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INTRODUCTION

The importance of food science and research to the nutritional and overall health of humans cannot be overstated. It plays a vital role throughout the food chain, from the production, processing, distribution, and storage of foodstuffs to their consumption, digestion, and nutrient absorption in the human body. Food science has been widely accepted as the application of basic sciences, including but not limited to chemistry, physics, engineering, molecular biology, and nutritional and health sciences.[1] The interfaces between these disciplines create limitless opportunities to approach food-related problems from different perspectives. Establishing efficiency in the utilization of resources, supporting new consumer demands, and tackling global challenges in food manufacturing and distribution are among the current urgent needs. This special collection attempts to cover physics-based approaches in designing food products, processes, and analysis techniques for the sustainable global food sector.

From the physical perspective, food is a dynamic, multi-dimensional, and multi-phase system. Hence, fundamental principles of food physics, biophysics, and physical chemistry can be applied to better understand and engineer different aspects of the food chain and resulting food properties. In this regard, the length scales, types of forces, and environmental conditions are useful variables in applying physics, identifying driving forces, and determining equilibrium or non-equilibrium states and phase changes. Both external and internal factors are involved in the equilibrium and non-equilibrium conditions of foods and food ingredients, as well as their properties. Gravitational, electrical, pressure, and chemical driving forces are some of the forces inducing changes in the system. Electrostatic repulsion and attraction, steric repulsion and van der Waals attraction, and depletion interactions are significant colloidal interaction forces operative in (in)stability mechanisms and macromolecular properties.

Food physics deals with interactions at a molecular scale, meso-scale structures such as colloids, and physical properties of foods and food ingredients at a macroscopic level. Soft matter physics is one of the most useful approaches in this field to understand food structures and dispersion systems where their (in)stability can be explained via thermodynamic principles.[2,3] Hard matter and brittle glass-like materials correspond to fat crystals in chocolate and potato chips, respectively.[3]

Mechanical forces, including shear, compression, and tensile, are important and relevant to many food processes (e.g., mixing, kneading, proofing, and chewing). These forces alone or in combination play roles in disrupting (e.g., breaking down oil droplets into smaller ones in emulsion systems), in forming interactions (e.g., disulfide bridges in bread dough), and in incorporating air into food systems (e.g., aerating ice cream through mixing). Ultimately, these forces lead to very diverse and complex food structures and architectures.

Food interacts with its environment and responds to pH, temperature, pressure, and humidity changes. Hence, it is also essential to understand the changes to food during storage to limit or control its degradation, deterioration, or separation. More interestingly, those responding features of foods with engineered designs can be triggered by exposing food to different environments, leading to shape or color change in time, known as the fourth dimension.[4] Thanks to the advancement of technologies and mathematical tools, novel research areas have emerged, such as additive manufacturing, cellular and precision agriculture, upcycling, and machine learning that transform the ways of food production, distribution, and consumption. Hence, physics-informed adaptation and transition to the new technologies will create resilient food systems.

In view of the above-mentioned aspects and scientific advancements, solutions to current food-related problems can be proposed through physics-based approaches and tools. Whether it is simply a mixture of two ingredients, such as water and sugar, or a complex multi-compartmentalized structure from components of very distinct characteristics like oil and water, fundamental principles in food physics at different stages (design, processing, transport, storage, etc.) provide useful parameters for controlling quality and ensuring safety. The representations of the observed, captured, or predicted phenomena through governing physics have been of great interest to researchers, academics, and industry professionals, as well as to other individuals. The special collection of food physics concepts and problems reflects the industrial applications and everyday observations using experimental and numerical techniques. The publications serve to address the pressing problems of making food and food systems more accessible, sustainable, and safer. They also help us better understand the underlying mechanisms and interactions in manufacturing our popular everyday foods.

SUMMARY OF AREAS COVERED

This special issue focuses on ways to understand the underlying physics of food systems, from production through consumption, including kinetics to explain the rate of change in these systems. The publications cover colloidal solutions, emulsions, foams, oleosomes, and gels. Destabilization, crystallization, and aging are the physical change phenomena discussed in the context of different systems, such as extruded proteins and gels. The authors exemplified that one physical concept or phenomenon can serve several purposes. It can also be represented differently, which may even seem contradicting or inapplicable at first glance. For instance, an instability mechanism in emulsions can be used to create novel architectures in oleosomes,[5] cross-link distance might be useful in determining the texture as well as stability of a candy,[6] simple supersaturated solutions can also undergo complex kinetic and thermodynamic processes,[7] flow is encouraged during three-dimensional (3D) printing but not after deposition,[4] and the discrete element method originated in rock mechanics can be applied to understand the transport phenomenon.[8]

Foams, emulsions, and oleosomes

There are several ways to generate air bubbles or CO_2 in food and beverages. Lyu *et al.*[9] captured one of the most interesting examples of foam formation and its collapse for their unique bottom-to-top beer pouring system. They carried out experimental and numerical studies and implemented a multi-phase Reynolds-averaged Navier–Stokes solver to account for heat and mass transfer between the phases. The temperature of the beer and the tap pressure are critical in foam development and the associated foam height. The foam stability is mainly dependent on the size of the bubbles.

Double emulsions are thermodynamically unstable systems but can be kinetically stable. This metastability, together with its complex structure, is a great opportunity to deliver nutrients and bioactive molecules at their desired location or mask (un)wanted aromatic compounds.[10] Sonmezler *et al.*[11] utilized pea flour to encapsulate olive leaf extract via double emulsion. By-products of olive production, olive leaves, contain valuable phenolic compounds with significant bioactive properties. Their antioxidant, anti-microbial, anti-viral, and anti-inflammatory roles depend on stability. Hence, encapsulation of these compounds benefits the protection and controlled release at the desired location in the body.

Zambrano and Vilgis[5] studied the gelation of soybean oleosomes containing negatively charged flexible polysaccharides, sodium alginate, and iota carrageenan through bridging flocculation. They showed that the structural and molecular makeups of polymers are the major determinants of the efficiency of the bridging ability. The driving factors are the electrostatic interactions and charge density. The bridging flocculation is an instability mechanism, yet its use can lead to gels with strong interactions, as proven by this study.

Linear and nonlinear rheology

Exploring fluid and soft matter microstructure experimentally is possible through linear and nonlinear rheology.[12,13] Chan *et al.*[14] addressed the rheological behavior of saltwater taffy using time-temperature superposition. They also discussed the role of water and sugar content as well as the extent of taffy pulling on its rheological behavior. Moreover, the effect of air, oil, and emulsifier on the governing flow behavior of taffy samples was covered. The rheology of saltwater taffy can be described by plateau modulus, characteristic relaxation time, and power-law exponent. In addition, sugar content, aeration, and emulsification are found to be significant in the rheological response.

Wang *et al.*[15] investigated the rheological properties, the break-up morphology, and the mechanism of the shear-thickening suspensions, which gets little attention compared to shear-thinning ones. In this work, they discussed the effect of nozzle geometry on the break-up morphology. The macaroni-type breakup corresponds to unique rheological properties of discontinuous shear thickening.

Werner-Cárcamo *et al.*[16] also discussed the linear to nonlinear transition of wax oleogels via Lissajous–Bowditch plots based on different cooling rates. Under small deformations, oleogels exhibited rigid behavior, while more plastic behavior was noted upon increased strains. Above 6% strains, the more plastic response was captured compared to quiescent conditions.

Extraction and flow

Flow and transport phenomena have broad applicability in food-related processes. Examples include the transport of material through the digestive tract and subsequently to the bloodstream and cells and the extraction of compounds from by-products or biological tissues.[17,18] Lee *et al.*[17] explored the relationship between the grinding size and coffee extraction in espresso coffee making, where flow and extraction are the major determinants of the observed phenomenon. The decreased grind size leads to flow instability and lower extraction due to the clogging effect of finely ground particles. Two possible pathways were presented to replicate the experimental observations. Coffee beans have porous microstructure mainly due to moisture loss during roasting. Then, beans are ground and placed into an espresso portafilter, where packed particles also represent a porous medium. When finely ground coffee beans are exposed to pressurized water in a densely packed environment (e.g., portafilter), they swell instantly (decreasing the porosity of the particles) and prevent the flow and extraction (due to smaller voids between the particles), ultimately leading to uneven extraction. Based on their findings, we can infer that different brewing setups for different coffee grind sizes are necessary for the desired extraction.

Bioactive compounds from plant tissues have utmost importance in food, pharmaceutical, and cosmetic industries. Cokgezme and Icier[19] explored experimentally the impact of electric fields on the destruction of cells. They applied the finite element method to determine the mass transfer during the extraction of oleuropein from olive leaves. They pointed out that frequency (1, 1000, or 2000 Hz) and wave type (sine or square) effectively modulate the final concentration in the oleuropein extraction. In addition, continuum-based computational models were proposed, where the diffusion coefficient was assumed constant for the first model. In contrast, the second model used a linear relationship between the cell disintegration index and mass transfer coefficient to determine the mass transfer rate and final oleuropein concentration. Better accuracy was achieved with the second model, which utilized the experimental data for effective diffusivity with lower RMSE and chi-square values.

Xue *et al.*[8] used smoothed particle hydrodynamics (SPH) coupled with the discrete element method (DEM) to simulate the two-phase flow of nearly spherical coarse calcium-alginate particles in a non-Newtonian fluid in a horizontal pipe. They benefited from the experimental observations for the model validation thanks to positron emission particle tracking as well as analytical solutions of radial velocity profiles. Their simulations investigated translational and rotational particle slip velocities, flow pressure field, and fluid vorticity. Particle angular velocities were significant, while the local translational particle slip velocities were small. As solid fraction becomes significant (i.e., close to packing), spin is negligible everywhere but not negligible close to the walls.

Creating a stable continuous flow is the first step in extrusion-based 3D printing to form string-like filaments for paste-like materials. However, the quality of a 3D shape depends on more parameters, starting from virtual dimensions (e.g., 3D shape design) to physical dimensions (e.g., optimization of food ink formulation, printing settings, and post-processing). Pulatsu and Udenigwe[4] identified a range of factors affecting the printing quality and shape complexity in additive manufacturing. They elucidated how to control and tune the properties of 3D-printed shapes toward the four-dimensional (4D) printing applications and underlined the necessity of flow physics under large deformations.

Crystallization and aging

Crystallization occurs in many food products, producing ice crystals in ice cream, fat crystals in butter and margarine, sugar crystals in powders, amylose crystals in starch, etc. During sugar crystallization, the diffusion of sucrose from the bulk solution to the thin layer at the interface crystal/solution occurs.[12] The driving force is chemical potential difference, and the rate is dependent on time, temperature, agitation, and presence/absence of impurities.[7,20] The size of the crystals may be large, as in the case of rock candies, while tiny crystals are desirable in fudge corresponding to their unique texture.[21] Hartge, Flöter, and Vilgis[7] studied crystallization in supersaturated sucrose solutions under agitation, different temperatures, and concentrations as simplified fondant model systems, qualitatively and quantitatively. They observed three stages in the crystallization process. A number of crystal conglomerates form, fracture, and break up significantly depending on temperature and composition, affecting the rheological behavior. Therefore, their growth and rate should be controlled, which lays the foundation for the confectionery industry. Werner-Cárcamo *et al.*,[16] on the other hand, focused on wax crystal formation in an oleogel setting and their complex behavior under large deformations. They highlighted the importance of cooling rate and shear flow for the nonlinear mechanical properties of wax oleogels toward the production of *trans*-fat free and low-saturate functional fats. Four dynamic zones regarding the crystallization process were discussed. Nucleation and crystal growth rates were reported to be the critical crystallization parameters to alter the gel microstructure and their rheological response. As noted in the article, the effect of applied forces, such as shear, can be detrimental or minimal depending on the processing stage. For instance, the shear damage is limited if the shearing is applied during the nucleation stage where there are no existing networks in the system. On the other hand, the system becomes more vulnerable to shear damage upon crystal formation. Hence, the timing of applied forces has equal importance and implications for the final product quality. Furthermore, the fat microstructure-oil binding capacity relationship was another discussion point. The transition from solid-to-liquid states can be observed when the yield stress value is exceeded, which determines hardness, spreadability, and stability corresponding to their potential use in plastic fat replacements.

Tireki *et al.*[6] studied the texture of different gummy candy formulation and their stability under different storage conditions by tracking their cross-link distance. Also, the empirical Weibullian models were used to compare the quality attributes of the candies at storage conditions. Hardness and average cross-link distances were influenced by the gelatin concentration, moisture content, storage time, and temperature but not by glucose syrup/sucrose ratio and starch concentration. The Weibullian models effectively quantify the physicochemical properties during storage and may also be extended to product development and quality assurance.

Ubbink and Muhialdin[22] performed a series of experiments to understand the effect of water content on the texturization of pea protein isolate (PPI) and studied the aging kinetics of extruded PPI by tracing Young's modulus values. The results indicate that Young's modulus decreases linearly with increasing water content. They also found a tenfold change in the aging rates when water content was increased by 20% in the extrudates. These findings are significant to improving plant-protein alternatives as creating anisotropic meat analog matrices is a step toward obtaining the desirable sensory properties and mouthfeel.

CONCLUSIONS

Food involves molecules of various structures and forms interacting with their surroundings. Ingredients (e.g., sugar and water) and processes (e.g., heating and mixing) can be simple but become complex in the food matrix. The addition of other ingredients (e.g., corn syrup, fat, and flavorings) may suppress or induce some changes or have no effect on the food matrix. Moreover, food processes involving shear forces can break interactions and structures or form bonds between components. On the other hand, both instability and stability can be desired depending on the application and conditions. The physical parameters, kinetics, empirical, and numerical models and classical theories in physics will undoubtedly find their place in different food matrix dynamics and processes within the defined boundaries, valid assumptions, and certain limitations in the search for providing better quality, improving efficiency, and introducing appropriate techniques.

This special topic has its roots in previous publications and books on food physics and owes its success to its contributing authors and readers. We hope that the knowledge shared through the publications will be a joyful experience for the curious food physics community and beyond, while the concepts and examples will be further researched and expanded.

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