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Functional modifications by physical treatments of dietary fibers used in food formulations

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Chemical modifications of polysaccharides for food and non-food applications have been practiced for years to improve their functional properties. Recent concerns from the public to reduce the use and exposure of chemicals during food production as well as pressure to develop clean label products have moved both the industry and academia to investigate physical modifications of polysaccharides to achieve better functionality. Physical modification of polysaccharides is very important to several industries, but principally to the food industry because the transformation of these molecules by physical means does not require the use of potentially toxic chemicals that could turn foods into unsafe products. Since the well proved nutritional benefits of dietary fibers many efforts are being put in the improvement of their functionality by physical means, which is the area that this review is focusing.

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Introduction

Fibers are non-starch polysaccharides of great interest to the food industry due to their proved role in preventing illnesses such as obesity, diabetes and cardiovascular diseases. Physical modification of fibers provides a great opportunity to convert low cost and undervalued fiber sources into natural, functional and nutritional ingredients. Different types of dietary fibers such as fruits fibers, as well as inulin and gums, are being incorporated in foods not only for their nutritional benefits but also for their functional properties (e.g. as gelling and thickening agents). Furthermore, fibers may be incorporated in food products as inexpensive, non-caloric bulking agents for partial replacement of flour, fat or sugar, as enhancers of water and oil retention and to improve emulsion or oxidative stabilities [1]. Dietary fibers are defined as carbohydrate polymers with ten or more monomeric units, which are not hydrolyzed by endogenous enzymes in the small intestine of humans [2]. They are classified in the following categories: first, edible carbohydrate polymers naturally present in foods as consumed; second, carbohydrate polymers, which have been obtained from food raw materials by physical, enzymatic or chemical means and that have shown physiological effects of benefit to health; third, synthetic carbohydrate polymers that have shown physiological effects of benefit to health [3]. Examples of natural dietary fibers are cellulose, hemicelluloses, pectic substances, gums, resistant starch, inulin, among others [1].

Physical processing of dietary fibers by application of thermomechanical treatment, high shear homogenization, cavitation by high intensity ultrasound, etc., can change the physicochemical properties of the fiber native structure. These changes must be characterized in order to know their effects on the nutritional and textural properties of fiber enriched food products [4]. One of the main properties of fibers that affect their incorporation in foods is solubility. For instance, insoluble fibers can cause problems during processing, and thus the main interest is to modify their structure to improve solubility and processability to be able to achieve higher incorporation in foods. In regards to functionality, the soluble fraction of fibers has demonstrated greater capacity to provide viscosity, ability to form gels and act as an emulsifier. Furthermore, it is easier to incorporate soluble fibers into processed foods and drinks.

Solubility and hydration properties of dietary fibers are closely related to their structure, and other factors such as porosity, particle size, ionic form, pH, temperature, ionic strength, as well as the type and magnitude of mechanical stresses acting on them [5]. In that sense, modification of fibers for their utilization as a valuable food ingredient, can be carried out by physical treatments. Several studies have found that the solubility of dietary fiber in water can be significantly increased by raising the specific mechanical energy input during extrusion because the strong

thermomechanical treatment applied in the treatment increases the soluble fraction of cereal fibers [6]. Treatments such as particle size reduction prior to extrusion have shown significant improvement in the properties of insoluble fibers. Moreover, ultrasound treatment has been used for increasing the soluble fiber content [7,8] and for modifying fibers from different sources, especially cereals. High shear homogenization is another process commonly used to increase the fiber water binding capacity [9], due to molecular degradation of the material by the high shear conditions prevailing in the homogenizer.

The effects of physical treatments on structural, rheological and physicochemical properties of different types of dietary fibers are revised and listed in Table 1. Physical treatments include extrusion, ultrasound, high pressure processing and homogenization.

Extrusion

Extrusion processing is a technology widely applied within the food industry which has been started to be used in the pharmaceutical industry and known as hot melt extrusion. The thermomechanical treatment inside the extruder affects the microstructure and chemical properties of the product as well as its macroscopic shape and appearance. An important application area is in the field of dietary fibers, obtained through extrusion processing of byproducts from the food industry. Extrusion of fibers alone for the production of physically modified food ingredients has not been investigated in great detail likely due to practical problems associated to the extrusion operation using fibers as the only raw material. Extrusion subjects the extruded material to high temperature, high pressure, and high shear forces, causing the internal moisture of the material to vaporize quickly at the exit of the extruder, thus modifying the fiber intermolecular

Table 1

Physical treatments on several types of dietary fibers

Fibers			
Extrusion	Andersson *et al*. (2016)	Wheat (WB) and rye brans (WB)	The content of soluble dietary fiber (SDF) of both WB and RB increases with no change in the total dietary fiber content
	Honcu *et al*. (2016)	Barley	Higher β-glucan and SDF contents were observed after extrusion of barley cultivars with standard starch composition
	Djurle *et al*. (2016)	Barley	Arabinoxylan content increased after extrusion, while its average molecular weight decreased
	Huang *et al*. (2016)	Orange pomace	There was a conversion of insoluble dietary fiber (IDF) to SDF with higher uronic acid content due to the modification of the material cell-wall structure
	Li *et al*. (2012)	Okara (soy pulp)	The extrusion increased the SDF
	Yang *et al*. (2017)	Bean dregs	After extrusion, the content of soluble dietary fiber was increased by 27%
	Lohani *et al*. (2017)	Corn flour, sorghum flour and apple pomace blend	Due to disruption of cell wall matrices and breakdown of high molecular weight complexed polyphenols, extractability of phenolic compounds was improved
	Sereno *et al*. (2007)	Xanthan gum	Extrusion processed xanthan gum improve the water solubility, being almost instantaneously dispersed even under manual mixing
Ultrasound	Li and Feke (2015)	Xanthan gum	Ultrasound to degrade the molecular weight of xanthan gum in aqueous solutions with salting in and salting out salts
			Salting-in and salting-out salts could increase or inhibit ultrasonic degradation by adjusting the molecular conformation of the xanthan
	Li and Feke (2015)	Xanthan gum	Solutions pyruvate-free xanthan gum exhibited high stability to degradation by ultrasound treatment
			Removing these groups enabled the molecular chains to adopt more compact and less susceptible conformations
	Li and Feke (2015)	Locust bean gum	Ionic strength had a minor impact factor on ultrasonic degradation of this gum, regardless of the particular salt species
	Li *et al*. (2016)	Arabinoxylan from wheat bran	Arabinoxylan were extracted from wheat bran and the modification in functional properties studied

Table 1 (*Continued*)

Fibers			
			The storage modulus of gel treated by ultrasound decreased with treatment and the phenolic compounds increased
	Li et (2017)	Konjac glucomannan (KGM)	After ultrasound, the apparent viscosity decreased rapidly and the intrinsic viscosity of KGM solution decreased gradually with time However, no change in primary structure was detected by Fourier transformation infrared (FT-IR) analysis
	Huang *et al*. (2015)	Garlic straw	The porosity and surface area of IDF were effectively improved by ultrasound, which proved enhanced functional and physicochemical properties of modified IDF, increasing the hydrophilic groups
	Fan *et al*. (2016)	Arabinoxylan from wheat bran	Modification of Chinese noodles by addition of ultrasound treated and not treated arabinoxylans Texture increased and water absorption increased and cooking loss rate decreased up to 1.0% of arabinoxylan addition
High hydrostatic pressure (HHP)	Ma *et al*. (2015)	Gum arabic	High pressure treatment had little effect on high quality gum arabic, but affected the poor quality gum arabic significantly
	Peng *et al*. (2016)	Sugar beet pectin	The weight-average molar mass of sugar beet pectin (SBP) decreased significantly with increased HHP The degree of esterification (DE) of SBP at pH 3 and 7 was unchanged, and decreased at pH 8 The degree of acylation (DA) of SBP at pH 3 and 7 did not change, but it decreased at pH 8
	Xie *et al*. (2017)	Purple fleshed potatoes	HHP increased the soluble fiber content by about 8%, but by using a combined HPH with high speed homogenization did not further improve the solubilization
Homogenization	Castro Porto *et al*. (2015)	Cashew tree gum	High pressure homogenization was able to increase the solubility and decrease the apparent viscosity of cashew tree gum
	Alvarez-Sabatel *et al*. (2015)	Inulin	High pressure homogenization reduced the critical minimum concentration needed to obtain homogeneous gel structures Application of very high homogenization pressures negatively affected the gel structure and yielded weaker gels with poorer water retention capacities
	Eren *et al*. (2015)	Xanthan gum	High pressure homogenization (HPH) decreased viscosity and viscoelastic properties of xanthan gum HPH also decrease the molecular weight and increase the polydispersity and the hydrodynamic volume
	Farzi *et al*. (2015)	Gum tragacanth	Homogenization caused reduction in particle size and an increase in the apparent viscosity and shear-thinning behavior of gum tragacanth
	Hua *et al*. (2017)	Tomato residue fiber	Tomato residue fibers were processed by high-speed homogenization (HSH) and high-pressure homogenization (HPH) HSH could break raw fibers to small particles, while HPH could reshape fibers to build network structure HSH and HPH could increase the soluble fiber content by 8%

and intramolecular spatial structure. Owing to the high temperature and shear conditions in a low moisture content environment, extrusion affects dietary fiber, protein, vitamins and other nutrients, both positively and negatively [10•]. Several studies used in this review have shown that extrusion has a positive effect on total

and soluble dietary fiber (SDF). The insoluble dietary fiber content decreases appreciably, probably due to disruption of covalent and non covalent bonds in the carbohydrate moieties leading to smaller and more soluble molecular fragments [11]. Besides, the high thermomechanical energy in the extrusion process can affect the structure of dietary fibers, and it has been reported that these changes are able to impart new functional properties to the fiber such as increasing the viscosity of systems using or promoting the formation of gels [12••]. During extrusion, processing parameters (pressure, water addition, temperature, screw speed and die shape, etc.) can be varied, but the temperature normally lies in the range 90–180 °C [13]. By varying the processing parameters different effects are achieved on dietary fiber [14]. Specifically, the water solubility index of extruded fibers was greatly enhanced by varying extrusion temperature and screw speed [14]. Extrusion has been applied to onion waste originated from the white outer fleshy scale leaves [15]. As a result of extrusion processing, an increase in the solubility of the cell wall pectic polymers and hemicelluloses was observed along with swelling of the cell wall material. However, carbohydrate composition of the cell wall material remained unaffected.

Several studies have focused on the effect of extrusion in cereal and cereal byproducts rich in dietary fibers. Andersson *et al.* [16] studied solubility and physicochemical properties changes of the main dietary fibers, arabinoxylan and β-glucan, from wheat (WB) and rye brans (RB) after extrusion. The content of soluble dietary fiber of both WB and RB increases with no change in the total dietary fiber content. The increase in the extractability and solubility of the dietary fiber could be due to a disruption of covalent and non-covalent bonds, leading to smaller and more soluble molecular fragments, which clearly indicates that the strong thermomechanical conditions applied during the extrusion process is able to transform some of the unextractable dietary fiber to extractable dietary fiber [17]. The molecular weight of β-glucan only decreased slightly during extrusion for both WB and RB. It appears that most of the molecular cleavage due to the thermomechanical action in the extruder is happening in the branch structures rather than the main chain of the fiber polymer, perhaps more commonly observed during enzymatic treatments. This is certainly an advantage of the physical treatment because the resulting high molecular weight of the treated β-glucan, which is advantageous from a physiological standpoint. For instance, high molecular weight β-glucans from oats have shown cholesterol-lowering effects [16]. Honcu *et al.* [18] and Djurle *et al.* [13] studied the effect of extrusion in barley. Honcu *et al.* [18] found that regardless of the barley genotype (normal non-waxy and waxy starches), the extrusion had no significant effect on the arabinoxylan content of the treated samples. However, significantly higher β-glucan and SDF contents were observed after extrusion of barley cultivars with normal starch composition. Furthermore, the molar mass of water-extractable β-glucan increased after extrusion independently of the barley variety. Djurle *et al.* [13] found that the arabinoxylan content was also increased, while its average molecular weight was decreased with extrusion.

Huang *et al.* [19] used extrusion to enhance the SDF content from orange pomace, a byproduct of juice extraction containing a high level of DF. The pomace was processed in a single-screw extruder at various barrel temperatures in the range (115–135 °C), feed moistures in the range (10–18 g/100 g), and screw speeds in the range (230–350 rpm). Compared with non-extruded pomace, the SDF fraction in the extrudate had a higher level of uronic acid. The results were indicating a conversion of insoluble dietary fiber to SDF due to the thermophysical treatment, which was promoting the modification of the material cell-wall structure, and degradation of insoluble dietary fibers (IDF). Furthermore, extrusion improved the physicochemical properties of the extrudate, by increasing its water-holding capacity, swelling, water solubility index, and cation-exchange capacity while decreasing its oil-holding capacity (OHC). Significant decreases in OHC in extruded orange pomace might be caused by lipophilic sites being released during extrusion. Similar results were reported by Li *et al.* [20], who found that extrusion of okara (soy pulp) increased the SDF content at expenses of decreases in the material IDF content. Thus, it can be postulated that the extrusion process significantly influences the structure of the fiber, increasing the number of short-chain soluble molecules.

Another type of physical modification of fibers is by blasting extrusion, which has shown to have great effect on dietary fibers modification [21]. In this process, a screw rotates at constant speed inside a high-pressure heated barrel. Due to the back and forth split between two and one stream the extrudate melt is subjected to a combination of high shear, turbulence, and cavitation effects as well as high temperatures. Under these conditions, the bonds of insoluble polysaccharides, for instance, cellulose hemicellulose and the continuous fiber matrix are partially disrupted and released as soluble saccharides. The technology was used to modify the dietary fiber of bean dregs and found that after extruding the fibers at 170 °C and a screw speed of 150 rpm the content of soluble dietary fiber was increased by 27% [22•].

Other authors have studied the effects of thermomechanical treatments on extrusion processing applied to blends. For example, Lohani *et al.* [23] studied the effects on corn flour, hydrodynamic cavitated sorghum flour and apple pomace blend on their total phenolic content, antioxidant activity along selected textural and functional properties. Due to disruption of cell wall matrices and breakdown of high molecular weight complexed

polyphenols during the treatment, extractability of phenolic compounds was improved [24]. These results are clearly showing that extrusion promotes alterations in the physicochemical, and functional properties of the extruded material. It also changes the properties of polyphenolic compounds and their antioxidant activity, which closely depend on the raw material and extrusion processing conditions such as feed moisture, screw speed, screw configuration, die geometry, temperature and residence time [25]. In another study, Lohani *et al.* [26] analyzed the blend of corn flour and hydrodynamic cavitated sorghum flour and apple pomace extruded in the presence of CO_2 to retain the total phenolic content and the antioxidant activity of the extruded blend. Products extruded in the presence of CO_2 had 12% and 7% more total phenolic content and antioxidant activity, respectively as compared with control extrudates, that is the blends extruded without CO_2.

Extrusion processing followed by drying and grinding of xanthan gum has demonstrated to enhance the dispersion properties of the gum, which in its native form exhibits clumping and poor mixing characteristics when dispersed in water [27]. Extrusion processed xanthan gum disperses almost instantaneously even under manual mixing. The reason for this behavior is that although the processed xanthan gum does not molecularly dissolve in cold water it able to swell and disperse better in water. The extrusion process is fairly consistent and the properties of the extruded product are uniform. At appropriate salt concentrations, the physically modified gum can mimic the behavior of starch, dispersing rapidly and developing viscosity irreversibly upon heating as the result of thermomechanical treatment which is able to convert the gum structure in a disordered form [12••].

Ultrasound

Ultrasound, which has been widely used in the laboratory and industrial food processes to improve the physicochemical properties of foods, can break chemical bonds of polysaccharides [28]. The breakage may change the surface hydrophilicity and loosen the tissue, which facilitate the release of bioactive factors, and mainly, promotes the solubilization of insoluble fibers [29]. In view of the advantages of moderate environment conditions, safety operation, and high efficiency, ultrasonic technology is often chosen for the modification of insoluble dietary fiber when dealing with small and medium scales. Ultrasound treatment also is frequently used for increasing the fiber extraction or improving their enzymatic treatments, although these uses are not considered in this review. The degree of modification of the fibers depends on their molecular structure, the power or intensity of the applied ultrasound, the application time, and the temperature, among other factors.

During the treatment, the passage of ultrasound waves through the material creates cavitation-induced micrometer-size bubbles that grow and collapse, which produce shock waves and small concentrated areas of high-pressure/shear gradients able to modify the structure of the molecules. The mechanism of fiber degradation by cavitation may result from the collapsed cavitation bubble and chemical reactions between the polymer and high energy molecules that promote the degradation of the fiber polymers [30,31••]. After ultrasound treatment, polysaccharides, in particular, can degrade to materials with low molecular weight that form solutions of low viscosity. Results seem to indicate that cavitation can produce molecular excision of the fiber main chain, resulting in products with a narrower molecular distribution. Ultrasonic treatment can also improve the bioactivity of polysaccharides [32].

Li and Feke [33] studied the application of ultrasound to degrade the molecular weight of xanthan gum in aqueous solutions under salting-in and salting-out aqueous conditions, and found that salting-in and salting-out salts could, respectively, increase or inhibit ultrasonic degradation due to changes in the molecular conformation of the gum molecules. Similar findings were reported by Saleh *et al.* [34]. In other study, Li and Feke [35], studied the influence of the pyruvate group on the efficiency of ultrasonic degradation of xanthan gum in aqueous solutions. Solutions pyruvate-free xanthan gum exhibited the highest stability to degradation by ultrasound treatment among all blend ratios studied, so removing the pyruvate group is likely enabling the molecular chains to adopt more compact and less susceptible to high shear and high fluctuating pressures conformations. Similarly, Li and Feke [36] studied the ultrasonic degradation of locust bean gum (LBG) in aqueous solutions at 25 °C. As a typical non-polyelectrolyte, the ionic strength had a minor impact factor on ultrasonic degradation of this gum, regardless of the particular salt species. In these studies the authors followed the ultrasonic degradation by rheological measurements in terms of intrinsic viscosity. With these findings, one of the main conclusions is that the extent of ultrasonic effects on the physicochemical properties of fibers depends on the molecular structure of the dietary fiber.

Li *et al.* [37] studied the extraction and modification of wheat bran arabinoxylans (WB-AX) by ultrasound treatment. They obtained arabinoxylans with molecular weights ranging from 580 to 800 kD and found that the molecular weight of WB-AX decreased with treatment time and power intensity. Viscoelastic parameters determined on treated samples, such as storage modulus (that is related to the WB-AX gel structure), decreased with the ultrasonic treatment. In a similar study [38] the effects of ultrasound treatment on the molecular weight and rheological properties of a food polysaccharide, konjac glucomannan (KGM) were evaluated. Upon the exposure of KGM solution (1%, w/v in water) to ultrasound, the

apparent viscosity decreased rapidly and the intrinsic viscosity of KGM solution decreased gradually with time (following a first order polymer degradation kinetics). The treatment also caused a significant reduction of particle size (*Z* average) of KGM aggregates and changed the rheological properties specifically, the decrease of the storage and the loss moduli (G"). Nevertheless, no change in primary structure was detected by Fourier Transformed Infrared (FT-IR) analysis [37]. This means that even though the high impact of ultrasonic treatment in the material rheological properties, is not translated to its structural degradation.

Huang *et al.* [32] studied the treatment of insoluble dietary fiber (IDF) from garlic straw with ultrasonic processing technology. Ultrasonic-treated IDF exhibited better functional and physicochemical properties than untreated IDF. Both the *in vitro* hypolipidemic and hypoglycemic effects of IDF, and its associated physicochemical properties, were significantly increased by ultrasonic pretreatment. Findings from structural analysis revealed that the porosity and surface area of IDF were effectively modified by ultrasound, which enhanced the functional and physicochemical properties of IDF. Structural analysis from scanning electron microscope and FT-IR spectroscopy indicated that ultrasonic treatment significantly degraded the microstructures of IDF from garlic straw and increased hydrophilic groups.

Fan *et al.* [39] investigated the degradation of arabinoxylans and the effects of their addition on Chinese noodles quality. They found an increase in the amount of ferulic acid in the modified arabinoxylans. Oxidative cross-linking of ferulic acid forced water migrate from gluten-starch network to arabinoxylan molecules, resulting in a reduction in the amount of bound water in the noodle matrix. Therefore, at 0.25% addition level, noodles containing ultrasound treated arabinoxylans showed higher strength and flexibility than control noodles, which incorporated non-modified arabinoxylans.

High pressure treatments

High hydrostatic pressure (HHP)

High hydrostatic pressure (HHP) in a range of pressures from 100 MPa to 1 GPa, is a non-thermal treatment that uses water or oil as a medium to transmit pressures to alter the structure of high molecular weight molecules [40•]. Applications include the preservation of meat products, fruit jams, fruit juices, salad dressings, guacamole, and many ready-to-eat foods. In all these cases, microbial and enzyme inactivation is achieved without altering the product organoleptic quality. High hydrostatic pressure can improve the functionality of biopolymers significantly through changing their inner structure [41,42]. Therefore, it is used in food industry for both food processing and food preservation. However, only the use of HHP for physical modification of dietary fibers is reviewed.

Ma *et al.* [43] studied the effect of HHP (at 800 MPa) on the emulsifying properties of two types of gum arabic: Acacia senegal (KLTA, 'premium' gum), and Acacia seyal (GCA 'secondary' grade). High pressure treatment changed the overall gum structure by causing the reduction of its hydrodynamic volume whereas high pressure and pH treatment changed the emulsification properties of both gums.

Peng *et al.* [44] investigated the effects of HHP on the structural and rheological properties of sugar beet pectin (SBP) at pH's 3, 7 and 8. The molar mass of SBP decreased significantly with increased HHP pressure but increased its viscosity, possibly because the protein contained in SBP (5–7%) denature, stretch or aggregate under the treatment. The degree of esterification (DE) remained unchanged at pH 3 and 7, while the degree of acylation (DA) was a little higher compared to the control. It is possible the HHP treatment caused the acetylated group to be exposed, in accord with the report by Shpigelman *et al.* [45]. DE and DA of SBP decreased significantly after treatment with HHP at pH 8, which might be owing to saponification or deacetylation of the pectin [46].

Xie *et al.* [42] examined the modification of dietary fibers from purple-fleshed potatoes with HHP in comparison with high pressure homogenization (HPH). The latter type of treatment is revised in the next section. Results suggest that HHP and HPH treatments had effect on the physicochemical, functional, and structural properties of dietary fibers (DF) obtained from purple-fleshed potatoes. HHP and HPH treatments increased the soluble dietary fiber, did not improve water holding capacity, but increased oil holding and swelling capacities and emulsion activity and stability. DFs treated with HPH also showed increased antioxidant activities and content of total phenolic compounds, indicating that high pressure treatment could affect the dietary fiber matrix, thereby inducing the release of embedded phenolic to increase antioxidant activities [47]. Since purple-fleshed potatoes are rich in hydrolysable polyphenols, these could explain the high antioxidant activities of dietary fiber [48]. Polyphenol can create hydrogen bonds between their hydroxyl groups and hydrogen atoms of polysaccharides (hemicelluloses) to encapsulate phenolic compounds and make their extraction difficult [49]. Hence, the increased antioxidant activities of high pressure treated dietary fiber might have resulted from the formation of soluble substances (i.e. 2-benzyl benzofuran) produced from the degradation of lignin and soluble fractions bound with phenolic induced by high pressure treatments [50].

High pressure homogenization

There are several types of homogenization processes usually used to prepare foams, emulsions and suspensions, but also they can be also used to introduce structural changes on dietary fibers. The high-pressure homogenization (HPH) process consists in forcing a fluid to flow

through a homogenizing valve using a positive displacement pump. When passing through the narrow gap the fluid undergone a significant pressure drop, and high shear forces are applied. Other effects such as cavitation, turbulence and shock waves occurring during that flow lead to the disruption of suspended particles and structural modifications of molecules, which depend on the pressure applied and the polysaccharide structure [51]. However, there is literature showing that high pressure homogenization influences functionality and the structure of dietary fiber, although it can also change the configuration of polysaccharides and suspended particles in suspensions [52–54].

Castro Porto *et al.* [51] studied the effect of HPH on cashew tree gum, and found that it reduced the gum consistency (apparent viscosity), swelling and oil absorption capacity, which were more pronounced with increasing applied pressure. The solubility of cashew tree gum was slightly increased and was dependent on the pressure used and heating temperatures used in the process. The HPH conditions also influenced the rheological properties of the gum solution, which showed a Newtonian behavior. However, the molecular weight was slightly affected by high pressure processing.

A high pressure homogenizer was used for modifying commercial dietary fibers. After mechanical treatment, fibers increased the content of bound non-freezable water, confirming that the water binding capacity changes systematically upon the treatment. Samples with higher water binding capacity had gel-like consistency which was related to higher specific volumes and swelling and possibly increased mutual entanglement [55].

Alvarez-Sabatel *et al.* [56] used different HPH treatments on long-chain inulins and changed their gelling properties. Inulin–water dispersions were subjected to HPH at pressures of 103, 207 or 296 MPa with two different homogenization configurations. The HPH process dispersed the inulin particles and reduced their sizes with increasing pressures. It also improved the inulin crystallization behavior, which was achieved by promoting stronger molecular interactions. The treatment was shown to induce the development of particulate gels, and reducing the critical minimum concentration needed to obtain homogeneous gel structures. However, the application of very high homogenization pressures, beyond 300 MPa, negatively affected the gel structure of products prepared with these fibers, yielding weaker gels with poorer water retention capacity.

Eren *et al.* [57] studied the effects of high-pressure homogenization (HPH) on the xanthan gum structure. Structured network of xanthan gum solutions was lost gradually depending on the severity of the HPH treatment, as evidenced by the observed changes in the viscosity and viscoelasticity of the treated materials. Reduction in molecular weight and a significant increase in polydispersity of the polymer, and also an increase in the hydrodynamic volume upon HPH treatment were the assumed causes of these rheological changes.

Similarly, Farzi *et al.* [58] used high shear homogenization for altering the structural and rheological properties of gum tragacanth (GT) dispersions. Results indicated that the treatment reduced the particle size and caused a significant increase in the apparent viscosity and shear-thinning behavior. The highest increase of apparent viscosity was found for solutions containing *Astragalus gossypinus* (one of three species of GT studied), which had a high insoluble fraction of fibers and larger aggregates. The treatment also caused the dominance of elastic modulus and gel-like behavior of products produced with the treated fibers. Hua *et al.* [59] studied the effects of high-speed homogenization (HSH) and HPH on tomato fibers extraction and fiber structures. During HSH processing, the medium is drawn axially into the gap between a rotor and a stator, whereby the sample particles are grinded under strong shear and thrust forces generated by high rotation speed (10 000–20 000 rpm). Both HSH and HPH treated materials increased the soluble fiber content by about 8%, but by using a combined HSH–HPH process did not improve the solubilization of the fibers. HSH could break-down raw fibers to small particles, while HPH could reshape fibers to build a network structure. Microfibrils were released and they were detected as elementary fibrils.

Hu *et al.* [60] compared two physical methods to improve the functional properties of insoluble dietary fiber of wheat bran. They investigated the effect of high-pressure homogenization, high-intensity sonication, and a combination of these two methods. The high-pressure homogenization and high-pressure homogenization plus high-intensity sonication treatments significantly improved the solubility, swelling, water-holding, oil-holding, and cation exchange capacitiesof the treated materials. However, the improvement of the above properties by high-intensity sonication alone was marginal. In most cases, the high-pressure homogenization process was as good as the combination of the two processes in improving the above-mentioned properties; hence, the contribution of high-intensity sonication in the high-pressure homogenization process was minimal.

Conclusions

Physical modifications of polysaccharides are very important for the food industry because they are processing tools able to produce better and improved functionalities on macromolecules, such as fibers, widely used in the preparation of food products. Modification of fibers is not an area widely studied yet but it is of great importance due to the relevance of fibers in the development of more

nutritious foods. Since there is a large variety of fibers, with different properties and poor functionality in their native state, physical modifications offer the potential to improve fiber functionality and achieve a higher fiber enrichment of foods to improve their nutritional quality without sacrificing their sensory properties.

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