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Abstract

Gels possess remarkable properties, and they hold particular importance in food science. After consumption, food gels undergo large deformation, which impacts the overall texture of the food. This process is influenced by various factors, including temperature, pressure, and presence of crosslinking agents. Comprehensive insights into the interplay among these factors and gel texture, combined with the theoretical exploration of gel deformation, enable the development of foods to meet consumer preferences. To bolster the development of food gels, in this review, we summarize the factors affecting the large deformation of gels. Moreover, we discuss various mathematical models established by food scientists to explore the large deformation of food gels and explore applications thereof. We expect that these insights into the large deformation of gels can lead to their increased utilization in the food industry.

Keywords: food gels; large deformation; theoretical basis; application

1. Introduction

Amidst global sustainability challenges, particularly those arising from population growth, environmental pressures, and energy consumption, development of innovative food products that address human nutritional requirements has become increasingly critical (Kell, 2022; Kumar et al., 2022). Among these innovations, gels have emerged as a promising solution. As elastic, semisolid soft materials with a three-dimensional (3D) network structure, gels demonstrate excellent controllability and large deformation characteristics (Gul et al., 2022; Yuan et al., 2025). The term "large deformation" indicates irreversible changes in the volume and shape of a gel due to external stimuli such as temperature, pH, or mechanical load, resulting in the fracture or collapse of the gel matrix and the permanent disruption of its molecular network. This property not only determines the performance of gels during food processing but also considerably affects the texture of food products (Gheorghita Puscaselu et al., 2020). Gels are used in a wide range of foods, from desserts, yogurts, to coatings for baked goods and fruits (Silva et al., 2020; Górska et al., 2024). In addition, they can be used as fat substitutes to maintain the nutritional value of foods and reduce their caloric content, thereby decreasing the risk of chronic conditions such as cardiovascular diseases and obesity (Nath et al., 2023; Nepovinnykh et al., 2019; Yang et al., 2020). However, the large deformation properties of gels, which are essential for their structural and functional optimization, remain poorly understood.

In laboratory settings, research on gel deformation primarily focuses on texture and rheological properties of gels. Texture analysis involves the assessment of various characteristics, such as stretching, compression, and puncture (St. Pierre et al., 2024), while rheological analysis primarily focuses on the viscoelastic properties and stress–strain responses of gels (Y. Wang & Selomulya, 2022). Modern rheometers can precisely determine the manner in which complex materials react to applied stress or strain, enabling the characterization of gel composition, structure, and processing effects. Customized gels with required characteristics can be fabricated by manipulating the polymer microstructure and surrounding medium (Nath et al., 2023). The complete rheological deformation curve of a viscoelastic gel typically comprises linear, nonlinear, and fracture regions (Fig. 1). Deformation is minimal in the linear region, whereas the nonlinear region shows more substantial deformation and is thus termed the "large deformation" region (Zhang et al., 2007). Under industrial processing conditions, gels are exposed to high levels of applied stress and strain. In such cases, mimetic mechanical tests prove to be invaluable for rheological characterization (Walayat et al., 2022).

In a previous review, Sinha et al. (2024) discussed a novel bi-gel system that combined the properties of organogels and hydrogels, focusing on how adjusting the organogel and hydrogel fractions can regulate their properties. Meanwhile, Lin et al. (2020) comprehensively reviewed the preparation methods for different types of emulsion gels (including bulk emulsion gels, emulsion gel particles, and fluid emulsion gels), their structure–property relationships, and their applications in the food industry. Moreover, B. Liu et al. (2024) systematically classified the mechanisms of food gel synthesis and discussed the application potential of gels in various functional foods, highlighting their applications in food packaging, satiety gel systems, nutrient delivery systems, food coloring adsorption, and food safety monitoring. While considerable research has been conducted on gels in food science, there remains a critical gap in understanding the manner in which the large deformation properties of these gels can be optimized for diverse applications. Although the existing research predominantly focuses on isolated factors such as pH, temperature, and crosslinking mechanisms, the interplay among these factors remains underexplored. Moreover, advancements in theoretical modeling and experimental tools have yet to be fully integrated into practical applications, limiting their potential effect on food innovation. Therefore, this review examines the factors influencing the large deformation of gels and discusses the mathematical models established by food scientists to explore this deformation in the context of food gel performance. This review aims to synthesize the current knowledge regarding the large deformation properties of gels, highlight the research gaps, and propose future directions to bridge the divide between fundamental research and industrial applications.

2. Theoretical framework for the large deformation of gels

The large deformation behavior of gels involves two key phenomena: (1) nonlinear elastic response, in which the relationship between force and deformation becomes nonlinear, and (2) material failure at a critical strain, referred to as the breaking strain. Both these conditions can be studied using stress–strain curves (Bot et al., 1996). Damage and fracture both need to be modeled to accurately simulate gel behavior. However, one key challenge lies in understanding the effect of fluid content on gel fracture. In addition, many models underestimate fracture resistance because they ignore the energy dissipation caused by fluid diffusion (Lake & Thomas, 1967). To address these issues, theoretical models and simulations need to incorporate fluid diffusion alongside the large deformation, damage, and fracture mechanisms that characterize gel behavior.

Mao and Anand (2018) developed a theoretical framework to explain the fracture of polymeric gels, incorporating the combined effects of fluid diffusion, large deformation, and damage. Their theory introduced two key ideas. First, it accounted for the changes in a gel's free energy due to entropy and internal-energy shifts caused by the stretching of polymer chains. Second, it posited that gel damage occurs through chain-scission, in which polymer chains break because of internal-energy changes rather than configurational entropy changes.

Small molecules can migrate into polymer networks, causing the network to swell and form polymeric gels. Hong et al. (2008) developed a theory combining mass transport and large deformation to explain this behavior. This theory suggested that the free energy of the gel arises from two molecular processes: the stretching of the polymer network and its mixing with small molecules. Small molecules and polymer chains both were treated as incompressible, and osmotic pressure was modeled using a Lagrange multiplier. The theory demonstrated that gels can deform through (1) rapid local rearrangement of molecules, which changes their shape without altering their volume, or (2) slower migration of small molecules, which affects both shape and volume. These mechanisms were modeled assuming that small molecules diffuse within the gel. This theory explains gel behavior under various conditions, such as those when a constrained gel layer is subjected to weight or deformation by means of a conical indenter. Such advancements enable more accurate modeling and a deeper understanding of gel deformation in complex scenarios.

2.1. Theoretical basis of the large deformation of gels

2.1.1. Free energy functions

Theories for hydrogel deformation were first proposed in pioneering works by Flory and Rehner (1943). These initial theories suggested that the Helmholtz free energy of a polymer network in an aqueous solution can be represented as the additive decomposition of the free energy of the elastic stretch of the polymer network and the free energy of mixing when the polymer network interacts with a solution. This decomposition has been widely used in subsequent theories of hydrogel behavior. Yang and Wang (2019) developed governing equations for functional gradient spherical hydrogels under spherically symmetric conditions by using the Flory-Huggins free energy function to simulate the nonuniform and large deformation swelling behavior of these hydrogels at a given internal pressure and chemical potential. According to the Flory theory, the more general form of the free energy of a hydrogel can be described as follows:

$$W = W_{net} + W_{mix} \sum_{r \neq s} W_r \quad (1)$$

where W_{net} and W_{mix} denote the free energy of network stretch and that of mixing, respectively. These two entities are applicable to all types of hydrogels. Meanwhile, W_r represents the free energy contributions of factors other than the solvent and is specific to certain types of gels.

These free energies include, but are not limited to, free energy of ionization (W_{ion}), polarization (W_{pol}), and dissociation (W_{dis}), which have been detailed previously (Z. Liu et al., 2015) and thus have not been repeated in this review.

2.1.2. Coupled diffusion–deformation theory

Baek and Srinivasa (2004) established thermodynamic theories of coupled diffusion and large deformation, paving the way for future continuum mechanics studies of hydrogel swelling. Yang et al. (2022) investigated the transient behavior of diffusion and deformation in hydrogels on the basis of the coupled diffusion theory. They stated that the diffusion of solutes from a spherical hydrogel occurs under the influence of fluctuating stresses. Meanwhile, the corners of a square hydrogel swell faster than the edges and interior, leading to deformation. Recent developments in coupled diffusion–deformation models have addressed some of these gaps by integrating solvent movement with mechanical deformation. However, these models often require extensive computational resources and are yet to be experimentally validated in complex food systems. Moreover, most existing models assume uniform material properties, limiting their accuracy in describing hybrid gels or multicomponent systems, both of which are commonly used in food formulations.

The equations governing gel swelling depend on the migration of solvent molecules. The flux is expressed (Bouklas & Huang, 2012) as follows:

$$j_i = \frac{cD}{kT}\frac{\partial \mu}{\partial x_i} \tag{2}$$

Moreover, it follows conservation laws:

$$\int_V \frac{1}{detF}\frac{\partial C}{\partial t}dV + \int_A j_i dA = 0 \tag{3}$$

where K is the Boltzmann constant, T is the temperature, V is the reaction volume, A is the reaction area, t is the time, C is the solvent concentration, D is the constant of solvent diffusivity, F is the deformation gradient, μ is the chemical potential, and c is the true solvent concentration.

2.1.3. Theories for large deformation of hydrogels

Under the influence of external stimuli, a hydrogel undergoes deformation from its initial reference state to its final current state. In describing this process of deformation, the deformation gradient F_{iK} (or F) is conventionally used. Fig. 2 shows the state of deformation of a hydrogel. Dutta et al. (2020) examined the hygroscopicity of white rice using deformation gradient equation modeling to identify a set of optimal process parameters in a temperature range of 25°C–80°C.

In the current state at time t, the marker X moves to a place with coordinates x(X,t). The deformation gradient is denoted (Z. Liu et al., 2015) as follows:

$$F_{iK}(X,t) = \frac{\partial x_i(X,t)}{\partial X_K} \tag{4}$$

Under conditions of equilibrium, the change in the free energy of the hydrogel is balanced via the external work performed on the gel. This thermodynamic equilibrium is usually expressed (Toh et al., 2014) as follows:

$$\int_V \delta W\, dV = \int_V B_i \delta x_i dV + \int_A T_i \delta x_i dA + \sum (\mu^r \int_V \delta C^r dV) \tag{5}$$

where W is the free energy of the gel; B_i is the external force; T_i is traction; and μ^r and C^r are the chemical potential and concentration of the r species, respectively.

2.2. Numerical simulation of hydrogel behavior

Numerical simulation is often employed to predict the behavior of hydrogels because it allows for us to study gels with complex geometries, which are often excessively complicated to study via analytical methods. The common simulation tools employed to study hydrogel behaviors include the finite element method, meshless methods, and molecular dynamics simulation.

2.2.1. Finite element method

The finite element method is a numerical solution method used for solving problems in elastic mechanics (Y. Liu et al., 2021). This method was rapidly developed following the availability of the electronic computer. Gels are soft materials and can undergo large deformations, and their mechanical behavior is influenced both by their polymer and solvent compositions. Currently, experimental methods are insufficient to accurately determine the mechanical properties of gel materials. Therefore, the finite element method has emerged as an important and commonly used simulation tool for study of gel deformation. With the development of monophase theories, the finite element simulation of hydrogel swelling has been expedited even further. ABAQUS and COMSOL Multiphysics, two finite element software, are currently the most popular tools employed for these simulations. ABAQUS can define material models through user-defined subroutines, while COMSOL Multiphysics is often used for the simulation of heavily coupled physical material models (Wu et al., 2023).

Nakauma et al. (2014) used a finite element model to simulate the compression of agar gel on different substrates, using linear elastic properties for their analysis. Their simulation results were validated through experimental findings. Meanwhile, Y. Liu et al. (2015) developed a finite element algorithm to model the uneven swelling of neutral hydrogels at equilibrium. In addition, Toh et al. (2014) employed the finite element method to simulate large, uneven deformations in gels under geometric constraints. Interestingly, using a custom subroutine in ABAQUS, they modeled gels as hyperplastic materials. These studies showed that finite element models can accurately predict the deformation of photothermal gels with complex shapes.

2.2.2. Ogden model

The Ogden model (Bergström, 2015) is a very general mathematical hyperelasticity model in which the Helmholtz free energy per reference volume is expressed in terms of the applied principal stretch. The Ogden model can be used to describe the mechanical behavior of materials under conditions of large deformation. This model is particularly suitable for hyperelastic materials, such as rubber and some polymers, as these materials exhibit nonlinear stress–strain relationships under the influence of large strains.

The first-order Ogden model expresses the mathematical relationship of compression stress with gel concentration, applied to fit the experimental data (Yao et al., 2022):

$$\sigma = \frac{2\mu}{\alpha}\left(\lambda^{\alpha} - \lambda^{\left(-\frac{\alpha}{2}\right)}\right) \quad (6)$$

where σ is the shear stress, μ is the shear modulus, and α is the Ogden constant.

The Ogden constitutive model has been widely adopted to describe the hyperelastic behavior of soft materials such as hydrogels and living tissues in the presence of uniaxial compression (Nedrelow et al., 2023). The first-order Ogden model was observed to be well-fitted to the effect of carbohydrates on the large deformation behavior of fish skin gelatin (X. Li et al., 2020). Moreover, Czerner et al. (2016) used the Ogden model to study the deformation and fracture behavior of physical gelatin gel systems and determined the shear modulus and strain hardening capability of the gels by means of the stress–stretch ratio curve.

2.2.3. BST model

In 1974, Blatz et al. (1974) proposed a strain energy density function based on a generalized measure of strain, which was later employed to study the large deformation of gels. This framework is referred to as the BST model. The BST model was derived from the rubber elasticity theory and has been employed to characterize the curvature of the stress–strain profile beyond the linear range. This model has been successfully applied to describe the deformation mechanics of various biopolymer food gels, including alginate (Zhang et al., 2005), mixed soy and κ-carrageenan (Cavallieri et al., 2010), and gelatin gels (Gravelle & Marangoni, 2021):

$$\sigma = \frac{2E}{3n}\left(\lambda^{n} - \lambda^{-2n}\right) \qquad n \sim \frac{d_f}{d_{f-1}} \quad (7)$$

where σ is the shear stress, λ is the stretch ratio, E is Young's modulus, and n is an elasticity parameter.

Theoretical models such as the Ogden and BST frameworks have significantly advanced the understanding of gel deformation, particularly in terms of comprehending nonlinear elasticity and fracture behavior. However, their application in food systems remains limited because of several challenges. The Ogden model, while effective at describing nonlinear stress–strain relationships, does not account for time-dependent viscoelastic properties, which are critical in dynamic processes such as extrusion and chewing. Similarly, the BST model offers robust predictions of gel fracture but struggles to incorporate solvent migration and environmental factors such as pH and temperature variations.

Thus, future advancements should focus on integrating these theoretical frameworks with machine learning and experimental data so as to improve their predictive power and practical relevance. For instance, machine learning could be employed to identify patterns in large datasets generated in rheological experiments, enabling models to better comprehend the multiscale behavior of gels. Moreover, hybrid models that combine microstructural dynamics with macroscopic deformation behavior might provide a more comprehensive understanding of gel mechanics under real-world conditions. By addressing these limitations, theoretical models might play a pivotal role in optimizing gel properties for applications such as 3D food printing, the development of dysphagia-friendly formulations, and bionic food design, bridging the gap between fundamental research and industrial practice.

3. Factors affecting the large deformation of gels

Various factors can influence the large deformation behavior of gels and can be split into two groups: internal and external. Notably, the internal factors are intrinsic to the gel and include gel concentration and gel composition. Meanwhile, the external factors include pH, temperature, high-pressure processing (HPP), crystal addition, crosslinking agents, and polysaccharide charge density. Food texture is affected by the large deformation characteristics of food gels (Gravelle & Marangoni, 2021). Understanding the manner in which these factors influence food properties might aid the development of novel food products customized to consumer demands.

3.1. Gel composition

Gel composition is an important intrinsic factor affecting the mechanical strength of gels. Proteins and polysaccharides are the most common gel components used in food products and have attracted considerable attention in the field of functional foods because of their low toxicity, edibility, biocompatibility, biodegradability, and affordability (K. Liu et al., 2021).

Polysaccharides strengthen gels by enhancing hydrogen bonding and forming robust double-network structures. For example, viscoelastic analysis has shown that curdlan expedites the formation of denser rice starch gels with a higher degree of solidity (Wang et al., 2024). Similarly, *Mesona chinensis* polysaccharide–tapioca starch gels exhibit excellent flexibility and durability, with a stable network structure maintained via hydrogen bonding (Huang et al., 2023).

Gelatin, a type of protein, facilitates the formation of hydrophobic interactions, disulfide bonds, and hydrogen bonds among globular proteins, transforming weak 3D gel networks into dense-layered structures. Gelatin can be categorized as aquatic or terrestrial depending on its source. In particular, aquatic gelatin is primarily derived from fish (fish skin, fish scales, and swim bladders), while terrestrial one is usually derived from the skin, bones, and connective tissues of swine and cattle (Derkach et al., 2022; Nurilmala et al., 2021; Zou et al., 2024). Among the different types of gelatin extracted from animal skins (pig skin, cow skin, and fish skin), pig skin and cow skin gelatin exhibit the greatest and poorest ability to resist deformation, respectively (Michelini et al., 2020). The gel strength of bovine bone gelatin, however, is greater than that of fish skin gelatin (T. Zhang et al., 2020). These variations highlight the manner in which the source and amino-acid composition of gelatin affect its ability to resist large deformations. The energy storage modulus of globular protein gels significantly increases when gelatin is added, suggesting that gelatin can improve the strength of these gels and stabilize the protein network structure (Ma et al., 2022).

The choice of gel components—proteins or polysaccharides—greatly influences the mechanical and sensory properties of a gel. While polysaccharides facilitate robust network formation via hydrogen bonding, proteins provide a tunable rheological behavior. Previous research has largely focused on these components in isolation, neglecting the manner in which hybrid gels comprising proteins and polysaccharides may offer superior large deformation characteristics. Thus, comparative studies on hybrid gel systems could facilitate the development of novel gel formulations for customized applications.

3.2. Gel concentration

Gel concentration is another intrinsic factor affecting the mechanical strength of gels. The minimum protein concentration required to form gels varies from one protein to another. For example, the minimal concentration required for gel formation is 0.6% for gelatin, 3% for egg albumin, 6.6% for soy proteins, and 4%–12% for whey proteins and varies depending on the pH and ionic strength (Le et al., 2017). In particular, gel concentration affects gel strength by altering the gel's microstructure. In low-concentration gels, the microstructure is loose and the pore size is large. Meanwhile, high-concentration gels are dense and have a small pore size (Cortez-Trejo et al., 2021). Horinaka et al. (2022) studied the effect of gel concentration on the cyclic deformation behavior of κ-carrageenan hydrogels. High-concentration κ-carrageenan hydrogels exhibited good elastic properties, whereas low-concentration κ-carrageenan ones showed a higher Young's modulus. Subsequently, Horinaka and Ogawa (2023) also explored the effect of agarose concentration on the cyclic deformation behavior of agarose hydrogels, and their findings were consistent with those related to κ-carrageenan hydrogels.

Gel concentration considerably impacts the mechanical properties and deformation behavior of gels. However, while high-concentration gels often exhibit improved strength and reduced deformability, the manner in which these properties interact with other factors—such as crosslinking density or temperature—remains poorly understood. Future studies should explore synergistic effects by investigating the manner in which the optimization of gel concentration can enhance gel stability during industrial processing conditions.

3.3. pH

The effects of pH on the large deformation of gels are primarily mediated through pH's effect on gel swelling, structural stability, and microstructure (Z. Liu et al., 2024). The response of different gels to pH varies based on factors such as gel composition, crosslinking agents, and environmental conditions. pH influences the structure of proteins by altering the balance of attractive and repulsive forces, which can lead to protein unfolding and denaturation (Tan et al., 2021). For example, Razi et al. (2019) studied egg white albumin and basil seed gum mixtures under different pH conditions at high pressure. The gels formed at pH 5.0 exhibited higher elasticity than those formed at pH 7.0, likely because of stronger electrostatic and hydrophobic interactions at pH 5.0 (Hosseini-Parvar et al., 2016). These findings showed that pH is a critical factor influencing the large deformation behavior of gels, highlighting its role in shaping of gel properties.

Proteins, as natural polyampholytes, can form gels through heat-induced gelation or cold gelation (Betz et al., 2012). The pH-dependent swelling behavior of protein gels has been extensively studied. Saglam et al. (2013) observed that protein particles in gels formed via emulsification and heat-induced gelation remained stable across a wide pH range but exhibited aggregation at pH ~5 likely because of reduced electrostatic repulsion near the protein's isoelectric point. This aggregation can cause substantial volume changes, affecting the rheological properties of the gel. Wang et al. (2021) studied whey protein gels containing glucose and fructose fabricated via the Maillard reaction at different pH levels. They observed that the elastic modulus of these gels depended on the strength of interactions between the protein molecules and sugar chains. The gels reached their maximum elasticity at different temperatures, and their elasticity decreased as the pH increased, demonstrating that pH influences molecular interactions within gels.

3.4. Temperature

The treatment temperature of gels is crucial for determining their strength and rheological properties. Meat, a common component of the diet for several populations worldwide, exhibits gel-forming and viscoelastic properties that depend on the bonds stabilizing the gel network (Tammatinna et al., 2007). Changes in treatment temperature can affect the strength, rheology, and sensory attributes of meat gels. For example, Mad-Ali et al. (2018) observed marked differences in gel strength and deformation among goat meat gels treated at different temperatures. They noted that preheating the meat prior to heating it to 90°C could enhance the gel's breaking force and deformation capacity, highlighting the importance of temperature in controlling meat gel behavior.

Starches too are key components of processed foods, and the gelatinization process during heating affects the rheological behavior of starch gels (Rocha et al., 2011). Albano et al. (2014) studied gels made from Peruvian carrot starch at different temperatures (10°C, 30°C, 50°C, and 70°C) and observed that they exhibited shear-thinning behavior and high thixotropy. Notably, the results demonstrated that the setting temperature substantially affected the consistency index of the gels. Further, Sha et al. (2019) observed that higher extraction temperatures of porcine gelatin reduced the gel strength, gelation point, and melting point, demonstrating the manner in which temperature affects the gelling properties of gelatin.

While pH and temperature are known to affect swelling and gelation kinetics, their interaction with mechanical stress during large deformation remains underexplored. For instance, acidic conditions can increase elasticity in egg albumin gels; however, the manner in which these conditions interact with thermal cycles to influence fracture behavior is still unclear.

3.5. High-pressure processing

HPP, a nonthermal sterilization method in which pressures ranges from 100 to 1000 MPa, is applied to food products, and it prevents spoilage without affecting the sensory or physicochemical characteristics of food (Fam et al., 2020; C. Ren et al., 2020). This treatment also provides functional effects and is widely used in the food industry (Mokrushin et al., 2022). HPP can lower the gelatinization temperature of starch, with higher pressures providing greater reductions in the gelatinization temperature (Balakrishna & Farid, 2020). In addition, HPP treatment can be employed to obtain starch gels with more stable crystallites, denser structures, reduced retrogradation, and increased gel stability (Guo et al., 2022).

Food products often comprise proteins and polysaccharides, which affect the texture, structure, and stability of gels because of their gelling, thickening, and surfactant properties. In mixed gels, HPP disrupts the interactions between proteins and polysaccharides, causing biopolymer complexes to dissociate and proteins to denature, which alters gel properties (Razi et al., 2019). Previously, HPP has been successfully applied in fish processing (Qin et al., 2022). Moreover, this technique is employed to modify protein properties in several foods, altering protein structure and affecting coagulation, aggregation, and gelation behavior (Moreno et al., 2015).

Velazquez et al. (2021) showed that HPP can create a soft flexible network in crabmeat gels, reducing their rigidity by fully denaturing the proteins and facilitating aggregation through disulfide bonding. In particular, HPP at 100 MPa afforded the crabmeat gels with optimal rheological properties. Similarly, Xu et al. (2024) observed that HPP caused the gradual unfolding of α-helixes in Tai Lake whitebait myofibrillar protein gels, transforming the α-helixes into β-sheets. Compared with untreated gels, these gels exhibited a 4.8-fold increase in gel strength and improved elastic and viscous moduli (G′ and G″).

3.6. Crystals

The large deformation properties of gels are influenced by natural crystallization during aging and can also be affected by the addition of external crystals. Aging causes retrogradation in gels, gradually altering their physical properties (Jiang et al., 2020). This process involves the crystallization of molecules in the gel, which results in the formation of an ordered structure. Retrogradation affects not only the texture, rheological behavior, and pasting properties of gels but also their crystalline and molecular structures (X. Liu et al., 2021).

Inulin, an oligosaccharide, forms gels containing a network of small crystals when mixed with water at high concentrations (J. Xu & Kenar, 2024). With time, these gels develop larger crystals and their fracture strain decreases. The retrogradation temperature also plays a role in this process: lower temperatures make the gels more brittle, and the maximum fracture force is generated during large deformation. Starch gel retrogradation is influenced by the water content, with higher water levels facilitating the formation of softer gels with well-defined crystallites (X. Liu et al., 2021).

The addition of crystals also affects gel deformation. Xiao et al. (2020) added cellulose nanocrystals (CNCs) to whey protein gels, increasing their water-holding capacity, strength, viscoelasticity, and thermal stability. CNCs restricted the water mobility within these gels and transformed the α-helixes of proteins into β-sheets. These findings were similar to those reported by X. Liu et al. (2021) who highlighted the role of moisture in gel deformation. Thus, naturally sourced CNCs are being explored as promising gel modifiers in the food industry.

3.7. Crosslinking agents

The water absorption capacity of a hydrogel depends on factors such as the type and density of the polymer and crosslinking agent used (Juan et al., 2022). Crosslinking agents are chemicals that link unsaturated compounds at the molecular level, forming a 3D network structure in gels. These agents are used in various fields, including the food industry, biomedicine, and materials science. In the food industry, enzymes and certain chemicals are the most commonly employed crosslinking agents (Table 1). Enzymatic crosslinking agents such as transglutaminase (TG) and various oxidases catalyze the formation of covalent bonds among proteins (Zheng et al., 2022). Chemical crosslinkers are typically small molecules that interact with proteins or other food components to yield a stable crosslinked framework, thus influencing food characteristics, particularly food texture. Other than these conventional crosslinkers, some specialized crosslinking agents can also be employed for specific applications. For instance, a novel crosslinking agent that contains whey protein, papain, glycerol, and epicatechin gallate exemplifies the recent advancements in crosslinking strategies (Liu et al., 2023).

Gelatin, a biopolymer derived from collagen, is widely used in food and pharmaceuticals owing to its swelling capacity, biodegradability, and biocompatibility (Echave et al., 2019). Although gelatin can form hydrogels upon cooling, its mechanical properties are often poor, necessitating the use of crosslinking agents (Uranga et al., 2020). Lin et al. (2023) observed that TG can crosslink fish gelatin (FG) in a dose-dependent manner, notably increasing gel strength (G′). Thus, the introduction of covalent crosslinks via TG can enhance the thermodynamic and mechanical stabilities of FG gels, creating more organized structures.

In summary, crosslinking agents greatly improve the strength, stiffness, and stability of gelatin hydrogels, which makes them valuable across various industrial sectors. However, the influence of crosslinking agents on the large deformation of gels warrants further exploration as this could help in the development of gels with improved properties and provide insights into the internal factors governing their large deformation.

Table 1. Crosslinking agents used in common gels (Alavarse et al., 2022).

Crosslinker	Source	Polymers	Mechanism	pH, Temperature
Transglutaminase	Bacteria, mammals, and plants	Gelatin, collagen, whey protein, soy protein, chitosan, and carboxymethyl cellulose	Presence of glutamic acid and lysine groups; acyl ligands/amine ligands from L-glutamic acid and L-lysine	5.5, 40°C
Horseradish peroxidase	Root (*Armoracia rusticana*)	Hyaluronic-Tyramine (®Corgel), alginate–tyramine, gelatin norbornene/4-arm poly(ethylene glycol) dihydrogen tetrazine, and silk-fibroin	Oxidation of phenolic and catechol groups (requires hydrogen peroxide addition), peroxidation, isomerization, dimerization, and enolization	7.0, 45°C
Tyrosinase	Microorganism, plants, and animals	Alginate, hyaluronic acid/gelatin, and glycol chitosan	Presence of phenolic/catechol groups. Oxidation (O_2 species), semi-quinone formation through Micheal addition, isomerization, dimerization, and enolization	6.5, 50°C
Whey protein	Animals	Protein and polysaccharides	Maillard reaction	7.0, 50°C
Epicatechin gallate	Plants	Gelatin	Aldehyde group in gallic acid reacts with the amino group to form a stable covalent bond	5.5, 45°C

Although considerable efforts have been made toward understanding the specific mechanisms through which these substances impact the large deformation in gels, continued research is still needed. Some researchers are now employing computational mechanics to examine the large deformation of gels, providing theoretical information that could aid the understanding of and improvement in gel properties.

4. Applications of the large deformation of gels

Gels, as abundant renewable biopolymers, have attracted attention because of their sustainability, affordability, and biocompatibility. Consequently, they have emerged as useful, cost-effective, and easily modifiable materials (Li et al., 2021). Their unique properties and wide application prospects have sparked interest across various sectors, including food (De Leon Rodriguez & Hemar, 2020), biomedicine (Z. Li et al., 2020), soft robotics (Jiang et al., 2023), and flexible electronics (Zhu et al., 2024). Gels have widespread applications in food products (Fig. 3), and gel texture notably impacts the taste of foods. Exploring the large deformation characteristics of gels, such as gel strength and viscoelasticity, can help in the development of foods customized to consumer preferences. Moreover, gels can be used for the production of easy-to-consume foods for individuals with chewing difficulties, thus addressing their specific needs.

4.1. Food texture

Texture refers to the sensations experienced when eating food, including the initial bite, chewing, and swallowing (Kutlu et al., 2022). Commonly referred to as “mouthfeel,” texture plays a key role in consumer perception because it represents the sensory experience of a food’s molecular, microstructural, and macrostructural composition. Therefore, texture is evaluated through visual assessment, touch, and sound (Cao & Mezzenga, 2020). Among these factors, the tactile feedback provided by the mouth during eating is the most important. The first bite, which breaks down the structure of the food, providing different sensory perceptions based on the gel’s fracture stress and strain (Franks et al., 2020). Gels with higher deformation capacity provide a softer initial bite but remain resilient, providing a satisfying chew. The large deformation behavior of gels also impacts the manner in which the gel breaks down and releases flavors, which is a crucial consideration while designing foods to suit consumer preferences. For example, softer gels are preferred in desserts, while firmer, more elastic gels are used in products such as gummies or meat analogs for a chewier texture.

The texture of solid and semisolid foods is attributed to the mechanics of food breakdown in the mouth (van Bommel et al., 2019). The consumer's first bite and chew are governed by the large deformation properties of the food (Gravelle & Marangoni, 2021). Instruments can be employed to analyze the fracture properties of gels, such as fracture stress and strain, which are directly related to their texture. In particular, fracture stress is associated with the perceived hardness of foods, while fracture strain is related to how easily the food deforms during the first bite (Nishinari et al., 2024).

4.2. 3D food printing

3D food printing is an advanced process combining 3D modeling, electromechanical control, food science, and other technologies to create food products through an additive manufacturing process (Wang et al., 2022). This method enables the production of customized foods that cater to specific consumer needs, enhancing their sensory qualities, nutritive value, and texture (Park et al., 2020). Foods such as chocolates, cakes, candies, and even artificial meat have been successfully produced via 3D printing (He et al., 2020). Compared with traditional food production methods, 3D printing offers benefits such as lower cost, simpler operation, and faster production of customized products (Umeda et al., 2024). During printing, gels undergo notable shear deformation because they are extruded through the printer nozzle. The large deformation properties of gels, including their yield stress and viscoelasticity, impact their ability to maintain and recover their shape after deposition for 3D printing. Gels that cannot recover well may collapse or lose their structure, resulting in printed products of poor quality. Therefore, gels need to be able to withstand large deformations while retaining their shape so as to ensure the successful 3D printing of complex food designs. Kim et al. (2022) developed a low-calorie form of surimi by combining carrageenan, a highly elastic protein substitute, with surimi through coaxial 3D printing. This process maintained the freshness and tenderness of surimi while reducing its caloric content, making it ideal for older adults or fitness-conscious individuals.

In recent years, 3D food printing has attracted significant attention, because of which natural food gels are being developed for printing. The deformability of these gels allows for us to modify their fluidity, elasticity, and thermal properties through additives or treatments, enabling the fabrication of suitable materials for 3D printing. This technology can improve the nutritional value of meals, benefiting both consumers without major health issues and those with nutritional disorders such as malnutrition (Anukiruthika et al., 2020). Notably, 3D printers can now create foods customized to consumer preferences by optimizing their flavor, texture, color, price, and nutritional content. Natural substances, such as plant oils and emulsions, can be used to modify the texture of printed food, influencing its printing behavior and gel characteristics (Yang et al., 2024; Liang et al., 2024). Developing natural modifiers for 3D printing can enable the development of customized food products that promote health and cater to a wide range of consumers, from children to older adults (Das et al., 2023).

Gels require high elasticity and stress recovery to maintain structural integrity during extrusion. While shear-thinning additives provide improved printability, achieving consistent postdeposition stability remains challenging. Future research should focus on hybrid gels that offer both high printability and customized textural properties.

4.3. Food preparation for individuals with dysphagia

Dysphagia is defined as the difficulty or inability to swallow liquids, solids, or semisolids, including drugs (Nishinari et al., 2023). This condition can lead to weight loss, malnutrition, dehydration, and serious health issues such as aspiration pneumonia (Icht et al., 2018). Individuals with dysphagia are advised to eat foods that are soft, moist, elastic, smooth, and easy to swallow. Because gels are smooth, soft, and easy to break down, they are ideal for this group of patients (Raheem et al., 2021). Gels prepared for patients with dysphagia should have low fracture stress and should easily deform when chewed. Optimal large deformation properties, such as high strain and low hardness, are important for controlling the texture and consistency of these gels, making them easy to swallow without any risk of choking or aspiration. By adjusting the viscoelastic properties of food gels via additives, these gels can be customized to meet the needs of patients with different levels of dysphagia, ensuring safe consumption. Thickeners modify the rheological properties of food, slowing its movement through the mouth and throat, giving muscles more time to react and reducing the risk of aspiration (Štreimikytė et al., 2020). Thus, gels can be used as thickeners to create softer, more cohesive foods that are easier to chew and swallow.

Pure et al. (2021) modified the texture of a high-protein gel to make it suitable for patients with dysphagia. After microwave processing, the gel became a soft solid. Fei et al. (2024) developed a salmon-protein-based composite emulsion gel with konjac glucomannan and an emulsion filler. Konjac glucomannan altered the protein structure, and the filler improved the gel's elasticity and strength (Luo et al., 2024). These changes made the gel safer to swallow and improved its cohesion, enhanced its mouthfeel, and reduced its stickiness.

Soft gels with controllable deformation properties are essential for individuals with swallowing difficulties. The current formulations focus on texture but often neglect sensory aspects such as flavor release and bioavailability. Thus, studies integrating rheological testing with sensory analysis are needed to optimize these products.

4.4. Bionic foods

Gel-based bionic foods are an innovation in the food gel technology and can replicate the structure and characteristics of natural foods (Zhou et al., 2023). They typically have a soft texture and rich taste, and they mimic the flavor and texture of meats and other foods (Du et al., 2023b). Plant-based meat alternatives are an important step in improving human health, conserving resources, and supporting animal welfare (Sun et al., 2021). These alternatives are also rich in essential nutrients, making them a great choice for daily nutrition. Moreover, the development of sustainable bionic foods, such as meat substitutes, is crucial to meeting the growing dietary demands, particularly in light of resource scarcity and environmental concerns (Yang et al., 2023). Bionic foods can provide viable alternatives to natural foods, helping mitigate these challenges (Du et al., 2022).

The ability of gels to deform without breaking is a key to simulating the texture of meat. Bionic foods require gels that stretch, compress, and recover in ways similar to natural tissues. Gel-based bionic foods that replicate the fibrous structure and chewiness of meat can be developed by controlling the deformation properties, such as elasticity and toughness. This replication is important for consumers' acceptance of plant-based alternatives. For example, Du et al. (2023a) used agarose/konjac glucomannan double-network hydrogels to imitate the texture of beef tripe. A 1:4 (w/w) ratio of agarose to konjac glucomannan resulted in a gel with a texture similar to that of cooked beef reticulum and rumen, enabling the production of artificial beef tripe.

Consumer surveys revealed widespread interest in the comparison of appearance, taste, and texture of bionic foods with traditional ones (Hoek et al., 2011). While substantial progress has been made in replicating the appearance and taste of natural foods by using flavor compounds and plant pigments, the real challenge lies in recreating the texture, particularly that of foods with complex structures. Through mechanical stretching, He et al. (2022) developed an anisotropic hydrogel that successfully imitated the texture and taste of meat. Likewise, for the simulation of the mouthfeel of other foods, bionic foods need to be processed to fully utilize the large deformation properties of gels. The replication of anisotropic textures in meat analogs requires gels with directional deformation properties. While recent advances in protein–polysaccharide composites show promise, scalability and environmental impact remain critical challenges to solve.

4.5. Food packaging

Hydrogels are useful as food packaging materials, particularly for controlling the moisture content, which significantly impacts the shelf life of food products (Batista et al., 2019). These gels are referred to as colloidal gels because their molecules are evenly dispersed in water. Their viscoelastic and structural properties are derived from polymer chains and their interactions with the surrounding medium (Ahmed et al., 2013). Packaging gels need to have sufficient strength to withstand large deformations caused by handling, transport, and environmental changes such as those in humidity. Their flexibility enables them to form a tight seal around different food products, and their ability to retain water helps in moisture regulation, extending the food's shelf life.

Hydrogels for packaging are made from natural polymers such as proteins, carbohydrates, and lipids, which can be sourced from plants or animals (Du et al., 2021). The main natural polymers used to prepare hydrogels for food packaging are presented in Table 2, along with their key features and properties. The proportion of these natural polymers can be adjusted to prepare hydrogels with the desired water retention capacity, flexibility, and mechanical properties (Jildeh & Matouq, 2020). Notably, hydrogels with good malleability and swelling properties are suitable as food packing materials (Alharaty & Ramaswamy, 2020). Moreover, these hydrogels need to exhibit good elasticity, tensile strength, and toughness, all of which represent their large deformation properties.

Table 2. Properties of natural polymer-based hydrogels used in food packaging applications (Leyva-Jiménez et al., 2023).

Polymer	Material	Origin	Solubility	Advantages	Disadvantages
Polysaccharides	Chitosan	Chitin	Polar solvents	Great mechanical properties; great antimicrobial property; gas/water barrier properties	Highly hydrophilic
	Starch	Plants	Water	Highly biocompatible with polymers	Highly hydrophilic, brittle
	Pectin	Fruits	Water	High biodegradability; biocompatibility with polymers	Unstable mechanical properties
	Gum	Resins	Water	Emulsifying properties	Unstable mechanical properties; poor gas/water barrier properties
	Alginate	Marine algae	Water, ethanol	Self-healing properties; formation of water vapor barrier	Instability against radiation or handling
	Bacterial cellulose	Bacteria	Water	Film forming versatility; great gas/wate barrier	Laborious process of isolation
Protein	Zein	Corn	Ethanol, acetone	Film forming properties	Brittleness
	Soy protein isolate	Soybean	Water, ethanol	Gas barrier properties; pH- and temperature-responsive films	Water resistance, rigidity, brittleness
	Whey	Milk	Water, ethanol	Great mechanical properties; reduced oxygen and carbon dioxide permeability	Moderate barrier to gas

Continue

Polymer	Material	Origin	Solubility	Advantages	Disadvantages
Protein	Casein	Milk	Water	Forms flexible and nonopaque films; gas and lipid barrier properties	Brittleness
	Wheat	Starch	Water	Moderate barrier to oxygen	Brittleness
	Gelatin	Collagen	Water	Great gelling capacity; pH- and temperature-responsive films	Highly hydrophilic
Lipids	Wax	Bees	Water by emulsion	Low water vapor barrier	Poor mechanical properties
	Acetoglycerides	Fatty acid	Water by emulsion	Stretch properties; reduced water vapor permeability	Low mechanical strength; low oxygen permeability
Another	Lignin	Wood	Water by emulsion	Antioxidant capacity; great mechanical properties	Highly hydrophilic, brittle
	Poly lactic acid	Corn biomass	Organic solvents	Great mechanical properties	Brittle and weak films

Despite their potential, the development of natural hydrogels for food packaging is still in its nascent stages and several challenges remain to be addressed. This has limited their widespread application in food packaging.

5. Conclusions

Gels are important in the field of food science. These materials have specific structural and functional properties that enhance the texture, taste, and stability of associated food products. A comprehensive understanding of the factors influencing the large deformation properties of food gels, including gel concentration, pH, temperature, and additives, is crucial to innovating and developing gel-based products. Theoretical models have undergone continuous refinement and improvement ever since the discovery of the large deformation of gels. This review highlights the different factors impacting the large deformation of gels and also discusses the theories and mathematical models developed to understand and simulate this process. Furthermore, it summarizes the application of the large deformation characteristics of gels in the fields of bionics and food science.

Although the application of gels with large deformation characteristics has grown in the food industry, several challenges continue to persist. The process of gel deformation is very complex and is influenced by a multitude of factors. The deformation of food gels during the process of eating cannot be fully simulated by mathematical models because these models cannot capture the intricacies of the process. Food consumption does not only involve mechanical actions such as chewing but also the enzymatic action of saliva and the electrical signals that transmit sensory information to the brain. Currently, this multifaceted process cannot be completely simulated through mathematical models or mechanical simulations. These problems need to be addressed in future research. We believe future research should focus on combining theoretical models with experimental data so as to more accurately predict gel behavior and develop blended gels customized for specific applications, such as 3D printing and the fabrication of dysphagia-friendly foods. Sustainable and scalable innovations, such as bio-based crosslinkers and mixed additive systems, should also be explored.

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Declaration of competing interest

The authors declare that they have no conflicts of interest regarding this study.

Figure captions

Fig. 1. Rheological responses in viscoelastic solids.

Fig. 2. Hydrogel undergoing deformation in response to external stimuli, and changes from the reference state X_K to the current state x_i.

Note: Image created using BioRender and published with permission

Fig. 3. Applications of food gels.

Note: Image created using BioRender and published with permission

Figures

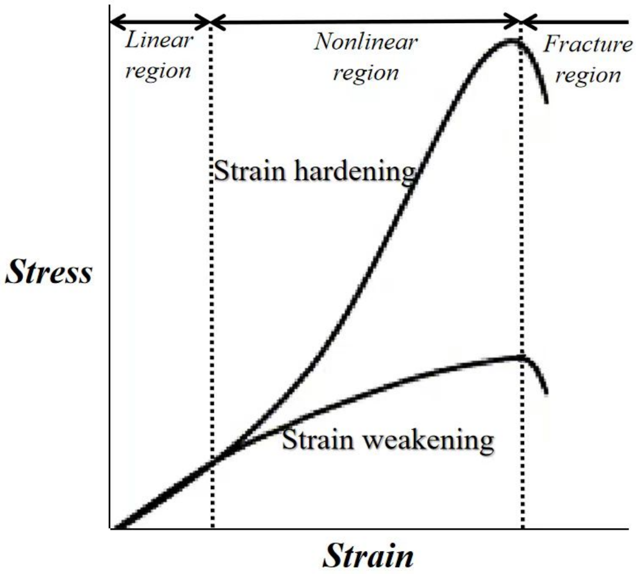

Fig. 1

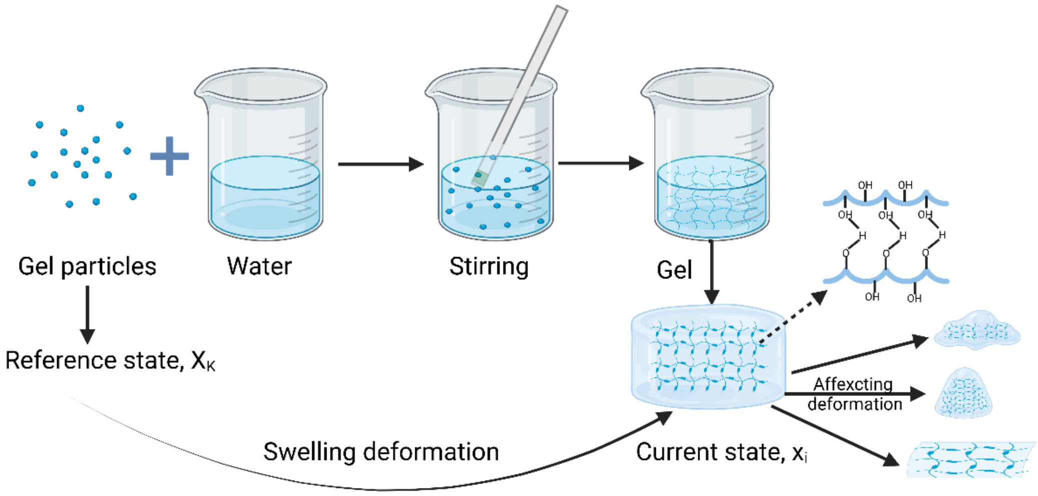
Gel particles
Water
Stirring
Gel
Reference state, X_K
Swelling deformation
Current state, x_i
Affexcting
deformation

Fig. 2

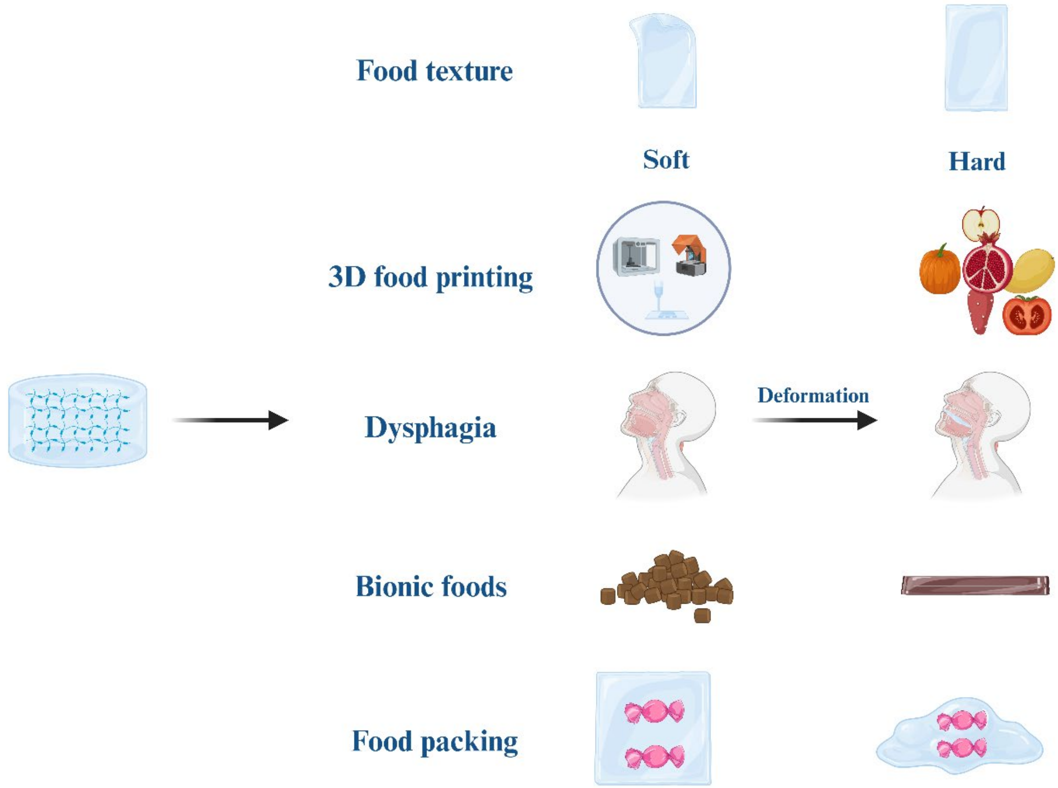
Food texture
Soft
Hard
3D food printing
Dysphagia
Deformation
Bionic foods
Food packing

Fig. 3

References

Ahmed, E. M., Aggor, F. S., Awad, A. M., & El-Aref, A. T. (2013). An innovative method for preparation of nanometal hydroxide superabsorbent hydrogel. Carbohydrate Polymers, 91 (2), 693-698. https://doi.org/10.1016/j.carbpol.2012.08.056

Alavarse, A. C., Frachini, E. C. G., da Silva, R. L. C. G., Lima, V. H., Shavandi, A., & Petri, D. F. S. (2022). Crosslinkers for polysaccharides and proteins: Synthesis conditions, mechanisms, and crosslinking efficiency, a review. International Journal of Biological Macromolecules, 202, 558-596. https://doi.org/10.1016/j.ijbiomac.2022.01.029

Albano, K. M., Franco, C. M. L., & Telis, V. R. N. (2014). Rheological behavior of Peruvian carrot starch gels as affected by temperature and concentration. Food Hydrocolloids, 40, 30-43. https://doi.org/10.1016/j.foodhyd.2014.02.003

Alharaty, G., & Ramaswamy, H. S. (2020). The Effect of Sodium Alginate-Calcium Chloride Coating on the Quality Parameters and Shelf Life of Strawberry Cut Fruits. Journal of Composites Science, 4 (3), 123. https://doi.org/10.3390/jcs4030123

Anukiruthika, T., Moses, J. A., & Anandharamakrishnan, C. (2020). 3D printing of egg yolk and white with rice flour blends. Journal of Food Engineering, 265, 109691. https://doi.org/10.1016/j.jfoodeng.2019.109691

Baek, S., & Srinivasa, A. R. (2004). Diffusion of a fluid through an elastic solid undergoing large deformation. International Journal of Non-Linear Mechanics, 39 (2), 201-218. https://doi.org/10.1016/S0020-7462(02)00153-1

Balakrishna, A. K., & Farid, M. (2020). Enrichment of rice with natural thiamine using high-pressure processing (HPP). Journal of Food Engineering, 283, 110040. https://doi.org/10.1016/j.jfoodeng.2020.110040

Batista, R. A., Espitia, P. J. P., Quintans, J. d. S. S., Freitas, M. M., Cerqueira, M.

Â., Teixeira, J. A., & Cardoso, J. C. (2019). Hydrogel as an alternative structure for food packaging systems. Carbohydrate Polymers, 205, 106-116. https://doi.org/10.1016/j.carbpol.2018.10.006

Bergström, J. (2015). Elasticity/hyperelasticity. Mechanics of solid polymers, 209-307. https://doi.org/10.1016/C2013-0-15493-1

Betz, M., Hörmansperger, J., Fuchs, T., & Kulozik, U. (2012). Swelling behaviour, charge and mesh size of thermal protein hydrogels as influenced by pH during gelation. Soft Matter, 8 (8), 2477-2485. https://doi.org/10.1039/C2SM06976H

Blatz, P. J., Sharda, S. C., & Tschoegl, N. W. (1974). Strain Energy Function for Rubberlike Materials Based on a Generalized Measure of Strain. Transactions of The Society of Rheology, 18 (1), 145-161. https://doi.org/10.1122/1.549353

Bot, A., van Amerongen, I. A., Groot, R. D., Hoekstra, N. L., & Agterof, W. G. M. (1996). Large deformation rheology of gelatin gels. Polymer Gels and Networks, 4 (3), 189-227. https://doi.org/10.1016/0966-7822(96)00011-1

Bouklas, N., & Huang, R. (2012). Swelling kinetics of polymer gels: comparison of linear and nonlinear theories. Soft Matter, 8 (31), 8194-8203. https://doi.org/10.1039/C2SM25467K

Cao, Y., & Mezzenga, R. (2020). Design principles of food gels. Nature Food, 1 (2), 106-118. https://doi.org/10.1038/s43016-019-0009-x

Cavallieri, Â. L. F., Garcez, M. M., Takeuchi, K. P., & Cunha, R. L. d. (2010). Heat-induced gels of soy protein and κ-carrageenan at different pH values. International Journal of Food Science & Technology, 45 (6), 1130-1137. https://doi.org/10.1111/j.1365-2621.2010.02247.x

Cortez-Trejo, M. C., Gaytán-Martínez, M., Reyes-Vega, M. L., & Mendoza, S. (2021). Protein-gum-based gels: Effect of gum addition on microstructure, rheological pr operties, and water retention capacity. Trends in Food Science & Technology, 116, 303-317. https://doi.org/10.1016/j.tifs.2021.07.030

Czerner, M., Fasce, L. A., Martucci, J. F., Ruseckaite, R., & Frontini, P. M. (2016). Deformation and fracture behavior of physical gelatin gel systems. Food Hydrocolloids, 60, 299-307. https://doi.org/10.1016/j.foodhyd.2016.04.007

Das, A., Bai, C. H., Chang, J. S., Huang, Y. L., Wang, F. F., Chen, Y. C., & Chao, J. C. (2023). Associations of Dietary Patterns and Vitamin D Levels with Iron Status in Pregnant Women: A Cross-Sectional Study in Taiwan. Nutrients, 15 (8). https://doi.org/10.3390/nu15081805

De Leon Rodriguez, L. M., & Hemar, Y. (2020). Prospecting the applications and discovery of peptide hydrogels in food. Trends in Food Science & Technology, 104, 37-48. https://doi.org/10.1016/j.tifs.2020.07.025

Derkach, S. R., Kolotova, D. S., Kuchina, Y. A., & Shumskaya, N. V. (2022). Characterization of Fish Gelatin Obtained from Atlantic Cod Skin Using Enzymatic Treatment. In Polymers (Vol. 14). https://doi.org/10.3390/polym14040751

Du, M., Lu, W., Zhang, Y., Mata, A., & Fang, Y. (2021). Natural polymer-sourced interpenetrating network hydrogels: Fabrication, properties, mechanism and food applications. Trends in Food Science & Technology, 116, 342-356. https://doi.org/10.1016/j.tifs.2021.07.031

Du, M., Zhang, Y., Zhao, Y., & Fang, Y. (2023a). Agarose/konjac glucomannan double network hydrogels to mimic the texture of beef tripe. Food Hydrocolloids, 135, 108173. https://doi.org/10.1016/j.foodhyd.2022.108173

Du, M., Zhang, Y., Zhao, Y., & Fang, Y. (2023b). Role of conformation transition of high acyl gellan in the design of double network hydrogels. Int J Biol Macromol, 233, 123583. https://doi.org/10.1016/j.ijbiomac.2023.123583

Du, M., Zhao, Y., Zhang, Y., Sun, S., & Fang, Y. (2022). Fabrication of agarose/fish gelatin double-network hydrogels with high strength and toughness for the development of artificial beef tendons. Food Funct, 13 (13), 6975-6986. https://doi.org/10.1039/D2FO00754A

Dutta, A., Subramanian, A. S., Chakraborty, R., & Erdogdu, F. (2020). Numerical modeling of water uptake in white rice (Oryza sativa L.) using variable diffusivity approach. Biosystems Engineering, 191, 116-128. https://doi.org/10.1016/j.biosystemseng.2020.01.011

Echave, M. C., Hernáez-Moya, R., Iturriaga, L., Pedraz, J. L., Lakshminarayanan, R., Dolatshahi-Pirouz, A., Taebnia, N., & Orive, G. (2019). Recent advances in gelatin-based therapeutics. Expert Opin Biol Ther, 19 (8), 773-779. https://doi.org/10.1080/14712598.2019.1610383

Fam, S. N., Kianoush, Khosravi-Darani, Massoud, R., Armita, & Massoud. (2020). High-Pressure Processing in Food. Biointerface Research in Applied Chemistry. Biointerface Research in Applied Chemistry, 11, 11553–11561. https://doi.org/10.33263/BRIAC114.1155311561

Fei, S., Li, Y., Liu, K., Wang, H., Abd El-Aty, A. M., & Tan, M. (2024). Salmon protein gel enhancement for dysphagia diets: Konjac glucomannan and composite emulsions as texture modifiers. International Journal of Biological Macromolecules, 258, 128805. https://doi.org/10.1016/j.ijbiomac.2023.128805

Flory, P. J., & Rehner, J. (1943). Mechanics of Cross-Linked Polymer Networks I. Rubberlike Elasticity. Journal of Chemical Physics, 11, 521–526. https://doi.org/10.1063/1.1723791

Franks, E. M., Jeltema, M., Luck, P. J., Beckley, J., Foegeding, E. A., & Vinyard, C. J. (2020). Morphological and masticatory performance variation of mouth behavi or groups. Journal of texture studies, 51 (2), 343-351. https://doi.org/10.1111/jtxs.12483

Gheorghita Puscaselu, R., Lobiuc, A., Dimian, M., & Covasa, M. (2020). Alginate: From Food Industry to Biomedical Applications and Management of Metabolic Disorders. Polymers, 12, 2417. https://doi.org/10.3390/polym12102417

Górska, A., Mańko-Jurkowska, D., & Domian, E. (2024). Comparative gelation characteristics of carrageenan via rheological and optical techniques: Glazing gels with different sweeteners. Food Hydrocolloids, 152, 109941. https://doi.org/10.1016/j.foodhyd.2024.109941

Gravelle, A. J., & Marangoni, A. G. (2021). The influence of network architecture on the large deformation and fracture behavior of emulsion-filled gelatin gels. Food Structure, 29, 100193. https://doi.org/10.1016/j.foostr.2021.100193

Gul, K., Gan, R. Y., Sun, C. X., Jiao, G., Wu, D. T., Li, H. B., Kenaan, A., Corke, H., & Fang, Y. P. (2022). Recent advances in the structure, synthesis, and applications of natural polymeric hydrogels. Crit Rev Food Sci Nutr, 62 (14), 3817-3832. https://doi.org/10.1080/10408398.2020.1870034

Guo, Z., Li, X., Yang, D., Lei, A., & Zhang, F. (2022). Structural and functional properties of chestnut starch based on high-pressure homogenization. LWT, 154, 112647. https://doi.org/10.1016/j.lwt.2021.112647

He, C., Zhang, M., & Fang, Z. (2020). 3D printing of food: pretreatment and post-treatment of materials. Crit Rev Food Sci Nutr, 60 (14), 2379-2392. https://doi.org/10.1080/10408398.2019.1641065

He, J., Khalesi, H., Zhang, Y., Zhao, Y., & Fang, Y. (2022). Jerky-Inspired Fabrication of Anisotropic Hydrogels with Widely Tunable Mechanical Properties. Langmuir, 38 (36), 10986-10993. https://doi.org/10.1021/acs.langmuir.2c01445

Hoek, A. C., Luning, P. A., Weijzen, P., Engels, W., Kok, F. J., & de Graaf, C. (2011). Replacement of meat by meat substitutes. A survey on person- and product-related factors in consumer acceptance. Appetite, 56 (3), 662-673. https://doi.org/10.1016/j.appet.2011.02.001

Hong, W., Zhao, X., Zhou, J., & Suo, Z. (2008). A theory of coupled diffusion and large deformation in polymeric gels. Journal of the Mechanics and Physics of Solids, 56 (5), 1779-1793. https://doi.org/10.1016/j.jmps.2007.11.010

Horinaka, J.-i., & Ogawa, S. (2023). Cyclic deformation behavior of agarose hydrogels prepared at different gelation concentrations. International Journal of Biological Macromolecules, 248, 125904. https://doi.org/10.1016/j.ijbiomac.2023.125904

Horinaka, J.-i., Takagaki, H., Tanaka, T., & Takigawa, T. (2022). Effects of gelation concentration on cyclic deformation behavior of κ-carrageenan hydrogels. International Journal of Biological Macromolecules, 218, 634-638. https://doi.org/10.1016/j.ijbiomac.2022.07.128

Hosseini-Parvar, S. H., Osano, J. P., & Matia-Merino, L. (2016). Emulsifying properties of basil seed gum: Effect of pH and ionic strength. Food Hydrocolloids, 52, 838-847. https://doi.org/10.1016/j.foodhyd.2015.09.002

Huang, S., Huang, W., Gu, Q., Luo, J., Wang, K., Du, B., & Li, P. (2023). Thermally reversible Mesona chinensis polysaccharide hydrogel. Food Hydrocolloids, 134, 108087. https://doi.org/10.1016/j.foodhyd.2022.108087

Icht, M., Bergerzon-Bitton, O., Kachal, J., Goldsmith, R., Herzberg, O., & Endevelt, R. (2018). Texture-modified foods and thickened fluids used in dysphagia: Israeli standardised terminology and definitions. J Hum Nutr Diet, 31 (6), 742-746. https://doi.org/10.1111/jhn.12581

Jiang, J., Xu, S., Ma, H., Li, C., & Huang, Z. (2023). Photoresponsive hydrogel-base d soft robot: A review. Materials Today Bio, 20, 100657. https://doi.org/10.1016/j.mtbio.2023.100657

Jiang, J., Zeng, J., Gao, H., Zhang, L., Wang, F., Su, T., Xiang, F., & Li, G. (2020). Effect of low temperature on the aging characteristics of a potato starch gel. International Journal of Biological Macromolecules, 150, 519-527. https://doi.org/10.1016/j.ijbiomac.2020.02.077

Jianpeng, Y., & Huiming, W. (2019). Chemomechanical analysis of a functionally graded spherical hydrogel. Chinese Journal of Theoretical and Applied Mechanics, 51 (4), 1054-1063. https://doi.org/10.6052/0459-1879-19-019

Jildeh, N. B., & Matouq, M. (2020). Nanotechnology in packing materials for food and drug stuff opportunities. Journal of Environmental Chemical Engineering, 8 (5), 104338. https://doi.org/10.1016/j.jece.2020.104338

Juan, L.-T., Lin, S.-H., Wong, C.-W., Jeng, U. S., Huang, C.-F., & Hsu, S.-h. (2022). Functionalized Cellulose Nanofibers as Crosslinkers to Produce Chitosan Self-Healing Hydrogel and Shape Memory Cryogel. ACS Applied Materials & Interfaces, 14 (32), 36353-36365. https://doi.org/10.1021/acsami.2c07170

Kell, S. (2022). Editorial foreword for "environment, development and sustainability" journal. Environment, Development and Sustainability, 24 (3), 2983-2985. 10.1007/s10668-021-02070-z. https://doi.org/10.1007/s10668-021-02070-z

Kim, S. M., Wen, Y., Kim, H. W., & Park, H. J. (2022). Textural and sensory qualities of low-calorie surimi with carrageenan inserted as a protein substitute using coaxial extrusion 3D food printing. Journal of Food Engineering, 333, 111141. https://doi.org/10.1016/j.jfoodeng.2022.111141

Kumar, R., Hegde, A. S., Sharma, K., Parmar, P., & Srivatsan, V. (2022). Microalgae as a sustainable source of edible proteins and bioactive peptides – Current trends and future prospects. Food Research International, 157, 111338. https://doi.org/10.1016/j.foodres.2022.111338

Kutlu, N., Pandiselvam, R., Saka, I., Kamiloglu, A., Sahni, P., & Kothakota, A. (2022). Impact of different microwave treatments on food texture. Journal of texture studies, 53 (6), 709-736. https://doi.org/10.1111/jtxs.12635

Lake, G., & Thomas, A. (1967). The strength of highly elastic materials. Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences, 300 (1460), 108-119. https://doi.org/10.1098/rspa.1967.0160

Le, X. T., Rioux, L.-E., & Turgeon, S. L. (2017). Formation and functional properties of protein–polysaccharide electrostatic hydrogels in comparison to protein or polysaccharide hydrogels. Advances in Colloid and Interface Science, 239, 127-135. https://doi.org/10.1016/j.cis.2016.04.006

Leyva-Jiménez, F. J., Oliver-Simancas, R., Castangia, I., Rodríguez-García, A. M., & Alañón, M. E. (2023). Comprehensive review of natural based hydrogels as an upcoming trend for food packing. Food Hydrocolloids, 135, 108124. https://doi.org/10.1016/j.foodhyd.2022.108124

Li, T., Chen, C., Brozena, A. H., Zhu, J. Y., Xu, L., Driemeier, C., Dai, J., Rojas, O. J., Isogai, A., Wågberg, L., & Hu, L. (2021). Developing fibrillated cellulose as a sustainable technological material. Nature, 590 (7844), 47-56. https://doi.org/10.1038/s41586-020-03167-7

Li, X., Liu, X., Lai, K., Fan, Y., Liu, Y., & Huang, Y. (2020). Effects of sucrose, glucose and fructose on the large deformation behaviors of fish skin gelatin gels. Food Hydrocolloids, 101, 105537. https://doi.org/10.1016/j.foodhyd.2019.105537

Li, Z., Zhang, S., Chen, Y., Ling, H., Zhao, L., Luo, G., Wang, X., Hartel, M. C., Liu, H., Xue, Y., Haghniaz, R., Lee, K., Sun, W., Kim, H., Lee, J., Zhao, Y., Zha o, Y., Emaminejad, S., Ahadian, S., Ashammakhi, N., Dokmeci, M. R., Jiang, Z., & Khademhosseini, A. (2020). Gelatin Methacryloyl-Based Tactile Sensors for Medical Wearables. Advanced Functional Materials, 30 (49), 2003601. https://doi.org/10.1002/adfm.202003601

Liang, W., Wang, Y., Li, C., Wang, P., Rong, J., Liu, R., Xiong, S., & Hu, Y. (2024). Development of easy-to-swallow and lipid-enhanced 3D printed surimi based on high internal phase emulsions. Food Hydrocolloids, 155, 110207. https://doi.org/10.1016/j.foodhyd.2024.110207

Lin, D., Kelly, A. L., & Miao, S. (2020). Preparation, structure-property relationships and applications of different emulsion gels: Bulk emulsion gels, emulsion gel particles, and fluid emulsion gels. Trends in Food Science & Technology, 102, 123-137. https://doi.org/10.1016/j.tifs.2020.05.024

Lin, Y., Du, H., Roos, Y., & Miao, S. (2023). Transglutaminase crosslinked fish gelatins for emulsion stabilization: From conventional to Pickering emulsions. Food Hydrocolloids, 144, 108979. https://doi.org/10.1016/j.foodhyd.2023.108979

Liu, B., Yang, H., Zhu, C., Xiao, J., Cao, H., Simal-Gandara, J., Li, Y., Fan, D., & Deng, J. (2024). A comprehensive review of food gels: formation mechanisms, functions, applications, and challenges. Critical Reviews in Food Science and Nutrition, 64 (3), 760-782. https://doi.org/10.1080/10408398.2022.2108369

Liu, B., Ye, H.-b., Liang, Q.-y., Jiang, L.-l., Chen, M.-m., & Yang, S.-b. (2023). Development and characterization of pectin and chitosan films incorporated with a new cross-linking agent. Journal of the Science of Food and Agriculture, 103 (4), 1964-1973. https://doi.org/10.1002/jsfa.12395

Liu, K., Chen, Y.-Y., Zha, X.-Q., Li, Q.-M., Pan, L.-H., & Luo, J.-P. (2021). Research progress on polysaccharide/protein hydrogels: Preparation method, functional pro perty and application as delivery systems for bioactive ingredients. Food Research International, 147, 110542. https://doi.org/10.1016/j.foodres.2021.110542

Liu, X., Chao, C., Yu, J., Copeland, L., & Wang, S. (2021). Mechanistic studies of starch retrogradation and its effects on starch gel properties. Food Hydrocolloids, 120, 106914. https://doi.org/10.1016/j.foodhyd.2021.106914

Liu, Y., Chen, Y., Huang, Y., & Wang, Y. (2021). Two-grid method for semiconductor device problem by mixed finite element method and characteristics finite element method. Electronic Research Archive, 29 (1), 1859-1880. https://doi.org/10.3934/era.2020095

Liu, Z., Basem, A., Mostafa, L., Jasim, D. J., Al-Rubaye, A. H., Salahshour, S., Hekmatifar, M., & Esmaeili, S. (2024). Investigating the effect of pH on the swelling process, mechanical and thermal attributes of polyacrylamide hydrogel structure: A molecular dynamics study. Case Studies in Thermal Engineering, 55, 104148. https://doi.org/10.1016/j.csite.2024.104148

Liu, Z., Toh, W., & Ng, T. Y. (2015). Advances in Mechanics of Soft Materials: A Review of Large Deformation Behavior of Hydrogels. International Journal of Applied Mechanics, 07 (05), 1530001. https://doi.org/10.1142/S1758825115300011

Luo, B., Chen, L., Peng, J., & Sun, J. (2024). Investigating the effects of oil type, emulsifier type, and emulsion particle size on textured fibril soy protein emulsion-filled gels and soybean protein isolate emulsion-filled gels. Journal of texture studies, 55 (4), e12855. https://doi.org/10.1111/jtxs.12855

Ma, Y., Wang, Y., Jiang, S., & Zeng, M. (2022). Effect of gelatin on gelation properties of oyster (Crassostrea gigas) protein. LWT, 158, 113143. https://doi.org/10.1016/j.lwt.2022.113143

Mad-Ali, S., Masniyom, P., & Benjakul, S. (2018). Characteristics and properties of g oat meat gels as affected by setting temperatures. Food Chemistry, 268, 257-263. https://doi.org/10.1016/j.foodchem.2018.06.084

Mao, Y., & Anand, L. (2018). A theory for fracture of polymeric gels. Journal of the Mechanics and Physics of Solids, 115, 30-53. https://doi.org/10.1016/j.jmps.2018.02.008

Michelini, L., Probo, L., Farè, S., & Contessi Negrini, N. (2020). Characterization of gelatin hydrogels derived from different animal sources. Materials Letters, 272, 127865. https://doi.org/10.1016/j.matlet.2020.127865

Mokrushin, S. A., Nazoikin, E. A., Zabenkova, N. A., Blagoveschenskiy, V. G., Terekhin, A. R., & Galkin, N. S. (2022). Selection of a system for automatic control of the sterilization process of canned food in an industrial autoclave. IOP Conference Series: Earth and Environmental Science, 1052 (1), 012136. https://doi.org/10.1088/1755-1315/1052/1/012136

Moreno, H. M., Bargiela, V., Tovar, C. A., Cando, D., Borderias, A. J., & Herranz, B. (2015). High pressure applied to frozen flying fish (Parexocoetus brachyterus) surimi: Effect on physicochemical and rheological properties of gels. Food Hydrocolloids, 48, 127-134. https://doi.org/10.1016/j.foodhyd.2015.01.029

Nath, P. C., Debnath, S., Sridhar, K., Inbaraj, B. S., Nayak, P. K., & Sharma, M. (2023). A Comprehensive Review of Food Hydrogels: Principles, Formation Mechanisms, Microstructure, and Its Applications. Gels, 9 (1), 1. https://doi.org/10.3390/gels9010001

Nedrelow, D. S., Townsend, J. M., & Detamore, M. S. (2023). The Ogden model for hydrogels in tissue engineering: Modulus determination with compression to failure. Journal of Biomechanics, 152, 111592. https://doi.org/10.1016/j.jbiomech.2023.111592

Nepovinnykh, N. V., Kliukina, O. N., Ptichkina, N. M., & Bostan, A. (2019). Hydrogel based dessert of low calorie content. Food Hydrocolloids, 86, 184-192. https://doi.org/10.1016/j.foodhyd.2018.03.036

Nishinari, K., Peyron, M.-A., Yang, N., Gao, Z., Zhang, K., Fang, Y., Zhao, M., Yao, X., Hu, B., Han, L., Mleko, S., Tomczyńska-Mleko, M., Nagano, T., Nitta, Y., Zhang, Y., Singh, N., Suk Meng, A. G., Pongsawatmanit, R., Gamonpilas, C., Moritaka, H., Kohyama, K., Yoshimura, M., Hirashima, M., Takemasa, M., Tsutsui, K., & Su, L. (2024). The role of texture in the palatability and food oral processing. Food Hydrocolloids, 147, 109095. https://doi.org/10.1016/j.foodhyd.2023.109095

Nishinari, K., Zhang, K., Yang, N., Gao, Z., Gamonpilas, C., Turcanu, M., Peyron, M.-A., Fang, Y., Nitta, Y., Yao, X., Zhao, M., Ishihara, S., Nakauma, M., Funami, T., Kohyama, K., Moritaka, H., Yoshimura, M., Takemasa, M., Hori, K., Matsuo, K., Michiwaki, Y., Zhang, Y., Singh, N., & Goh Suk Meng, A. (2023). Rheology for Safe Swallowing 1. Nihon Reoroji Gakkaishi, 51 (4), 219-248. https://doi.org/10.1678/rheology.51.219

Nurilmala, M., Darmawan, N., Putri, E. A. W., Jacoeb, A. M., & Irawadi, T. T. (2021). Pangasius Fish Skin and Swim Bladder as Gelatin Sources for Hard Capsule Material. International Journal of Biomaterials, 2021 (1), 6658002. https://doi.org/10.1155/2021/6658002

Park, S. M., Kim, H. W., & Park, H. J. (2020). Callus-based 3D printing for food exemplified with carrot tissues and its potential for innovative food production. Journal of Food Engineering, 271, 109781. https://doi.org/10.1016/j.jfoodeng.2019.109781

Pure, A. E., Yarmand, M. S., Farhoodi, M., & Adedeji, A. (2021). Microwave treatm ent to modify textural properties of high protein gel applicable as dysphagia food. Journal of texture studies, 52 (5-6), 638-646. https://doi.org/10.1111/jtxs.12611

Qin, L., Fu, Y., Yang, F., Chang, Z., Zou, C., Gao, H., Jiang, D., & Jia, C. (2022). Effects of polysaccharides autoclave extracted from Flammulina velutipes mycelium on freeze-thaw stability of surimi gels. LWT, 169, 113941. https://doi.org/10.1016/j.lwt.2022.113941

Raheem, D., Carrascosa, C., Ramos, F., Saraiva, A., & Raposo, A. (2021). Texture-Modified Food for Dysphagic Patients: A Comprehensive Review. Int J Environ Res Public Health, 18 (10). https://doi.org/10.3390/ijerph18105125

Razi, S. M., Motamedzadegan, A., Matia-Merino, L., Shahidi, S.-A., & Rashidinejad, A. (2019). The effect of pH and high-pressure processing (HPP) on the rheological properties of egg white albumin and basil seed gum mixtures. Food Hydrocolloids, 94, 399-410. https://doi.org/10.1016/j.foodhyd.2019.03.029

Ren, C., Hong, B., Zheng, X., Wang, L., Zhang, Y., Guan, L., Yao, X., Huang, W., Zhou, Y., & Lu, S. (2020). Improvement of germinated brown rice quality with autoclaving treatment. Food Science & Nutrition, 8 (3), 1709-1717. https://doi.org/10.1002/fsn3.1459

Rocha, T. S., Cunha, V. A., Jane, J. L., & Franco, C. M. (2011). Structural characterization of Peruvian carrot (Arracacia xanthorrhiza) starch and the effect of annealing on its semicrystalline structure. J Agric Food Chem, 59 (8), 4208-4216. https://doi.org/10.1021/jf104923m

Sağlam, D., Venema, P., de Vries, R., & van der Linden, E. (2013). The influence of pH and ionic strength on the swelling of dense protein particles. Soft Matter, 9 (18), 4598-4606. https://doi.org/10.1039/C3SM50170A

Sha, X.-M., Hu, Z.-Z., Ye, Y.-H., Xu, H., & Tu, Z.-C. (2019). Effect of extraction te mperature on the gelling properties and identification of porcine gelatin. Food Hydrocolloids, 92, 163-172. https://doi.org/10.1016/j.foodhyd.2019.01.059

Silva, K. C. G., Bourbon, A. I., Pastrana, L., & Sato, A. C. K. (2020). Emulsion-filled hydrogels for food applications: influence of pH on emulsion stability and a coating on microgel protection. Food Funct, 11 (9), 8331-8341. https://doi.org/10.1039/D0FO01198C

Sinha, S. S., Upadhyay, A., Singh, A., Mishra, S., & Pandey, N. (2024). Bigels a versatile gel composite for tailored application in food industries: A review. Food Structure, 41, 100380. https://doi.org/10.1016/j.foostr.2024.100380

St. Pierre, S. R., Darwin, E. C., Adil, D., Aviles, M. C., Date, A., Dunne, R. A., Lall, Y., Parra Vallecillo, M., Perez Medina, V. A., Linka, K., Levenston, M. E., & Kuhl, E. (2024). The mechanical and sensory signature of plant-based and animal meat. npj Science of Food, 8 (1), 94. https://doi.org/10.1038/s41538-024-00330-6

Štreimikytė, P., Keršienė, M., Eisinaitė, V., Jasutienė, I., Lesauskaitė, V., Damulevičienė, G., Knašienė, J., & Leskauskaitė, D. (2020). Formulating protein-based beverages for the dysphagia diets of the elderly: viscosity, protein quality, in vitro digestion, and consumers acceptability. Journal of the Science of Food and Agriculture, 100 (10), 3895-3901. https://doi.org/10.1002/jsfa.10431

Sun, C., Ge, J., He, J., Gan, R., & Fang, Y. (2021). Processing, Quality, Safety, and Acceptance of Meat Analogue Products. Engineering, 7 (5), 674-678. https://doi.org/10.1016/j.eng.2020.10.011

Tammatinna, A., Benjakul, S., Visessanguan, W., & Tanaka, M. (2007). Gelling properties of white shrimp (Penaeus vannamei) meat as influenced by setting condition and microbial transglutaminase. LWT - Food Science and Technology, 40 (9), 1489-1497. https://doi.org/10.1016/j.lwt.2006.11.017

Tan, M., Ye, J., & Xie, J. (2021). Freezing-induced myofibrillar protein denaturation: Role of pH change and freezing rate. LWT, 152, 112381. https://doi.org/10.1016/j.lwt.2021.112381

Toh, W., Ng, T. Y., Hu, J., & Liu, Z. (2014). Mechanics of inhomogeneous large deformation of photo-thermal sensitive hydrogels. International Journal of Solids and Structures, 51 (25), 4440-4451. https://doi.org/10.1016/j.ijsolstr.2014.09.014

Umeda, T., Kozu, H., & Kobayashi, I. (2024). Analysis of Pumpkin Paste Printability for Screw-Based 3D Food Printer. Food and Bioprocess Technology, 17 (1), 188-204. https://doi.org/10.1007/s11947-023-03116-y

Uranga, J., Nguyen, B. T., Si, T. T., Guerrero, P., & de la Caba, K. (2020). The Effect of Cross-Linking with Citric Acid on the Properties of Agar/Fish Gelatin Films. Polymers, 12 (2), 291. https://doi.org/10.3390/polym12020291

van Bommel, R., Stieger, M., Boelee, N., Schlich, P., & Jager, G. (2019). From first to last bite: Temporal dynamics of sensory and hedonic perceptions using a multiple-intake approach. Food Quality and Preference, 78, 103748. https://doi.org/10.1016/j.foodqual.2019.103748

Velazquez, G., Méndez-Montealvo, M. G., Welti-Chanes, J., Ramírez, J. A., & Martínez-Maldonado, M. A. (2021). Effect of high pressure processing and heat treatment on the gelation properties of blue crab meat proteins. LWT, 146, 111389. https://doi.org/10.1016/j.lwt.2021.111389

Walayat, N., Liu, J., Nawaz, A., Aadil, R. M., López-Pedrouso, M., & Lorenzo, J. M. (2022). Role of Food Hydrocolloids as Antioxidants along with Modern Processing Techniques on the Surimi Protein Gel Textural Properties, Developments, Limitation and Future Perspectives. Antioxidants, 11 (3), 486. https://doi.org/10.3390/antiox11030486

Wang, J., Liu, Y., Zhao, M., Sun, Q., Li, M., Wang, Y., Zhang, Y., & Xie, F. (2024). Effect of curdlan addition and thermal sterilization on the structural and properties of rice starch gel. International Journal of Biological Macromolecules, 271, 132593. https://doi.org/10.1016/j.ijbiomac.2024.132593

Wang, M., Li, D., Zang, Z., Sun, X., Tan, H., Si, X., Tian, J., Teng, W., Wang, J., Liang, Q., Bao, Y., Li, B., & Liu, R. (2022). 3D food printing: Applications of plant-based materials in extrusion-based food printing. Critical Reviews in Food Science and Nutrition, 62 (26), 7184-7198. https://doi.org/10.1080/10408398.2021.1911929

Wang, Y., & Selomulya, C. (2022). Food rheology applications of large amplitude oscillation shear (LAOS). Trends in Food Science & Technology, 127, 221-244. https://doi.org/10.1016/j.tifs.2022.05.018

Wen-qiong, W., Pei-pei, Y., Ji-yang, Z., & Zhi-hang, G. (2021). Effect of temperature and pH on the gelation, rheology, texture, and structural properties of whey protein and sugar gels based on Maillard reaction. Journal of Food Science, 86 (4), 1228-1242. https://doi.org/10.1111/1750-3841.15659

Wu, A., Wang, W., Zhang, K., Shen, S., Duan, W., Pan, R., Luo, X., & Chen, H. (2023). Multiphysics coupling analysis of heat pipe reactor based on OpenMC and COMSOL Multiphysics. Annals of Nuclear Energy, 194, 110115. https://doi.org/10.1016/j.anucene.2023.110115

Xiao, Y., Liu, Y., Wang, Y., Jin, Y., Guo, X., Liu, Y., Qi, X., Lei, H., & Xu, H. (2020). Heat-induced whey protein isolate gels improved by cellulose nanocrystals: Gelling properties and microstructure. Carbohydrate Polymers, 231, 115749. https://doi.org/10.1016/j.carbpol.2019.115749

Xu, J., & Kenar, J. A. (2024). Rheological and Micro-Rheological Properties of Chico ry Inulin Gels. Gels, 10 (3), 171. https://doi.org/10.3390/gels10030171

Xu, M., Ni, X., Liu, Q., Chen, C., Deng, X., Wang, X., & Yu, R. (2024). Ultra-high pressure improved gelation and digestive properties of Tai Lake whitebait myofibrillar protein. Food Chemistry: X, 21, 101061. https://doi.org/10.1016/j.fochx.2023.101061

Yang, Q., Wang, X., Ma, L., & Li, H. (2022). 3 - Linear and nonlinear deformation behavior of hydrogels. In H. Li & V. Silberschmidt (Eds.), The Mechanics of Hydrogels (pp. 41-72): Woodhead Publishing. https://doi.org/10.1016/B978-0-08-102862-9.00009-9

Yang, R., Bao, L., Liu, Y., Liang, J., Zheng, B., Miao, W., Shi, X., Gao, P., Zhou, R., & Zhao, Y. (2024). Plant oil body as an effective improver for surimi-based 3D printing. Additive Manufacturing, 93, 104422. https://doi.org/10.1016/j.addma.2024.104422

Yang, X., Gong, T., Lu, Y.-h., Li, A., Sun, L., & Guo, Y. (2020). Compatibility of sodium alginate and konjac glucomannan and their applications in fabricating low-fat mayonnaise-like emulsion gels. Carbohydrate Polymers, 229, 115468. https://doi.org/10.1016/j.carbpol.2019.115468

Yang, Y., Zheng, Y., Ma, W., Zhang, Y., Sun, C., & Fang, Y. (2023). Meat and plant-based meat analogs: Nutritional profile and in vitro digestion comparison. Food Hydrocolloids, 143, 108886. https://doi.org/10.1016/j.foodhyd.2023.108886

Yao, Y., Chen, S., & Huang, Z. (2022). A generalized Ogden model for the compressibility of rubber-like solids. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 380 (2234), 20210320. https://doi.org/10.1098/rsta.2021.0320

Yuan, Y., Zhang, Q., Lin, S., & Li, J. (2025). Water: The soul of hydrogels. Progress in Materials Science, 148, 101378. https://doi.org/10.1016/j.pmatsci.2024.101378

Zhang, J., Daubert, C. R., & Allen Foegeding, E. (2007). A proposed strain-hardening mechanism for alginate gels. Journal of Food Engineering, 80 (1), 157-165. https://doi.org/10.1016/j.jfoodeng.2006.04.057

Zhang, J., Daubert, C. R., & Foegeding, E. A. (2005). Fracture Analysis of Alginate Gels. Journal of Food Science, 70 (7), e425-e431. https://doi.org/10.1111/j.1365-2621.2005.tb11471.x

Zhang, T., Sun, R., Ding, M., Li, L., Tao, N., Wang, X., & Zhong, J. (2020). Commercial cold-water fish skin gelatin and bovine bone gelatin: Structural, functional, and emulsion stability differences. LWT, 125, 109207. https://doi.org/10.1016/j.lwt.2020.109207

Zheng, H., Zhao, M., Dong, Q., Fan, M., Wang, L., & Li, L. (2022). Extruded transglutaminase-modified gelatin–beeswax composite packaging film. Food Hydrocolloids, 132, 107849. https://doi.org/10.1016/j.foodhyd.2022.107849

Zhou, X., Yu, J., Qian, S., & Chen, Y. (2023). Study on texture detection of gelatin-agar composite gel based on bionic chewing. Journal of Food Measurement and Characterization, 17 (5), 5093-5102. https://doi.org/10.1007/s11694-023-02016-1

Zhu, G., Javanmardia, N., Qian, L., Jin, F., Li, T., Zhang, S., He, Y., Wang, Y., Xu, X., Wang, T., & Feng, Z.-Q. (2024). Advances of conductive hydrogel designed for flexible electronics: A review. International Journal of Biological Macromolecules, 281, 136115. https://doi.org/10.1016/j.ijbiomac.2024.136115

Zou, Y., Chen, X., Lan, Y., Yang, J., Yang, B., Ma, J., Cheng, M., Wang, D., & Xu, W. (2024). Find alternative for bovine and porcine gelatin: Study on physicochemical, rheological properties and water-holding capacity of chicken lungs gelatin by ultrasound treatment. Ultrasonics Sonochemistry, 109, 107004. https://doi.org/10.

1016/j.ultsonch.2024.107004