely that solutions will be found; at the moment, the food industry uses stainless steel, but a move to more hygienic materials will be significant in water saving.

It may also be possible to optimize conditions at product changeover. Processes such as "ice pigging" have been proposed in which a plug of ice is used to sweep product out and speed changeover [100]. We have recently [101] described experiments in which cleaning times were reduced by more than 25 % by adjusting process conditions. This is an area where rapid progress might be made without significant investments in new plants that will be needed to use new materials.

A Shift in Manufacturing Methods

Modifications in the food manufacturing industry are needed to make the food system more sustainable.

- *Local manufacture* The supply chain model for major food companies has been to create a small number of very large factories that exploit economies of scale. As transport costs become more expensive, this model becomes more difficult to justify—the length of the supply chain becomes excessive.

To some extent, this is already happening. For example, major consolidation in the brewing industry has resulted in a very small number of huge brewers who make a small number of heavily marketing international brands that are produced to be stable through very long supply chains. In response, in the UK and the USA a large number of localized craft breweries have been established—such breweries produce products of superior quality that outweighs any cost disadvantage resulting from small batch production.

The more efficient model could be a shift to a smaller number of localized factories. Sourcing products locally change the supply chains, which may become more efficient food systems. Some studies for farming exist [102] but not for food processing.

- *Distributed manufacture* Many food supply chains involve the transport of foods that are substantially water. It is arguable that the most efficient food supply chain involves the "tea bag"—not only is more than 99 % of the material supplied at point of consumption, but the water is heated to a level where the product is safe. It might be possible to adopt this model more widely, to convey only the valuable ingredients, such as particular flavors, and add other ingredients later at the local level, as described above.

The above model will require that foods are reconstituted locally, such as by rehydration. Drying is a very common processing operation, but control of microstructure and rehydration is critical [103, 104].

A completely new approach is the 3D printing ("additive manufacture") which has been proposed for local food manufacturing. Commercial printers are becoming available, but the equipment needs a further development [105]. Feasible systems require much new engineering science to understand how to create structures—it will also need surfaces and processes that are hygienic.

- *Processing with less water* Many food processes involve the successive addition and evaporation of water, for example baking and the manufacture of bread. If it were possible to lower the water added at the start, then both energy and water would be reduced. Often (as in baking) water takes part in reactions as well as acting as a solvent and as an aid in mixing—so there will be a limit, driven by the basic science, to what can be done to reduce water usage. Where for example water is used as a solvent, such as in creating a solution that is later spray-dried, reducing the water load has direct benefit.

The food industry is a major contributor to energy and water usage. A more sustainable food industry requires significant changes in food manufacturing and transportation. In some cases, advances in materials science are needed, as in the development of new clean materials from which to build the next generation of food processing plants. In others, Food Engineering is required; changes in supply chains will require innovations to food manufacturing and transportation. Local assembly of high-value products will require greater understanding of food components and structures, as well as new supply chains.

Dry Fractionation for Sustainability

The growing food production and consumption can result in major environmental problems as the world population exceeds 7 billion and is expected to reach 9.2 billion in 2050 [106]. Many consumers, especially in transition countries, will benefit from increasing affluence and develop a lifestyle with higher environmental burden. Such lifestyle is likely to favor a diet with meat as protein intake is found to increase with income [107]. A transition from a livestock to a plant-based protein supply would enhance sustainable food production [108]. As energy resources are also limited, despite recent developments on shale gas exploitation, alternative sources for energy and chemicals are required. One possibility is the use of biomass for biofuels production. It has been estimated that one third of the corn in the USA in 2016 will be used for biofuels production. As a consequence, the demand for the acreage used for fuel instead of food production will increase and result in increased corn prices. Sustainable food production is one of the major challenges of the twenty-first century. Besides the transition to a plant-based diet, the demand of the continuously growing population should be met by more efficient conversion of feedstock into a wide range of high-quality, healthy and tasty foods.

Ingredient Separation Processes

Current processing of food ingredients from staple crops such as corn, wheat and soy involves the use of copious amounts of energy and water. The present processes aim at full isolation of components such as protein, starch and lipids, which require separation in water. Subsequently, evaporation and drying are required to remove the solvent water. An illustrative example is the fractionation of wheat into starch and gluten. Conventionally, wheat is milled and hulls and germs are separated mechanically from the flour. The flour is mixed with water to produce dough that is further diluted into a batter. The starch is suspended in the water, while the gluten remains as a highly swollen matrix. Subsequently, the gluten is dried and the aqueous phase, which contains 0.3–2 % (w/w) of solids, is separated into a relatively pure starch fraction and a fraction that is rich in gluten by hydrocyclones. The starch fraction is concentrated and finally dried. This fractionation process requires large amounts of water, first to wash out the starch and finally to achieve an effective separation through hydrocycloning. However, a reduction in the use of water will lead to a lower starch yield from the gluten and a lower quality of gluten.

Peighambardoust et al. [109] reported an innovative separation principle using a spontaneous gluten–starch segregation during well-defined shear flow in a cone-in-cone shearing apparatus. Surprisingly, segregation occurred only in wheat dough at 60 % (w/w) solids and not in diluted samples. A high-quality gluten (including soluble gluten) was obtained providing a superior bread quality compared to similar amounts of commercially available gluten [110]. Although up-scaling of the shearing apparatus remains a hurdle for industrial applications of the process, a conceptual design of the new separation process indicated enormous savings on energy and water consumption. A different separation concept under development employs deterministic ratchets or lateral displacement arrays to separate suspended particles in semi-concentrated systems (up to 12 % v/v) [111, 112]. Deterministic ratchets consist of periodic arrays of obstacles which are spaced to cause suspended particles with the smallest sizes to be displaced. The major advantage compared to membrane filtration is the inherent absence of particle accumulation in the flow direction as the characteristic gap size exceeds the particle size. Moreover, the process allows high throughput separation as it was discovered that particle displacement became more effective at increasing Reynolds numbers [110].

Within the European Commission funded project “MagPro2Life,” magnetic separation processes were explored, further developed and scaled up for industrial production purposes. Paramagnetic particulates were surface-modified in a more (click chemistry) or less (ion exchange characteristics) selective manner in order to enable the adsorption of specific proteins or protein groups from wastewater streams (e.g., soy whey) of food manufacturing processes [113].

The magnetic separation process-related developments included microfluidic-based basic approaches for scaling-up solutions of complete separation processing lines for food, feed and pharmaceutical components [113]. A microfluidic-based magnetic separator is shown in Fig. 14, while Fig. 15 shows a pilot-scale centrifugal separator for the selection of the super-paramagnetic particulates before elution of the adsorbed surface protein layers. The protein layer consisted, for example, of Bowman–Birk inhibitor (BBI) that is a functional protein of interest in medical applications for cancer therapy.

Production of Functional Ingredients

Affluent consumers tend to incorporate more proteins and high-energy foods in their diet. Such trend is shown by increased meat in diet, but also by an intake of refined ingredients (protein, starch and lipids) incorporated into energy-dense processed foods. Typical examples for the latter are snack foods, sauces, cookies and candies, but also traditional fast foods such as cheeseburgers, French fries and soft drinks. Consumption of such foods is strongly connected to the prevalence of obesity in the Western world [115, 116]. To ensure a healthy lifestyle, the World Health Organisation recommendation is to eat fruits and vegetables and to reduce fat, sugar and salt intake [117]. Specifically, the WHO report promoted the reformulation of mainstream food products in order to reduce the amount of salt, added sugar, saturated fat and trans-fatty acids. Other studies indicated that health benefits come from whole meals rather than from intake of isolated constituents [118].

We have investigated partial dry fractionation processes of milling of feedstocks [119]. Dry fractionation involves fine milling and subsequent separation of flour particles, for example, on the basis of particle size using air classification, into enriched fractions. The process is more energy efficient compared to conventional wet isolation (it is ultimately concentrated) and able to produce ingredient fractions with high (native) functionality. While conventional wet fractionation aims at a production of one high-purity ingredient, dry fractionation produces multiple functional fractions and thus makes efficient use of the entire crop. Fractions can be subsequently used in food (or at least high value) applications. Hitherto, dry fractionation has been successful for production of protein and starch concentrates from pulses or cereals and for the fractionation of wheat bran into enriched fractions [120]. The separation technique relies on the specific tissue architecture of seeds, which for example for peas is built up from starch granules embedded in a protein matrix (Fig. 16). The pea cotyledon tissue breaks up into different-sized particles during milling, and then, air classification is used to classify the flour into a fine protein fraction and a coarse starch-rich fraction. Since the separation relies on fracture behavior of seeds, we have investigated how physical properties of pea starch and protein vary as a function of temperature and water content. Glass transition temperatures were established for both components and correlated to their differences in fracture behavior [121]. Functionality of pea protein concentrates was derived from their water holding capacity (WHC) which showed that liquid

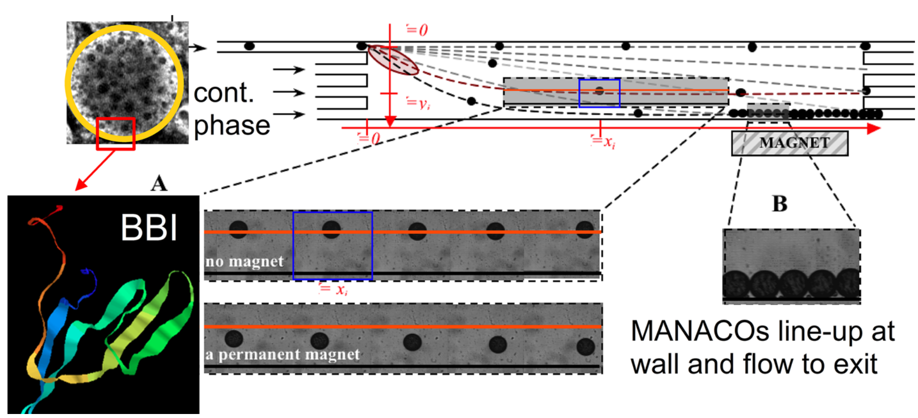


Fig. 14 Microfluidic-based magnetic separation device for collection of magnetic nanocontainers (MANACOs) loaded with specific adsorbed proteins [114]

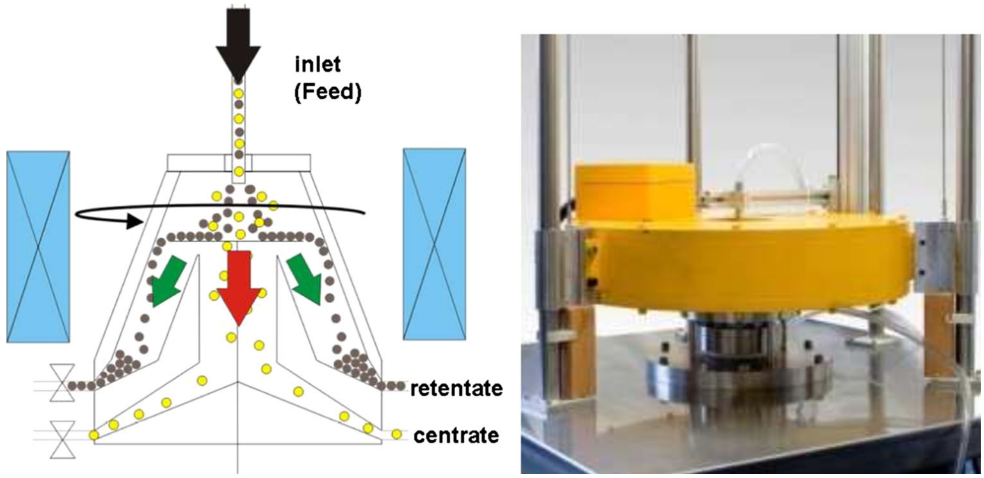


Fig. 15 Pilot scale magnetic centrifuge for separation of super-paramagnetic magnetic particles/magnetic nanocontainers loaded with specific adsorbed proteins [113]

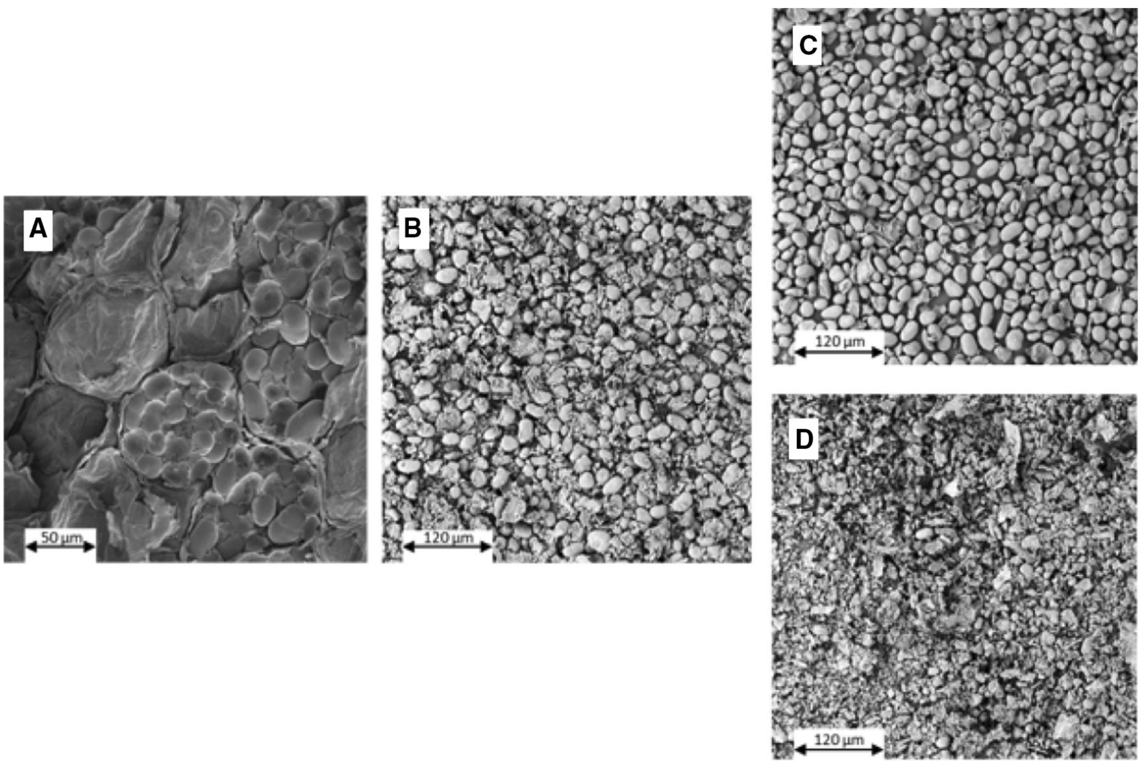


Fig. 16 Scanning electron microscope pictures of **a** pea cotyledon with starch granules embedded in the protein matrix (23 and 48 w/w % of protein and starch, respectively), **b** finely milled pea flour **c** starch-rich (≈70 w/w % starch) coarse fraction and **d** protein-rich (≈55 w/w % protein) fine fraction produced. The latter two fractions were prepared by air classification

pea protein solutions contained 26 % (w/w) of protein. This value was explained by the high solubility of pea protein in its native state [122]. Upon heating, it was found that the WHC could be increased up to conventional WHC values for pea protein isolates. Besides air classification, electrostatic separation was explored as a means to fractionate millings into ingredient fractions. Electrostatic separation employs characteristic tribo-electric charging behavior of materials and subsequently the electrostatic forces as a driving force for separation. We have evaluated fractionation of wheat bran into β-glucan and arabinoxylan-rich fractions [120]. In order to expand the applications of dry fractionation, scientific knowledge of dry-processed ingredient fractions during product preparation is needed. It is expected that the availability of a wider variety of ingredient fractions with high (native) functionality will contribute to the development of high-quality and healthy foods.

Semi-concentrated and dry fractionation processes for plant-based ingredients have enormous saving potential on water and energy use. Moreover, the processes should focus on delivering (native) functional ingredient fractions rather than on ingredients fully refined for molecular purity. Functional fractions could provide the basis for healthy foods that reflect the biological composition of whole foods.

Innovations and Academic Research

The British Royal Society has provided a listing of the top 20 food innovations [123]. Process-/engineering-related innovations included refrigeration, pasteurization/sterilization, canning, baking, grinding/milling, fermentation, microwave oven and frying. A more comprehensive attempt to summarize top food inventions of the last 50 years is provided in Table 1.

An highly interesting historical development of Food Engineering has been given by Aguilera [124] who showed the change from process engineering concentrating on high throughput, low-cost preservation in 1850–1950 followed by the current emphasis on product engineering with emphasis on food safety and quality, health and human well-being. The product engineering approach becomes also evident when looking on topics of recent ICEF Conferences (ICEF 8, ICEF 11) as shown in Table 2.

Karel [125] also proposed development of key scientific "knowledge-based" compounds (e.g., food properties), the development of quantitative relationships between food properties and quality attributes and stressed the need for models and sensor systems for food quality attributes.

Challenges and Research Agenda

The concept of bio-guided processes was first postulated by Ward et al. [126] as they suggested that consumers were the drivers for gentle process selection. The Strategic Research Agenda 2007–2012 of the European Technology Platform on Food for Life [127] has provided a powerful concept suggesting to design processes, products and tools that improve health, well-being and longevity ("add life to years"), and the Institute of Chemical Engineering [128] provided a comprehensive summary of key challenges, essential issues and concerns affecting quality of life (Fig. 17).

The ETP [127] identified six key challenges:

(1) Ensuring that the health is the easy choice for consumers.
(2) Delivering a healthier diet.
(3) Developing quality food products.
(4) Assuring safe foods that consumer can trust.
(5) Achieving sustainable food production.
(6) Managing the food chain.

Within the key challenge, three (developing quality food products) essential goals have been identified:

- producing tailor-made food products
- improving process design, process control and packaging
- improving understanding of process–structure–property relationships
- understanding consumer behaviors in relation to food quality and manufacturing

The concept of "reverse engineering," adapting processing of food to the preferences, acceptance and needs (PAN concept) of the consumer has subsequently been introduced where improved understanding of process–structure–property relationships play a vital role [127]. Based on these concepts, future needs in Food Engineering have been identified (Table 3).

A few examples will attempt to demonstrate some of the research pathways to meet these needs.

Tailor-made Foods Engineering technologies, such as high hydrostatic pressure, pulsed electric fields or ultrasound, are useful tools in the generation of tailor-made foods. For example, high pressure can be used to modify foods and affect material properties. Pressure-induced polysaccharide gels have different properties from heat-induced gels [129], high-pressure–low-temperature processing has significant impact on milk protein behavior [130], and high-pressure treatment of sausage batter offers

Table 1 Key food inventions since mid-twentieth century

Irradiation and microwave heating	Point of use processing
Extrusion	Emerging technologies
Aseptic processing	– Ohmic and RF heating
Water activity	– Steam injection
Hurdle concept/minimal processing	– High pressure
Packaging (aseptic MAP, smart, etc.…)	– Pulsed electric fields
RTE meals	– Atmospheric plasma
	– Light and light pulses (IR, UV)

Table 2 Product engineering topics at ICEF Conferences

Topic	ICEF conference
Food rheology	ICEF 8
Food structure	ICEF 8
Minimal processing	ICEF 8
Process control	ICEF 8
Environmental/food waste	ICEF 8
Engineering properties of foods, food materials	ICEF 11
Process control, modeling and control of processes, quality and safety	ICEF 8
Emerging processes/novel food processes	ICEF 8, ICEF 11
Novel food processes	ICEF 11
Food product engineering	ICEF 11
Food products and process applications	ICEF 11

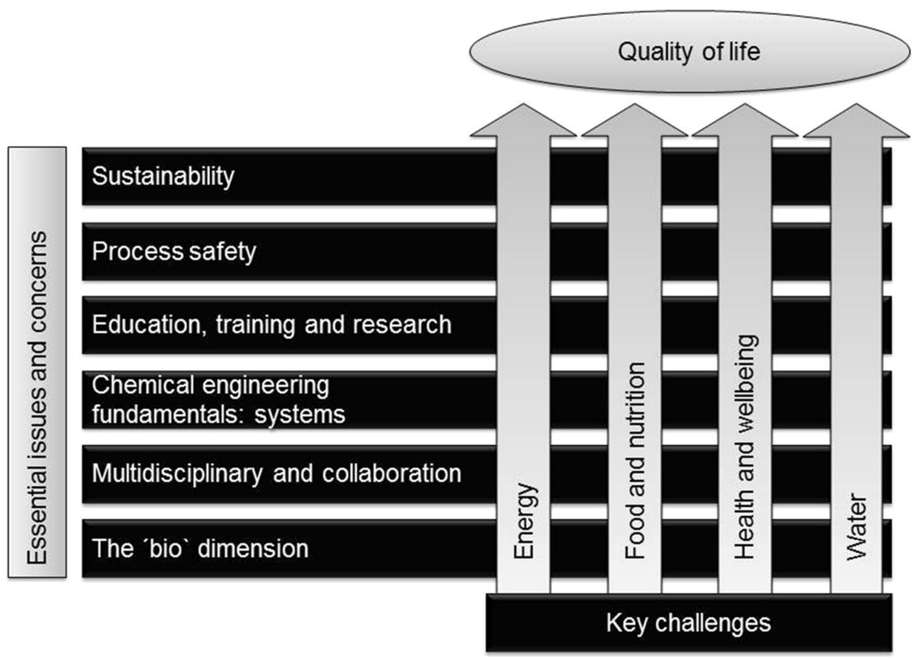


Fig. 17 Chemical engineering and quality of life [128]

Table 3 Future needs in Food Engineering

Tailor-made foods	Science-based processes
Process–structure function relationships	Reevaluation of traditional processes
Targeted process-personalized nutrition	Kinetics and mechanisms
Emerging technologies	
Process control & modeling	Resource engineering
New tool boxes	Waste recovery and utilization
Sensor technologies	New raw materials
Scalable processes	Interfaces
Small-scale processes	Digestion engineering
Microfluidics	Biotransformations
Nanotechnology	Metabolite engineering
	Technology transfer

a wide range of new product development opportunities due to unique gelling behavior of sausage components [131]. Textural changes of high-pressure–high-temperature processing of vegetables have been demonstrated by Hendrickx [132], and pulsed electric field treatment of meat products could significantly alter meat structures batter. Pulsed electric fields have also been shown to affect texture, nutrient composition and secondary metabolite production [133, 134].

Schössler et al. [135] convincingly showed that ultrasound treatment on vegetable structures affected food properties during subsequent processing. Spray freezing has been developed [136] as a useful method to retain probiotic viability during freezing, and high-pressure treatment has increased heat stress resistance allowing low-energy spray-drying of probiotics [137] rather than the lengthy, energy, intensive freeze-drying process. Powerful modeling concepts have been suggested to better understand digestion behavior of food particulates [138, 139].

Sustainability Sustainability has to be part of any modern food processing operation. Surprisingly, few radical changes have occurred since the first book on food sustainability was published more than 30 years ago [140]. Since packaging has become an integral part of processing, special attention needs to be given to food packaging materials and food waste as well as to food preparation. Consequently, a reevaluation of existing processes/technologies is needed in light of energy use and in order to gain better understanding of process–structure–property relationships. For example, a comparison of materials used in pizza baking resulted in surprising differences in mass and heat transfer caused by the heat transfer materials (steel, soapstone, marble) used [141, 142].

The cutting energy required for vegetables could be reduced by 50 %, while oil uptake of potatoes was reduced after structural changes occurring in a pulsed electric field pretreatment [143].

Sustainable food production requires new raw materials. Since emerging technologies have different needs of action than conventional thermal processing, the possibility exists to use raw materials not being considered so far for food use. In addition, the increased interest in food biotechnology [140], enabling sustainable food production using renewable sources being termed as bioeconomy, offers the application of gentle and energy-efficient processing tools [144]. Microbial biomass, plant biomass and single-cell proteins can be regenerated as potential food sources using emerging technologies. Insects have also become another potential food source [145, 146] where emerging technologies can aid in the development of innovative recovery processes.

Interfaces The future of Food Engineering needs to be based on working at interfaces with other branches of science, including chemical and mechanical engineering; materials science; medical and nutritional sciences as well as consumer science and gastronomic engineering.

The chain integration approach as suggested by the European Technology Platform: Food for Life [127, 147] and by having more transparency in the food chain [148] are essential steps in that direction. The recent EU-COST Action on electroporation where food scientists, electrical engineers and medical researchers share their experience to improve pulsed electric field processes and applications is an useful example of such a collaboration [149]. The creation of a new journal, Frontiers in Nutrition and Food Science Technology [150], can be seen as an attempt to better integrate nutrition and food science.

Science-based processes need to be developed with atmospheric plasma being a good example [151] to gain more knowledge regarding kinetics and mechanisms involved in food safety, functionality and quality rather than maintain the "cook and look" approach. More attention needs to be devoted to sustainability issues, to transparency in the food chain and finally working at interfaces, creating an innovation climate including open innovation concepts and increased public–private partnerships to be able to tackle the grand challenges of securing a safe and healthy food supply via Food Engineering research [152–155].

Food Engineering Programs

Universities within the European countries have a large number of Bachelor of Science and Master of Science programs (respectively 210 and 200). A large number of universities for example in Germany, Italy, Spain or France have a wide diversity of academic programs in the food-related disciplines. The programs often include teaching and training dedicated to fundamentals of Food Science, Food Physics and Food Chemistry or Microbiology. On the other hand, food technology programs emphasize commodities and are seen as training for dairy, meat, cereal, animal products or even nutrition needs.

There are approximately 70 PhD programs, but very few are dedicated to Food Engineering. According to TrackFast (www.trackfast.eu) and ISEKI databases (www.iseki-food.net), Food Engineering is exiting only in very few institutions. Some of the food-related bachelor and masters programs are listed in Table 4.

Although Food Engineering exists in a small number of educational programs, it is rather included in Chemical Engineering, Agricultural Engineering or Biotechnology curricula. In such programs, only a small part of the content deals with Food Engineering. In addition, some of the food

Table 4 Examples of titles and topics of food-related bachelor and masters programs in Europe

Bachelor programs	Food Science and Technology, Food Science, Food Technology, Food Engineering, Biotechnology, Viticulture and Enology, Processes of Animal Products, Nutrition and Food Science, Process Engineering—Food Technology
	Food Innovation Management, Food Innovation, Food Service, Gastronomic Sciences, Food and Business
Masters programs	Food Science and Technology, Food Science and Engineering, Industrial Biotechnology, Innovative Enology, Food Microbiology, Food Chemistry, Life Science Technology, Agrofoodchain
	Food Enterprise Development, Food Business

sector-dedicated masters programs are devoted to Food Engineering.

An EU-funded initiative explored the requirements for food-related academic curricula (TrackFast programme www.trackfast.eu). A set of expected skills was established. It was obvious that knowledge in Food Engineering, including Food Chemistry, Physics, Heat and Mass Transfer areas, was necessary, but the European countries highlighted the importance of soft skills (Table 5). The second important finding of the TrackFast program was the significant differences between countries for the expected skills.

The existing masters programs include a huge number of topics, and a common program content across European institutions is missing, even though heat and mass transfer and unit operations are typically covered. It is obvious that the role of Food Engineering is not clear and an undefined common set of content dominates the masters programs. A more uniform program structure would be useful for food companies, for research and for academic education.

Existing masters degree programs suffer a lack of important topics which have become more important in Food Engineering, for example: reaction engineering, and kinetics, bioengineering, enzyme processing, process control, process analytical technology, sensors, automation, robotics, modeling. But also skills in management, nutrition, sensory evaluation, legislation, law and regulations, microbiology and other specific topics are expected to be included in program learning outcomes.

Future education in Food Engineering must take into account the challenges the higher education system has to face. At least two dimensions will be important: the innovation for socioeconomic activities and the innovation in education approaches. Both are key stakes considering the Food Engineering education system.

A large number of articles and conferences deal with a set of new constraints, new stakes and challenges for the food industry: bioeconomics, food security, population growth, food safety, changing eating behavior, globalization, climate change, energy cost and change in value chain, fossil fuel prices, sustainability and other emerging challenges. The recognized answer is the capacity of innovation, creation of new products, new services, new processes able to deal with an evolving situation and to face new challenges. Innovation could be important for

Table 5 Examples and details of expected soft skills (www.trackfast.eu)

Fundamental soft skills	Details
Communication skills (i.e., oral and written communication, listening, interviewing, etc.)	Demonstrate the use of oral and written communication skills. This includes such skills as writing technical reports, letters and memos; communicating technical information to a nontechnical audience; and making formal and informal presentations
Critical thinking/problem-solving skills (i.e., creativity, common sense, resourcefulness, scientific reasoning, analytical thinking, etc.)	Define a problem, identify potential causes and possible solutions, and make thoughtful recommendations
	Apply critical thinking skills to new situations
Professional skills (i.e., ethics, integrity, respect for diversity)	Commit to the highest standards of professional integrity and ethical values
	Work and/or interact with individuals from diverse cultures
Lifelong learning skills	Explain the skills necessary to continually educate oneself
Interaction skills (i.e., teamwork, mentoring, leadership, networking, interpersonal skills, etc.)	Work effectively with others
	Provide leadership in a variety of situations
	Deal with individual and/or group conflict
Information acquisition skills (i.e., written and electronic searches, databases, Internet, etc.)	Independently research scientific and nonscientific information
	Competently use library resources
Organizational skills (i.e., time management, project management, etc.)	Manage time effectively
	Facilitate group projects
	Handle multiple tasks and pressures

facing the fundamental change in economical competition: acceleration of technological innovation, increase with information exchanges, quick evolution of consummation centers and urbanization. A set of key items is proposed:

- *New answers* competition, intensive innovation, innovation-based competition, open innovation;
- New theory emerge on design and engineering of products;
- New ways of cooperation's between companies;
- New skills are necessary, more cross-disciplinary approaches are expected;
- New students with new ways of working and expectations;
- Food process conception and sustainability;
- Over time, gradual integration of multiple constraints (cost, microbiological safety, sensory aspects, chemical safety, nutritional value… and environmental constraints);
- Will it be possible to comply with the constraints of sustainability without having to go back on some of the constraints previously integrated?
- Is it possible to respond by optimizing existing technologies, or is it necessary to fundamentally redesign food processing methods, the relationship between agriculture and industry, and the organization of food chains?

All higher education systems propose innovations in order to teach better to a population of students that is also changing. New teaching approaches based on different tools and philosophy are proposed and in some cases applications concern Food Engineering. The use of digital tools, development of serious games, the use of Massive Open Online Courses (MOOC) is developing at very high speed. Such initiatives change certainly the way of teaching, the way of learning, but not a lot the content. If this way of learning of students without teacher appears an interesting one, the learning by doing is also in a great change with significant implications on Food Engineering. Teaching and training become more close together. For example, innovation laboratories dedicated to food appear to be important practical approaches. The number of projects between companies and universities on real products is also increasing. In a general view, more and more cooperation with food companies and equipment manufacturers is established, and as a consequence, real-life projects are becoming a part of education.

Competition in order to foster innovation between students contest (EcotroFood) are being proposed and commercialized, and more and more awards (EFCE PhD awards) are appearing. It is probably one of the most interesting open initiatives in Food Engineering to build new content by collaboration with others disciplines in order to establish new cross-disciplinary content-based network projects across Europe.

In conclusion, a set of new challenges appears important for Food Engineering education programs:

- European programs follow the Bologna Agreement based on 3 + 2 years of education toward an academic MSc award.
- To be able to introduce courses and programs covering entrepreneurship and innovation.
- To promote new teaching methods and pedagogy.
    - New generation of students.
        - Internet-social networks.
        - Web 2.0 generation.
    - Lower financial support to programs.
    - Resistance to changes.
- To boost industry's participation in education.
- To develop a quality framework in education: quality standards (certification, label).
- New skills for new jobs: To be aware of the skills that industries expect from graduates and follow how they evolve over time.
- To motivate and accompany young students interested in a career in the food industry because of lower importance of food science and technology studies/curricula and competition from other scientific fields.

Final Remarks

The European Food Engineering education and research occur at multiple levels. There are significant new processing methods developed for the food industry to take into account structure formation in food processes as well as opportunities to manufacture more uniform and stable nutrient delivery systems using novel emulsification technologies. The research strongly contributes to knowledge in sustainable food processing and efficient use of energy and water. Novel food processing technologies are being introduced, while significant changes in the education system are taking place.

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