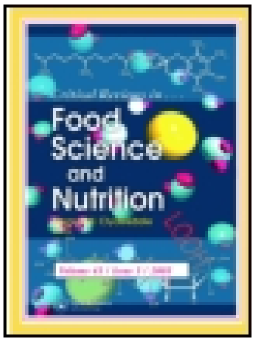

Critical Reviews in Food Science and Nutrition

ISSN: 1040-8398 (Print) 1549-7852 (Online) Journal homepage: https://www.tandfonline.com/loi/bfsn20

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Ilkem Demirkesen Mert

CRITICAL REVIEWS IN FOOD SCIENCE AND NUTRITION
https://doi.org/10.1080/10408398.2018.1555134

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REVIEW

The applications of microfluidization in cereals and cereal-based products: An overview

Ilkem Demirkesen Mert

Ministry of Agriculture and Forestry, Food Enterprises and Codex Department, Ankara, Turkey

ABSTRACT
Although, the consumption of food consisting of fiber presents some important nutritional, functional and health benefits, manufacturers and researchers have reported that the use of high amount of fiber worsens the product quality. Besides, consuming large quantities of dietary fiber delays intestinal gas transit. In cereal grains, phenolic compounds are covalently bound to indigestible polysaccharides thus this complex bran matrix restricts its release in small intestine resulting in low bioavailability. Therefore, in order to overcome the problems related to the characteristics of fiber, the use of large quantities of dietary fiber in cereal based products as well as the low bioavailability of phenolic compounds; food scientists explore alternative milling methods to traditional treatments. The potential use of microfluidization in cereal-based products including wheat bran, corn bran, zein, rice bran and starches has been highlighted. Functionalization through microfluidization has been applied as a prospective method for production of fibrous structures from cereal brans and it improves surface areas, water holding capacity, swelling capacity, porosity, oil-holding capacity, cation-exchange capacity and the exposure of the phenolic compounds and hence the associated antioxidant capacity of fibers. Microfluidization also offers a promising method for the formation of complexes between starches and a fatty acid, which has potential to create a new functional resistant starch ingredient with increased viscosity and improved water-holding properties. Microfluidized cereal by-products provide some important unique functional and nutritional properties to bakery products. In this perspective, this paper provides an overview of the findings on the use of microfluidization in cereals and cereal-based products.

KEYWORDS
Microfluidization; dietary fiber; phenolic compounds; cereal; cereal based products

Introduction

It is generally recognized that a constant intake of dietary fiber is inversely related with the risk of cardiovascular and coronary heart disease, diabetes, insulin sensitivity, obesity and colon cancer. This negative relationship can be attributed to dietary fiber, phenolic compounds and other bioactive compounds found in cereal grains (Wang, He, and Chen 2014). Dietary fiber has also been indicated to have a great potential for binding toxic heavy metals as a bio-sorbent. In addition to fiber, the reduced risk for developing these mentioned chronic diseases has also been linked to the presence of phytochemicals in bran. It has been reported that pheonolic compounds may modulate cellular oxidative status and avoid oxidative damage of important biomolecules such as DNA, membrane lipids, and proteins. The health effect of dietary fiber, on the other hand, has mainly been associated to its behavior in gastrointestinal tract. The health effects of dietary fiber as well as phenolic compounds were reviewed by Elluch (2011), Wang, He, and Chen (2014) and Capuano (2017). In addition to its health benefits, dietary fiber can also impart some functional properties to foods such as improved water holding capacity, viscosity, oil holding capacity and swelling capacity. Indeed, dietary fiber enhances rheological properties of dough/batter and improves volume, texture, color, sensory characteristics, water retention capacity and hence shelf-life of bakery products (Mert et al. 2014). However, it has been reported that consuming large quantities of dietary fiber increases gas production and also delays intestinal gas transit. Although the adverse effects of use of high level of dietary fiber in bakery products have been stated in many published studies, it has been reported that drawbacks associated with the use of high amount of dietary fiber in cereal-based products have been overcome by the use of different processing technologies such as traditional milling/grinding techniques, microfluidization, thermal treatment, extrusion cooking and bioprocessing (Mert et al. 2014; Cikrikci, Demirkesen, and Mert 2016; Yildiz, Demirkesen, and Mert 2016). Among these emerging techniques, microfluidization has been highlighted to have positive effects on functional properties as well as on physiological effects of dietary fiber and phenolic compounds (Wang et al. 2013b; Mert et al. 2014).

During microfluidization, food are exposed to intense shear rates, high velocity impact forces, ultrahigh pressure, instantaneous pressure drop and hydro-dynamic cavitation

CONTACT Ilkem Demirkesen Mert ilkem.mert@tarimorman.gov.tr; ilkemdemirkesen@gmail.com Ministry of Agriculture and Forestry, Food Enterprises and Codex Department, Ankara, Turkey.
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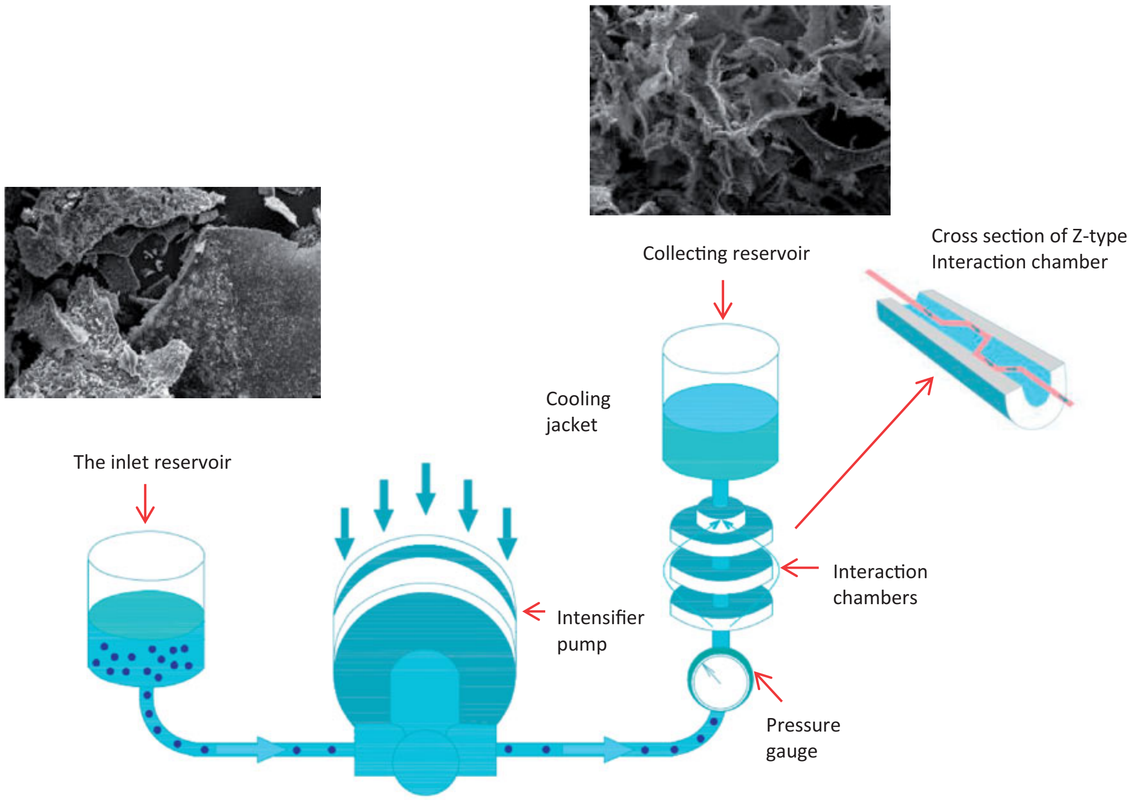

Figure 1. Microfluidizer prosessor.

and therefore these effects create the formation of uniform distribution of particles/emulsions. There is increasing worldwide interest in the use of microfluidization due to the advantages of this technology over traditional grinding/milling methods. The application of microfluidization processing for food technology began with its use for the emulsification of milk products and then it has attracted the attention of the scientific community. Now, it is being used for various food products such as fruit juices, proteins, gums, cereals/cereal by-products etc. Comparing traditional milling methods, microfluidization technology possess many advantages. A smaller size means a larger surface area of fine particles and that provides enhancement of water holding capacity, swelling capacity, viscosity, porosity, oil-holding capacity and cation-exchange capacity. It has also been reported that the bioavailability of bound phenolic compounds was found to be higher due to the exposure of the phenolic compounds and the associated antioxidant capacity of fibers through microfluidization process. Functionalization through microfluidization has been applied as a potential method for the production of fibrous structures from cereal brans. Then, these novel fibers used in bakery products to enhance rheological properties of dough/batter and to improve volume, texture, color, sensory characteristics and storage time of bakery products. This technology also allowed producing bakery products with much less flour content. Microfluidization treatment has also been utilized for the modification of properties of many macromolecules such as whey protein. Microfluidization has also been applied to formation of a new functional resistant starch ingredient with increased viscosity and water-holding properties. This review summarizes recent researches on the application of microfluidization in cereal and cereal products along with their health benefits and functional properties.

The working mechanism of microfluidizers

Microfluidization process is a novel mean of high pressure homogenization technique has been gaining popularity in different areas such as pharmaceutical, biotechnology, chemical, energy, cosmetics and nutraceuticals/food. It is a combined processing mechanism of hydro-dynamic cavitation, intense shear rates, ultrahigh pressure and instantaneous pressure drop, high-velocity impact forces and high-frequency vibration with a short treatment time (McClements and Rao 2011). A microfluidizer contains a reaction chamber in which the fluid flows in a channel is forced to divide into two or more microstreams when extremely high levels of shear stress and turbulence are induced (Figure 1). Thus, the microstreams are mixed by colliding with each other at very high speeds up to 400 m/sec and with the wall surface that resulted in the formation of fine emulsions/fine particle distribution (Mccrae 1994; Mert 2012). Then, the product is effectively cooled and can be collected in the output reservoir. Because of instantaneous pressure drop at the exit of the interaction chamber, fluid subjected to microfluidization process is expanded resulting in loosing of the tightly packed architecture of the particles and thus pores or cavitation are formed inside fluid (Figure 1).

The equipment can have different types of chambers: Z and Y types (Figures 2 and 3). In the Y-type interaction

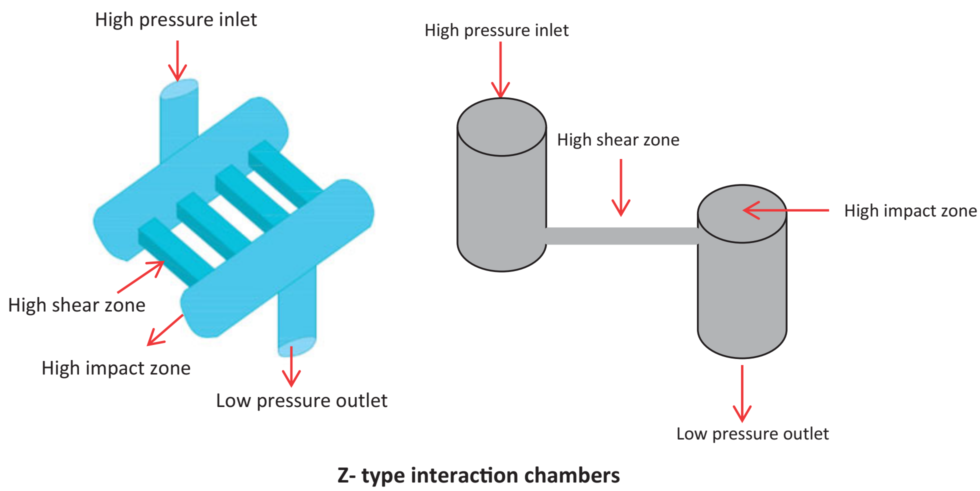

Figure 2. Microfluidizer Z-type interaction chambers.

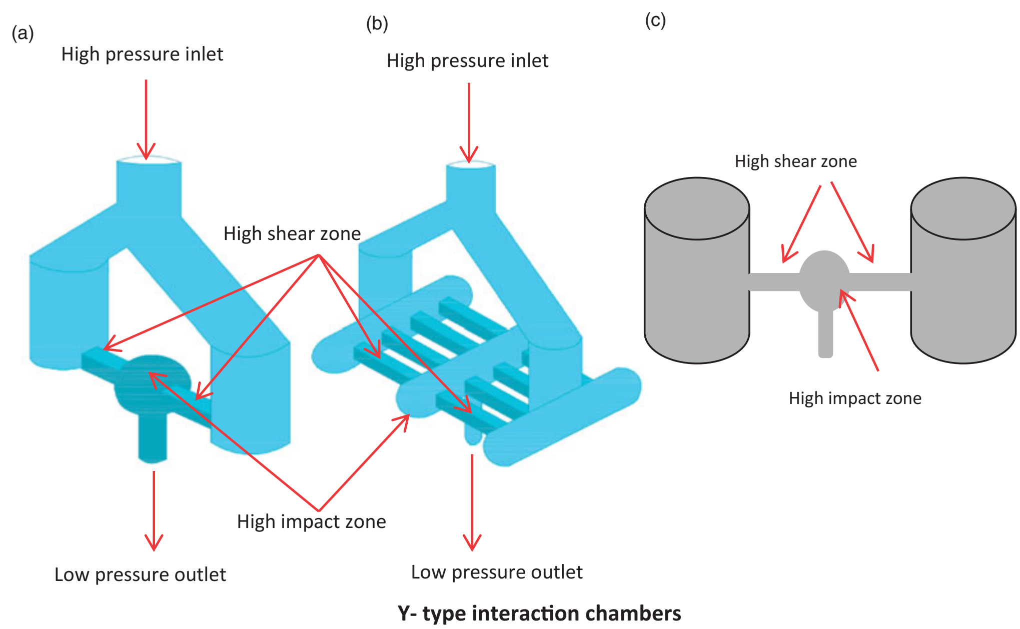

Figure 3. Microfluidizer Y-type interaction chambers.

chamber of microfluidizer, the fluid is forced to divide into two microstreams at the inlet of the chamber and the fluid velocity is increased suddenly due to the extreme decrease of the pipe diameter (Figure 3). Then, these two microstreams collide with each other at tremendously high speeds up to 400 m/sec and with the wall surface that resulted in the formation of fine emulsions within an interaction chamber (Mccrae 1994: Mert 2012; Ocampo-Salinas et al. 2016). In a Z-type interaction chamber, an incoming fluid stream under high pressure is forced through one or more zigzag microchannel varying the direction of the flow resulting in collision of particles (Figures 1 and 2). Shear forces also has a significant role on dispersing of particle agglomerates or reduction of particle size (Ocampo-Salinas et al. 2016). Although, laminar extension flow is considered to be responsible for droplet disruption at the inlet of the chamber, inertial forces in turbulent flow together with hydro dynamic cavitation is the main flow behavior in microfluidizer (Jafari, He, and Bhandari 2007). Due to the processing mechanism, Z chambers are typically used for solid dispersions including cell disruption (Figure 2), while Y chambers are applied for processing liquid-liquid dispersions such as emulsions, liposomes etc. (Figure 3).

The schematic of microfluidizer processor and the fixed geometry interaction chambers is depicted in Figure 1. Although, microfluidization is known as a novel mean of high pressure homogenization, the working principle of microfluidization is different from high-pressure (valve) homogenization in which the shear is caused by sudden restriction of flow under high pressure through a restrictive valve (Sanguansri and Augustin 2006). In case of high pressure homogenizer, the pressure fluctuates during the operation due the movement of the homogenizing valve and therefore the fluid usually carries large particles with wide-ranging size distribution. A microfluidizer, on the other hand, offers high pressure to pump multi-phase fluids through the microchannels of an interaction chamber while exposing the fluids to high shear. A microfluidizer can operate either in batch or continuous processing mode and the product temperature can be controlled by a heat exchanger. Furthermore, the system provides advantages to work with a wide range of products such as high solid contents, high viscosities and fluids. The combination of intensifier pump and fixed geometry utilizes the delivery of constant process pressure profile. The product is passed through the microfluidizer at the target pressure when it stays constantly for majority of the compression strokes and hence the particle size would be smaller and the size distribution would be narrower. The zero pressure portion is also applied which characterizes the suction strokes where no food is given to system and processed through the interaction chamber, thus the final quality of food is not affected (Su and Mesite 2016).

Utilization of microfluidization in different food products

Microfluidization has traditionally been used in the pharmaceutical industry in order to produce emulsion-based products. Research into the application of microfluidization processing for food technology began with its use for the emulsification of milk products. Recent years, its applications in food related research have gained interest and now it is being used for various food products such as milk based products, fruit juices, proteins, gums and cereals etc. Furthermore, some researchers have also focused on the use of microfluidization technology for microbiological and toxicological safety of food products. The studies showing the use of microfluidization processing on various food products are given in Table 1. In case of dairy industry, it has been applied to produce nanoemulsions for processing of a range of milk based products such as infant formulae, cheese, yogurt and ice cream. These studies showed that microfluidized milk contained smaller emulsion particles as compared to homogenized milks. Milk treated by microfluidizer had fewer intact or semi intact micelles forming on the membrane surface of the fat globule, hence microfluidization process also decreased fat separation of milk during storage significantly (Cobos, Horne, and Muir 1995; Dalgleish, Tosh, and West 1996). This technique has also been utilized for the production of nonfat or low-fat ice creams, which had a slower meltdown (Olson, White, and Richter 2004). The researchers also demonstrated that microfluidization treatment improved water retention of yoghurts and also increased interconnectivity in the protein networks with embedded fat globules (Ciron et al. 2010, 2011). Rheological properties of yogurts such as thickness, creaminess, cohesiveness and viscosity were also enhanced with the use of this technology (Ciron et al. 2011). In a very current study of us, microfluidization process has also been investigated for development of emulsion-based yoghurt like gels from hazelnut. The results of our latest work suggested that fermented yoghurt like products can be produced without any additional ingredient such as milk powder or a hydrocolloid (Demirkesen, Vilgis, and Mert 2018). In dairy industry, it has also been applied for the production of cheese (Lemay, Paquin, and Lacroix 1994; Lebeuf, Lacroi, and Paquin 1998; Tunick et al. 2000) and cream liqueurs (Paquin and Giasson 1989). Water holding capacities of some juices such as tomato (Kubo, Augusto, and Cristianini 2013), ketchup (Mert 2012) were improved by the use of microfluidization technology. Microfluidization treatment has also been utilized for the modification of properties of many macromolecules such as whey protein (Koo et al. 2018a, b), soy protein (Shen and Tang 2012; Song et al. 2013) and starch (Kasemwong et al. 2011) and it has been observed that this technique shreds and homogenously distributes large particles into fibrous structures. In our studies, we also explored the utilization of microfluidization method on dietary fiber from different sources and then we demonstrated the improvement of quality of bakery products with the incorporation of microfluidized fiber (Mert et al. 2014; Cikrikci, Demirkesen, and Mert 2016; Yildiz, Demirkesen, and Mert 2016). Chen et al. (2013) studied the effect of microfluidization method on physiochemical and functional properties of insoluble dietary fiber from peach and oat. This study pointed out that microfluidization effectively reduced particle sizes of fiber and triggered the redistribution of fiber composition from insoluble to soluble fractions and hence enhanced the physicochemical properties (water-holding capacity, swelling capacity and oil-holding capacity) of insoluble dietary fiber. The result of the study also indicated that microfluidization lowered postprandial serum glucose ability and increased inhibitory activity towards pancreatic lipase of insoluble dietary fiber.

Utilization of microfluidization for cereal industry

The utilization of microfluidization in the production of dietary fiber from wheat bran and wheat gluten

Cereal brans main by products produced by milling have been recognized with their rich composition in terms of dietary fiber, vitamins, minerals, antioxidants, phenolic lipids, phytosterols and other phytochemicals (Özkaya et al. 2017). A wheat kernel consists three main parts: bran (19–15%), germ (2–3%) and endosperm (80–85%). The multi-layered outer skin of the edible kernel, wheat bran, is rich in important minerals such as iron, zinc, magnesium, manganese and phosphorus, antioxidants, vitamin B and E and fiber. Therefore, the utilization of wheat bran in different products for human consumption is growing gradually over the years as the awareness of consumers and their demand for healthier foods increase. Wheat bran is composed of three principal fractions: testa, aleurone and pericarp. It contains 37–53% total dietary fiber more than 90% of which is water insoluble fiber (xylans, cellulose, lignin, galactan and fructans). Wheat bran is also good source of bioactive compounds (alkylresorcinols, ferulic acid, flavonoids, carotenoids, lignans and sterols) (Onipe, Jideani, and Beswa 2015). The health effect of dietary fiber has been associated to its behavior in gastrointestinal tract and published reports have indicated that numerous health benefits related to consuming diet high in dietary fiber including reduced risk of cardiovascular and coronary heart disease,

Table 1. An overview of research articles conducted on microfluidization of food products.

Food industry	The application purpose	References
Milk homogenization, production of low fat yogurt/nonfat yogurt/yogurt like gels, cheese and cream liqueur	The effect of microfluidization on size distribution of milk particles	Strawbridge et al. (1995)
	The effects of composition, process and acidification conditions on products from recombined milks using the microfluidizer	Cobos, Horne, and Muir (1995)
	The effect of microfluidization on disruption of casein micelles	Dalgleish, Tosh, and West (1996)
	The use of microfluidization for the production of the heat-treated non- and low-fat milk samples	Ciron et al. (2010)
	The impact of microfluidization on rheological properties of yogurts	Ciron et al. (2011)
	The effect of microfluidizatied milk on cheddar cheese composition, color, texture, and yield	Lemay, Paquin, and Lacroix (1994)
	The effect of incorporation of denatured and microparticulated whey protein in young cheddar cheese	Lebeuf, Lacroi, and Paquin (1998)
	The effect of microfluidization on microstructure of mozzarella cheese	Tunick et al. (2000)
	The use of microfluidization for the production of cream liqueur	Paquin and Giasson (1989)
	Development of emulsion-based yoghurt like gels from hazelnut by microfluidization	Demirkesen, Vilgis, and Mert (2018)
	The effect of microfluidization on the enzymatichydrolysis: Disruption of *Lactobacillus delbrueckii* ssp. *bulgaricus* 11842 cells for lactose hydrolysis in dairy products	Bury, Jelen, and Kalab (2001)
Fruit juices	The effect of high pressure homogenization on the physical stability, particle size distribution, pulp sedimentation, serum cloudiness, juice color and microstructure of tomato juice	Kubo, Augusto, and Cristianini (2013)
	The effect of microfluidization on microstructure, physical properties and available lycopene content of the ketchup product	Mert (2012)
Protein	The effect of microfluidization on mean particle size and distributions of soya protein isolate and size-effect of microfluidization on the properties of final suspension and the resultant soy protein films	Song et al. (2013)
	The influence of microfluidization on particle size and emulsion stability of soy protein isolate	Shen and Tang (2012)
	The effect of microfluidization on physical properties of whey protein fibrils with chitosan	Koo et al. (2018a)
	The effect of microfluidization on functionality of whey protein fibrils	Koo et al. (2018b)
	The effect of microfluidization on rheological and microstructural properties of soy protein isolate emulsions	Tang and Liu (2013)
Ethanol production	The use of microfluidizer to improve its enzymatic hydrolysis and ethanol yields of wheat straw	Turhan et al. (2015)
Starch	The use of microfluidization to improve the functionality of resistant starch with the increase of water retention and viscosity	Augustin, Sanguansri, and Htoon (2008)
	The effect of microfluidization on the structure of cassava starch granule.	Kasemwong et al. (2011)
Production of fiber from different cereals		
Wheat bran/wheat gluten	Effects of microfluidization process on physicochemical properties of wheat bran	Wang et al. (2012).
	Effects of microfluidization on antioxidant properties of wheat bran	Wang, Raddatz, and Chen (2013a)
Corn bran/zein	Modeling the effects of microfluidization conditions on properties of corn bran	He et al. (2016)
	Effects of microfluidization treatment and the presence of quercetagetin on the physical, structural, thermal, and morphological characteristics of zein nanoparticles	Sun et al. (2016).
	Effects of microfluidization on microstructure and physicochemical properties of corn bran	Wang et al. (2013b)
Rice bran	Microfluidization treatment of rice bran: effect on Pb (II) ions adsorption in vitro	Wang et al. (2018)
	The effect of particle size of insoluble dietary fiber from rice bran on its phenolic profile, bioaccessibility and functional properties	Zhao et al. (2018)
Bakery industry (cake, bread, cookie and gluten-free bread)	Production of microfluidized wheat bran fibers and evaluation as an ingredient in reduced flour bakery product	Mert et al. (2014)
	Different sized wheat bran fibers as fat mimetic in biscuits: its effects on dough rheology and biscuit quality	Erinc, Mert, and Tekin (2018)
	Microfluidization of agro by-product to functionalized dietary fiber and evaluation as a novel bakery ingredient	Yildiz, Demirkesen, and Mert (2016)
	Production of hazelnut skin fibers and utilization in cakes	Cikrikci, Demirkesen, and Mert (2016)
	The effects of microfluidization on rheological and textural properties of gluten-free corn breads	Ozturk and Mert (2018a)
	The use of microfluidization for the production of xanthan and citrus fiber-based gluten-free corn breads.	Ozturk and Mert (2018b)

diabetes, insulin sensitivity, obesity and colon cancer. In the European Prospective Investigation into Cancer and Nutrition (EPIC), a negative relationship between dietary fiber intake and mortality, particularly from circulatory, digestive, and non- cardiovascular and non-cancer inflammatory diseases has been demonstrated (Chuang et al. 2012). Dietary fiber has also shown to have a great potential for binding toxic heavy metals as a bio-sorbent. It has been reported that the health effect of dietary fiber in gastrointestinal tract can especially be related to factors such as the effect of plant cell walls on bioavailability, the effect of dietary fiber on the rheological and colloidal state of digesta, the binding of dietary fiber with phenolic compounds, bile salts, mineral ions, and digestive enzymes and also the fermentation of dietary fiber in the large intestine and hence its effect on gut microbiota composition (Capuano 2017). High water-holding capacity, swelling, oil-holding capacity and cation exchange capacity of insoluble fibers have been reported to increase digesta viscosity by decreasing the free water content of digesta and hence retard the digestion and absorption of nutrients (Takahashi et al. 2009). The reduced risk of these diseases has also been linked with the presence of phytochemicals in wheat bran. It has been documented that antioxidants are believed to avoid chronic diseases by preventing oxidative damage of important biomolecules such as DNA, membrane lipids, and proteins through multiple mechanisms. However, consuming large quantities of dietary fiber increases gas production and also delays intestinal gas transit (Capuano 2017). Furthermore, a high level of dietary fiber adversely affects the quality of products such as color, texture, volume, sensory and storage time (Demirkesen et al. 2010). In addition, phytic acid in cereal bran, which has high affinity for interacting with protein to from insoluble protein-phytate complexes and chelation properties with multivalent minerals in the intestinal track, also reduces their bioavailability (Özkaya et al. 2017). It has been reported that most of bound phenolic compounds in cereal grains are not accessible to attack by enzymes in the human gastrointestinal tract, resulting also in low bioavailability. These factors, which limit the use of large quantities of dietary fiber in products, have promoted food manufacturers and scientists to explore alternative fiber production methods to traditional treatments. Therefore, recent comprehensive and detailed studies have been conducted on suitable processing technologies to enhance physiochemical and health-related properties including hydration properties, oil holding capacity, digestibility, solubility, functionality, antioxidant activity, etc., of various types of dietary fiber and cereal bran by improving of the nutritional profile of products while by decreasing the required amount of dietary fiber. Suriano et al. (2018) stated the noticeable effect of particle size on the functionality, physicochemical as well as on the physiological effects of wheat bran. The physicochemical features of wheat bran led to selective changes in the gut microbiota of mouse and this created an effect to counteract the bloom in Enterobacteriaceae, related to liver inflammation. Thus, the authors proposed that wheat bran having smaller particle size played a significant role in management of inflammatory disorders outside the gut, namely in the liver. It has also been reported that particle size affects not only the fermentability of dietary fiber but also the availability of bound polyphenols such as ferulic acid having role as antioxidants along the gastro-intestinal tract and to be released by the intestinal microbial communities (Suriano et al. 2018). It has been stated that particle size had also an important role in hypocholesterolemic activities (Wu, Wu, and Chau 2009). Stewart and Slavin (2009) has conducted a study to evaluate the role of wheat bran particle size (large/coarse *v.* small/fine) as well as wheat bran fraction (whole bran *v.*aleurone *v.* aleurone by-product) in short-chain fatty acid production using a batch *in vitro* fermentation system with human fecal inoculum. The result of study showed that small/fine particle size and by-product fraction of bran increased short-chain fatty acid production compared with large/coarse particle size, and aleurone and whole bran. The enhancement of the cholesterol-lowering activities of carrot insoluble fiber and cellulose with decrease in particle size has also been shown by Chou, Chien, and Chau (2008).

Because of the soft structure and relatively low density of wheat bran, reduction of its size below 40 μm cannot be achieved by the application of conventional milling. The development of new grinding techniques, such as ball, jet and ultrafine milling has promoted to certain improvement in the functionality of wheat bran (Mert et al. 2014). In many studies, microfluidization process has been found the one of the most promising ones for cereal processing among the emerging technologies. Wang et al. (2012) conducted a study to examine the effect of microfluidization process on physicochemical characteristics of wheat bran. The result of the study showed that microfluidization process increased specific surface area and bulk density of wheat bran particles. Further decreases in the particle size and increases in surface area were obtained as the number of passes increased, but these changes became slower. Confocal laser scanning pictures indicated that microfluidization process separated the structural components of wheat bran. Water holding capacity and swelling capacity tests of wheat bran showed that the bran's hydration properties increased with microfluidization process due to reduction in particle size. Hydration properties of fiber depend on swelling property and water holding/binding capacity. While factors such as particle size, shape, and elasticity affect water trapped between the dietary fibers particles, water trapped within pores or surface of dietary fibers particles depends on the total surface area of dietary fibers particles and that of intraparticle voids (Capuano et al. 2017). It has been also mentioned that in addition to considerably reducing effect on particle size, microfluidization can also expand particles suspended in the liquid stream due to rapid pressure decrease at the exit of the interaction chamber. The expansion in particles loosened microstructure of the particles as well as created pores or cavities inside the particles. Such microstructure variations along with size reduction promoted a larger surface area and more water binding sites (e.g. polar groups or uronic acid groups) to the surrounding water. On the contrary, in traditional grinding processes, particle size is reduced by solid shear stress and compression leading to collapse of fiber matrix and pores. Increased porosity and capillary attraction of wheat bran also improved the physical entrapment of oil. It has been hypothesized that microfluidization treatment might expose uronic acids or ion-binding sites on the increased surface area, and hence resulted in increases in cation-exchange capacity. The author suggested that the physiological significance of dietary fiber with high cation-exchange capacity indicates its ability to entrap, destabilize and disintegrate the lipid emulsion and thus capability to reduce the diffusion and absorption of lipids as well as cholesterol (Wang et al. 2012). The authors mentioned that microfluidization was an effective process to reduce particle size and bulk density, and substantially to increase specific surface area, water-holding capacity, swelling capacity, oil-holding capacity and cation-exchange capacity. The effectiveness of the microfluidization process in improving the antioxidant capacity of bound phenolic compounds in wheat bran, and the role of microfluidization on the contents of surface-reactive, solvent extractable, alkaline and acid hydrolyzable phenolic compounds were also studied (Wang, Raddatz, and Chen 2013a). It has been observed that microfluidization process increased specific surface area of wheat bran particles and the inert phenolic compounds covalently bound to or physically entrapped in the fiber matrix could therefore be exposed at the surfaces of the insoluble fraction and become reactive. Therefore, the exposure of the phenolic compounds and the associated antioxidant capacity of products increased with increases of the extent of microfluidization within the experimental range. Microfluidization treatment was found to be not strong enough to break the covalent linkages between phenolic acids and the other fiber components and to release the phenolic compounds, but it was found to be effective in increasing the alkaline and acid hydrolyzable phenolic contents of wheat bran and their antioxidant capacity.

Wheat gluten has been used in food industry due to its remarkable role in wheat starch industry and being a rich source of plant proteins. It is essential to modify its range of functional properties such as solubility, emulsifying and foaming ability to expand its applications in the foods. Yan et al. (2013) observed that microfluidization process effectively improved the emulsifying property and foam stability of wheat gluten in water, but decreased the foaming capacity of wheat gluten in water and emulsifying and foaming properties of wheat gluten in pH = 2 aqueous solution. The results indicated that although the solubility of wheat gluten in pH = 2 aqueous solution was higher than that in water, the emulsifying and foaming properties had also found to have noticeable relationships with solubility, surface hydrophobicity, structural properties and molecular weight.

The utilization of microfluidization in the production of dietary fiber from corn bran, and zein

Corn bran and corn fiber is underutilized by-product of the dry and wet corn-milling industries. Although both of them are primarily composed of the pericarp, corn fiber also consists of cell wall material from the endosperm. The main chemical composition of corn bran is composed of dietary fiber, which is nearly completely insoluble (70–87%). The insoluble dietary fiber in corn bran comprises of cellulose, hemicellulose and only a small amount of lignin. The remaining part is composed of starch, lipid, protein, ash, phenolic compounds and other trace phytochemicals. While corn fiber contains more than two times ferulate phytosterol esters, which can be recovered in corn fiber oil, corn bran has two times more ferulic acid (Rose, Inglett, and Liu 2010). The ferulic acid of corn fiber gum can form gels via oxidative crosslinking, in the presence of hydrogen peroxide and peroxidase. Ferulic acid bound to soluble corn bran gum has a role on delivering beneficial antioxidants to the colon for disease prevention. Unlike to free phenolics which are rapidly absorbed in the upper gastrointestinal tract, bound phenolics can be released by microbial esterases in the lower gastrointestinal tract and thus offer radical-scavenging activity in this region of the colon, a region chronically under oxidative attack, and prone to disease. Thus, the phenolic antioxidants in corn bran prevent many chronic diseases that are believed to be closely associated to the process of oxidative damage to important biomolecules such as DNA, membrane lipids, and proteins through multiple mechanisms (Rose, Inglett, and Liu 2010). Besides diets containing corn bran are less likely to cause discomfort since corn bran has a lower level of intestinal gas excretion. Although much the research concerning the use of corn bran and corn fiber has focused on their conversion to fuel ethanol; in recent years, the utilization of corn-milling co-products in food products began with the addition of corn bran to cereal products such as breads, cakes and muffins with the aim of increasing of their nutritional value. For the purpose of broaden the use of microfluidization process in different food products; Wang et al. (2013b) investigated the influences of the microfluidization process (three different sizes of interaction chambers and two different passes) on microstructure and physicochemical properties of corn bran. The mean particle size of corn bran decreased and specific surface area increased effectively with the microfluidization process. Microscopic analysis showed that a gradual disintegration of original cell wall structure and the dissociation of different bran tissues were found to be more pronounced with an increased number of passes (Figure 4). Bulk density decreased with elevated extent of microfluidization treatment since the packed density of particulate fiber depends on the true density, particle size, particle shape, surface area and morphological characteristics of pores. Therefore, microfluidization process dramatically changed the microstructure by increasing surface areas and thereby leading to a significant increase in porosity of corn bran (Figure 4). It has also been stated that particle size, specific surface area, porosity and microstructure are prominent factors that affect not only water-holding capacity but also swelling capacity. High water holding and swelling capacity reflects the potential of fiber to be used to prevent syneresis, modify viscosity, texture and mouthfeel characteristics and reduce calories of formulated food products. Furthermore, fiber having high

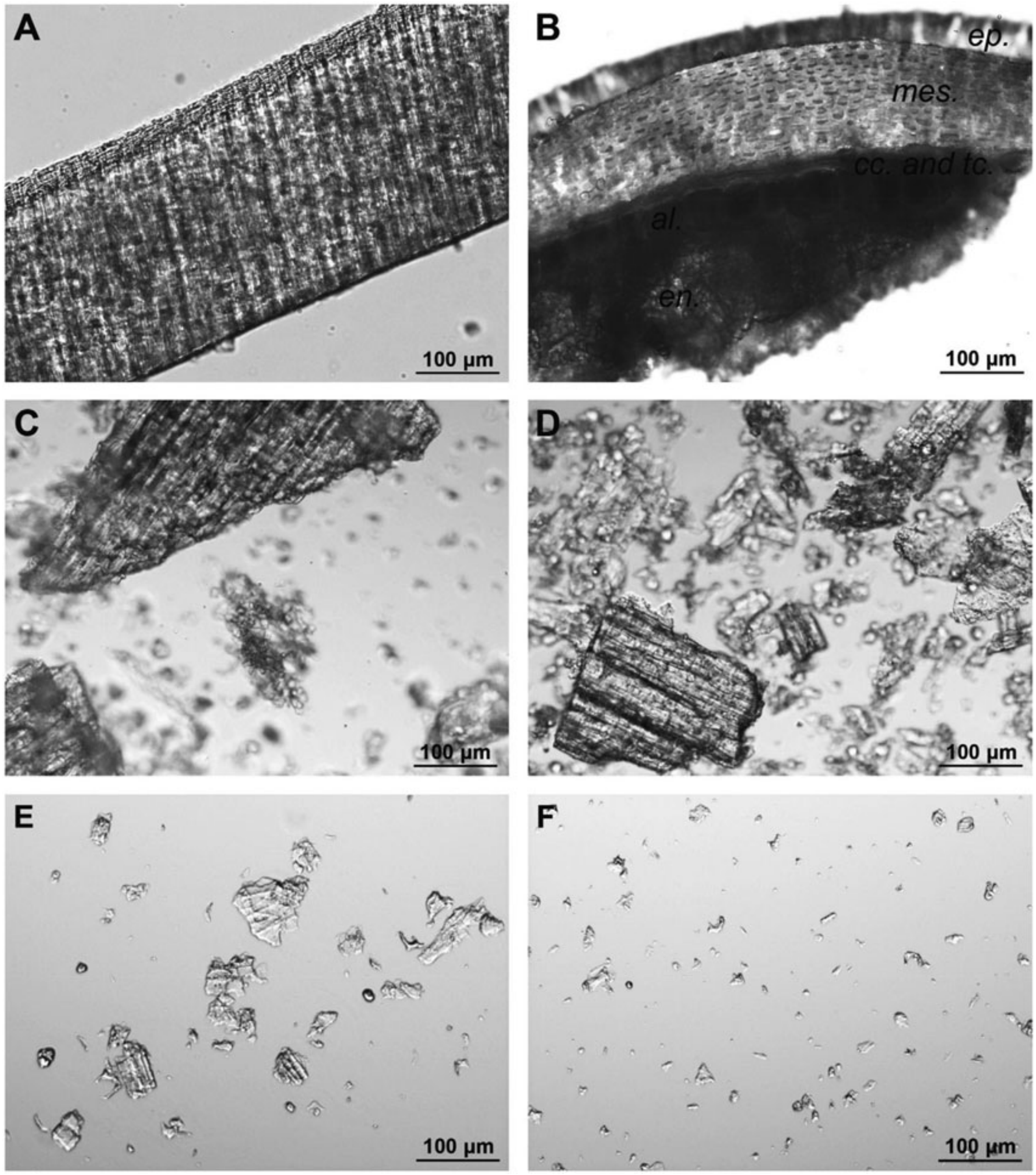

Figure 4. Bright field microscopy images of longitudinal and transversal cross-section of the bran portion of corn kernels (A and B), ground raw corn bran (C), and microfluidized corn bran: IC300 2 passes (D), IC200 2 passes (E), and IC87 5 passes (F). Reproduced from Wang et al. (2013b) with the permission from the publisher.

hydration properties has a positive effect on gut health, to increase stool weight and potentially to slow down the digestion process and the rate of nutrient absorption (Capuano 2017). The findings of the study of Wang et al. (2013b) indicated that water holding and swelling capacity increased with increase in the extent of microfluidization treatment. In literature, different findings have been reported about the influence of particle size on water-holding capacity and swelling capacity. One possible explanation for the contradictory findings in the discrepancies in the relationship between particle size and hydration properties of insoluble dietary fiber used technologies is the used size reduction technology and the source of fiber. For example, some authors reported a dramatic increase of water-holding capacity and swelling capacity with decrease in particle size during microfluidization treatments of several fibers, while the opposite trend was also observed for different type fibers (Gupta and Premavalli 2010). In addition, it is known that branched dietary fibers have less ability to form ordered structures in solutions and are therefore they are water-soluble (pectins, gums, oligosaccharides, etc.), while linear dietary fibers are likely to form ordered structures in solutions and therefore they have limited water-soluble ability (cellulose, lignin, and some hemicelluloses etc.) Generally, soluble dietary fibers have higher water holding capacity than insoluble dietary fiber that creates differences in their technological functionality and their physiological effects (Capuano 2017). In this study, it has been reported that as compared to microfluidization process, the extensive compression and shearing forces generated during a traditional grinding process might lead to collapse of fiber matrix as well as pores. On the contrary, the loosened microstructure and reduces in size of fiber might lead to formation of a larger surface area and new surfaces hydrophilic groups resulting in the improvement of the hydration properties of insoluble fiber ingredients causing to an opposite effect on hydration properties of fiber treated by microfluidization method. In the study of Wang et al. (2013b), it has been demonstrated that the increases in water holding and swelling capacity might related to formation of micropores or cavities inside the particles due to the rapid release of pressure at the exit of the interaction chamber. The formation of more water binding sites due to the expansion of particles might be resulted in the interaction of fibers with water easily that finally causing to an increased water holding capacity. Similar to the hydration properties, contradictory findings about the relationship between particle size reduction and oil holding capacity of insoluble dietary fiber can be found in literature. The authors related the increase in oil holding capacity of microfluidized corn bran to the improvement of physical entrapment of oil by capillary attraction due to the increase in the porosity and surface areas. The result of their findings showed that microfluidized corn bran enhanced oil holding capacity in binding bile acids and cholesterol, removing them from the micelles and therefore avoiding their intestinal absorption or reabsorption. Cation-exchange capacity of fibers also increased with microfluidization process. The increase in cation-exchange capacity with decreasing particle size was suggested to be because of the formation of more uronic acids or ion-binding sites on the elevated surface area of the treated samples. The authors also observed that cation-exchange capacity of corn bran was found to be higher than that of wheat bran since corn bran had higher amount of trapped uronic acids within the cell wall matrix of corn bran that reflects higher levels of exposure of these uronic acid moieties or ion-binding sites after the microfluidization process. The authors also hypothesized that a higher cation-exchange capacity has a stronger capability to entrap, destabilize and disintegrate the micelles and hence the formed fiber-micelle complexes can behave as barriers that delay or reduce the diffusion and absorption of dietary lipids and also cholesterol. He et al. (2016) modeled the effects of microfluidization conditions (processing pressure and number of passes) on physicochemical and antioxidant properties of corn bran. A higher pressure was found to be favorable for swelling capacity, water-holding capacity, surface reactive phenolic content, and DPPH radical scavenging activity, whereas a relatively low pressure was found to be promising for oil-holding capacity. However, these properties of microfluidized corn bran had a negative linear relationship with passes. The authors mentioned the importance of choosing a suitable number of passes for a microfluidization process by balancing benefits and operating costs.

Corn gluten meal consists of the protein fractions of maize, and zein is the major storage protein (50% of the total protein) present in maize. Zein is a class of prolamine and it consists of lipophilic amino acid residues. It has been fractionated into four polypeptide chains having different molecular weights. Zein is composed of 62–74% of endosperm and hence the main properties of corn gluten meal are dependent on zein. Zein is soluble in alcohol but has high hydrophobicity due to its a high amount of hydrophobic amino acid residues such as leucine, proline, alanine, and phenylalanine. Therefore, it is extracted from corn gluten meal using solvent extraction (Ozturk and Mert 2018a, b). As an amphiphilic molecule, it is capable of self-assembling into distinctly different structures (spherical colloidal nanoparticles), i.e., rods, sheets, and spheres. Due to its low water uptake and good texture, it has high coating capacity. In addition to its high coating capacity, it has high biodegradability, and biocompatibility, thus zein has been applied in modified release systems for the delivery of bioactive compounds (Dahiya et al. 2018). Although zein does not create a viscoelastic dough at room temperature, above its glass transition temperature, approximately 35 °C and when moisture contents higher than 20%, it offers cohesive, stretchable, and extensible dough. Therefore, zein has a great potential to be used in zein based gluten-free dough and breads (Ozturk and Mert 2018a, b). Sun et al. (2016) conducted a study to determine the influences of microfluidization process and the addition of quercetagetin on the physical, structural, thermal, and morphological characteristics of zein nanoparticles. The microfluidization process caused to the structural changes of zein and enhanced the thermal stability of zein nanoparticles. The formation of interactions between zein and quercetagetin resulted in the fluorescence quenching and variations in the circular Dichroism Spectroscopy intensity of zein primarily because of the hydrogen bonds and hydrophobic effects. The result revealed that the combination of microfluidization treatment and the addition of quercetagetin with mass ratio of zein to quercetagetin of 40:1 presented the morphology of nanospheres with more compact structure compared to native zein nanoparticles and uniform particle distribution. It has been hypothesized that using the combination of microfluidization treatment and addition of quercetagetin might be a promising approach to develop new food-grade biopolymers with better thermal behaviors and structural properties that could be used in development of the potential delivery systems for bioactive compounds.

The utilization of microfluidization in the production of dietary fiber from rice bran

Rice is a member of the grass family of Oryza sativa (Asian rice) or Oryza glaberrima (African rice). It can be consumed as white, milled or polished form. It is one of the most widely consumed staple cereal crop over a half of the world's population. It has the lowest level of protein and the lowest dietary fiber content among the cereals (Mert et al. 2016). However, it has the highest protein digestibility among the staples and also the highest energy digestibility, probably because of its low dietary fiber and tannin content. Furthermore, lysine the first limiting essential amino acid in cereal proteins, is highest in oats and rice among cereal proteins. During the milling, first the outermost layer, the hull, is removed to produce brown rice since this process prevents the loss of nutrients but it occurs with the further processing to obtain white milled rice (Dapčević-Hadnađev, Hadnađev, and Pojić 2018). Therefore, brown rice is considered as whole grain. Rice bran, a by-product of the milling process, constitutes approximately 10% of the weight of brown rice and it is a mixture of substances, including protein, fat, ash, and crude fiber.

Rice bran consists of tiny fractions of rice hull which acts as ash content and it is underutilized as animal feed or directly discarded. Depending on milling process, rice bran has $10-23\%$ bran oil and the defatted rice bran has 35–50% dietary fiber and main content of it (90%) is insoluble dietary fiber. Rice oil is extracted from 15 to 20% of rice bran and used for medicine. It is also used to decrease cholesterol level. Rice bran has been indicated to have in vitro hypoglycemic and hypolipidemic properties, such as changing the conformation and hindering the activity of porcine pancreatic lipase, binding glucose and retarding α-amylase action. The hypocholesterolemic effect of it has also been shown. Moreover, rice bran has also a significant role in reduction of fasting and postprandial serum glucose levels. In addition to its effect to control diabetes, it is used to prevent cardiovascular disease and to improve the immune system, athletic performance and liver function and it is used as an antioxidant (Zhao et al. 2018). In a very recent study of Zhao et al. (2018), the effect of superfine processing on the phenolic profiles, bioaccessibility and functional properties of insoluble dietary fiber from rice bran was examined. The result of study revealed that superfine grinding increased higher water holding capacity, swelling capacity and nitrite ion adsorption capacity and reduced oil holding capacity of rice bran. The insoluble dietary fiber powder of superfine rice bran had also a higher extractability in terms of both free and bound phenolics, higher phenolic bioaccessibility and higher antioxidant properties as compared to its coarse counterpart. The extractable phenolic profile in insoluble dietary fiber of superfine rice bran was also found to be different from that of counterparts. Consequently, the authors suggested that superfine grinding can be used for improving the functional properties, the phenolic content and bioaccessibility of different dietary fibers. Thus, Wang et al. (2018) conducted a study to explore the effect of microfluidization process on insoluble dietary fiber from rice bran about the sorption characteristics of Pb(II) and digestibility in vitro. They also analyzed the influence of the physicochemical properties (water-holding capacity, oil-holding capacity, cation exchange capacity and total negative charge capacity) of modified insoluble dietary fiber from rice bran on the sorption capacity of Pb(II), cholesterol, and sodium cholate. Microfluidized insoluble dietary fiber from rice bran had a higher capability to adsorb cholesterol and sodium cholate. Microfluidization process did not change the primary structure. It has been observed that Pb(II) adsorption occurred on the surface of fiber particulate based on its structure and physicochemical properties. Thus, the authors indicated a feasible approach for improving of the adsorption capacity of insoluble dietary fiber from rice bran, especially the adsorption of Pb(II).

The utilization of microfluidization for the modification of the structures of starches

The influence of microfluidization process on starches was also examined. Starch is one of the most abundant substances in nature and produced from grain or root crops. Its ability to form inclusion complexes with several chemical constituents, including fatty acids, fatty alcohols, mono- and diglycerides, emulsifiers, and many small flavor compounds has long been recognized. During the gelatinization process, the amylose forms a helical inclusion complex with a fatty acid. Such inclusion complexes have important roles for the modification of properties and functionality of starch such as reducing the solubility in water, retarding retrogradation, decreasing the viscosity of gelatinized starch, and affecting the progress of in vitro digestibility. A number of studies have been conducted on modification of starches by high-pressure techniques to create novel functional properties such as low gelatinization temperature, higher degree of swelling, better solubility, and higher viscosity properties. It has been revealed that high-pressure homogenization is a promising method for the formation of complexes (Meng et al. 2014). In order to examine the effects high-pressure homogenization on the complexes between starch and different categories of fatty acids, the degree of complex formation, the crystal structure, the thermal stability and the in vitro digestibility has been studied. Since lipids typically have poor dispersivity in starch dispersion due their low water solubility; they can be dispersed uniformly as small droplets in starch dispersion in the presence of the combined influence of high pressure, intense mechanical shear, turbulence, and cavitation. Moreover, the high pressure and high shear force conditions of the homogenization process led to the starch pastes to release amylose from the disintegrated swollen starch granules. In vitro digestibility findings showed that the starch–fatty acid complexes induced by homogenization showed a lower hydrolysis rate compared with the control sample (without a fatty acid) and belonging to a slowly digested starch. This study showed the potential formation of helical inclusion complexes for starch and fatty acids through high-pressure homogenization technique. The results of these studies conducted on modification of starches by high-pressure techniques have showed the significant relationship between physical starch properties and pressure and time. However, process time during high-hydrostatic pressure treatment is economically undesirable in the starch industry that limits its application in industrial production. Therefore, Augustin, Sanguansri, and Htoon (2008) investigated the influence of microfluidization on a suspension of a resistant starch ingredient (high-amylose corn starch with 58% resistant starch) in water that was previously heated (121 °C/60 min) and subjected to shearing using a high-shear mixer. Heating and shearing of starch suspensions led to decrease in the resistant starch content to ~30% either with or without a subsequent microfluidization treatment. However, microfluidization process promoted further reduction in the estimated molecular weight of the starch. Although both heating and shearing of the starch suspension increased the viscosity of starch suspension, further increases were observed with the use microfluidization process. The authors tested the performance of the treated starch suspensions in stirred yoghurts. Substitution of 3% milk solids in yoghurts with starch suspensions which were heated, sheared and microfluidized increased the viscosity and decreased syneresis of yoghurts. The results showed that a treatment process for resistant starch with the combination of microfluidization process had a potential to create a new functional resistant starch ingredient with increased viscosity and water-holding properties.

Cassava starch is generally produced by the wet milling of fresh cassava roots of which the main constituent is starch. Cassava starch has many important features, such as high level of purity, high paste viscosity, excellent thickening characteristics, high paste clarity, high freeze-thaw stability, desirable textural characteristics and a bland taste. It is well known that functional properties of the starches are related to the form of semi-crystalline granules. Since most of native starches is not suitable for industrial applications, the modification of the structures of starches mainly their semi-crystalline regions by various physical methods such as extrusive degradation processes, microwave degradation, radioactive degradation, and ultrasonic degradation has been used. Kasemwong et al. (2011) used microfluidization method to modify starch granules and the effect of microfluidization process of cassava starch–water suspension on the structure and thermal properties has been evaluated. Microstructural observation showed that cassava starch granules were partially gelatinized after microfluidization and a gel-like structure was formed on a granular surface, however the birefringence of native and microfluidization treated starch granules was not significantly different. Laser scattering measurements indicated that microfluidization increased granule size at 150 MPa. Even though the crystalline structure of the starch granule partially lost their integrity during microfluidization, crystallinity values further decreased with the pressure that meaning the poor order of crystalline glucan polymer structure in starch. FTIR result showed that microfluidization process significantly affected the intensity of bands of the amorphous and crystalline part in cassava starch structure. According to thermal analysis, microfluidization treatment caused to a significant decrease of melting enthalpy. The increased microfluidizing pressure and increased shear stress during microfluidization promoted the gelatinization of cassava starch. The effect of microfluidization was possibly due to increased disruption of the more swollen granule and further leaching of the amylose from the granule.

The utilization of microfluidization for the production of bakery products

The functional benefits of cereal brans have already been underlined in many studies conducted on bakery products. In these studies, it has been shown that cereal brans offer some important unique functional and nutritional properties to products in terms of color, texture, shelf life, cooking performance, and their dietary fiber content. In our one of the study (Mert et al. 2014), microfluidization was employed to produce highly branched fibrous structure form of wheat bran as a milling process and the effects of microfluidized wheat bran on the rheological properties of cake batter samples and quality parameters in cake products were determined. According to SEM pictures the differences between the microstructure of regular wheat bran and microfluidized wheat bran samples (three passes) showed the noticeable effect of the microfluidization process (Figure 5). Since microfluidization process provided high shear rates and consistent pressure during its operation, more homogenous particle distribution with the formation of the finely separated

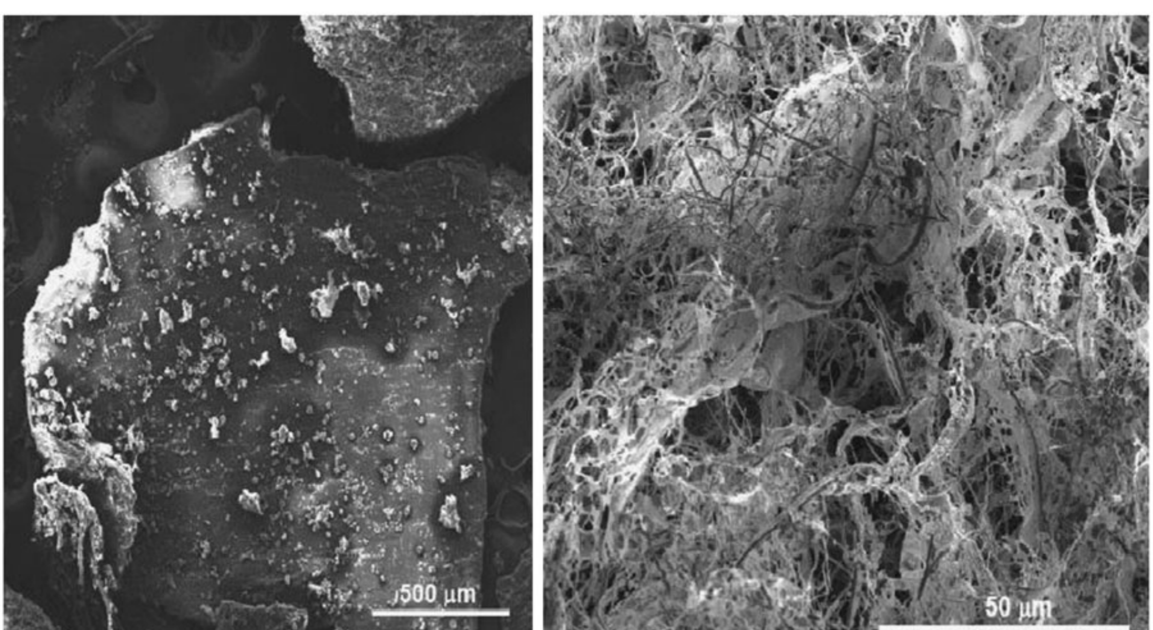

Figure 5. SEM micrographs of (a) wheat bran and (b) microfluidized wheat bran (three passes) samples. Reproduced from Mert et al. (2014) with the permission from the publisher.

fibrous structure with greater surface area was observed. Such a network of entangled fibers improved water holding and binding capacities. Furthermore, the intertwined fibrous structure of microfluidized wheat bran could hold noticeably higher amount of water and sustained suspension form in water, while very quick sedimentation and phase separation were observed visually in both regular wheat bran and ball-milled wheat bran samples. The relation between the swelling capacity and water holding capacity of fiber with viscosity has been reported in literature. In general, soluble fibers are characterized by their ability to increase viscosity and this property is associated to slow the emptying of the stomach, reduce the glycemic response and plasma cholesterol, delay the absorption of some nutrients in the small intestine, and lower serum cholesterol levels. On the other hand, insoluble fibers are characterized by their porosity, their low density and by their ability to increase fecal bulk and decrease intestinal transit since they can increase digesta viscosity by decreasing the free water content in digesta and thus reduce nutrient absorption (Takahashi et al. 2009). Therefore, it should be noted that swelling capacity and water holding capacity of fiber plays a critical role not only on its health benefits but also on its functional characteristics.

The result of this study has also revealed that the change in the structure of wheat bran during microfluidization process caused to the liberation of the phenolic compounds resulting in increased free phenolic content of wheat bran. According to rheological experiments, the increased surface area of fibers also allowed bran fiber to intertwine and form strong fibrous matrix giving higher consistency index, yield stress, and viscoelastic moduli values in batter samples. Various flour formulations have also been examined in the presence of microfluidized wheat bran, and a fibrous network of microfluidized wheat bran in reduced flour-containing samples promoted a gluten-like strength to the batter and consequently to cake samples. It has been stated that entanglement of fiber generates a resistance to flow causing to an increase in consistency index values of batter samples at constant wheat flour level. Furthermore, the presence of fibers had a role on the reducing of the available water in the mixture and limited the plasticizing effect of water. These factors resulted in the elevated yield stress and consistency coefficient of batters with increasing amount of wheat bran or microfluidized wheat bran. When microfluidized wheat bran was incorporated in batter, resulting cake products had firmer texture than control (prepared without addition of wheat bran) and regular wheat bran-containing samples (prepared with wheat bran which went through a size reduction step using a rotor beater mill) having higher cutting force and hardness values, but lower cohesiveness. It has been pointed out that while very low viscosity and viscoelastic properties may avoid the incorporation of gas bubbles during mixing and the gas liberated by the baking powder, very high viscosity and viscoelastic properties of batters may also prevent expansion of gas bubbles. Therefore, microfluidized wheat bran incorporated cakes had inferior quality features with very hard texture and compact structure. On the other hand, in the reduced flour-containing samples, it was also not possible to obtain acceptable quality from control cakes because of the lack of sufficient gluten protein in batter formulation (Figure 6). Consequently, we suggested that such a property of microfluidized wheat bran might be used to produce cake products with much less flour content. Addition of microfluidized wheat bran reduced moisture loss while it retarded to increase in firmness during staling. The result of this mentioned study also revealed that microfluidization can be used as a novel milling technology to produce fibrous products with enhanced physical properties and also microfluidized wheat bran could be used as an alternative functional ingredient in bakery products.

Microfluidized wheat bran with the attempt of decreasing fat content was also used in biscuit samples. It is well known that fat is extensively used in biscuits to impart some important features. It contributes to rheological properties of cookie dough and overall it gives tenderness, moisture retention, uniform grain, improved texture and sensory and longer shelf-life products. Due to the deleterious health effects of saturated and trans-fat consumption on human health, reducing fat in every-day's diet has become a public health issue and a concern for most consumers. Furthermore, the incorporation of different nutritionally rich ingredients for their diversification has also been receiving attention from both academia and industry. However, the quality problems related to the reduction of fats remains to be a technological challenge. Erinc, Mert, and Tekin (2018) studied the effects of various particle sized and different amount of plant fibers as fat mimetic for biscuit formulations instead of biscuit fat. In this study, the fibers with different particle sizes obtained from wheat bran were intended to be used instead of fat in biscuit formulations. Water holding capacity of short fiber (microfluidized) was higher than those of long (not milled) and medium one (milled by a colloidal mill). Therefore, wheat fiber having different proportions of water holding ability was compared in this study for their functionality as fat mimetic. Raw material analysis showed that the composition in terms of total fibers was found to be similar, but their water holding capacity was found to be different and it increased with reducing particle size. In case of short dough products such as biscuit and cookies, strong gluten network formation is usually avoided and therefore such products contain significant amount of fat which hinders their interactions with gluten resulting in improved tenderness. In the presence of sufficient amount of fat, fat can surround and isolate the starch and the proteins that breaks the continuity of the protein and starch structure and creating desired texture in biscuits. Replacing the fat with bran fiber in biscuit formulation reduced the plasticizing effect of lipid molecules. Furthermore, the result of the study showed that fibers especially the microfluidized one (short fiber) hold water more effectively, which decreased free water and limited the plasticizing effect of water molecules. The effect of both restricted fat and restricted water led to higher resistance creep stress in fiber added dough samples. Therefore, more and lower

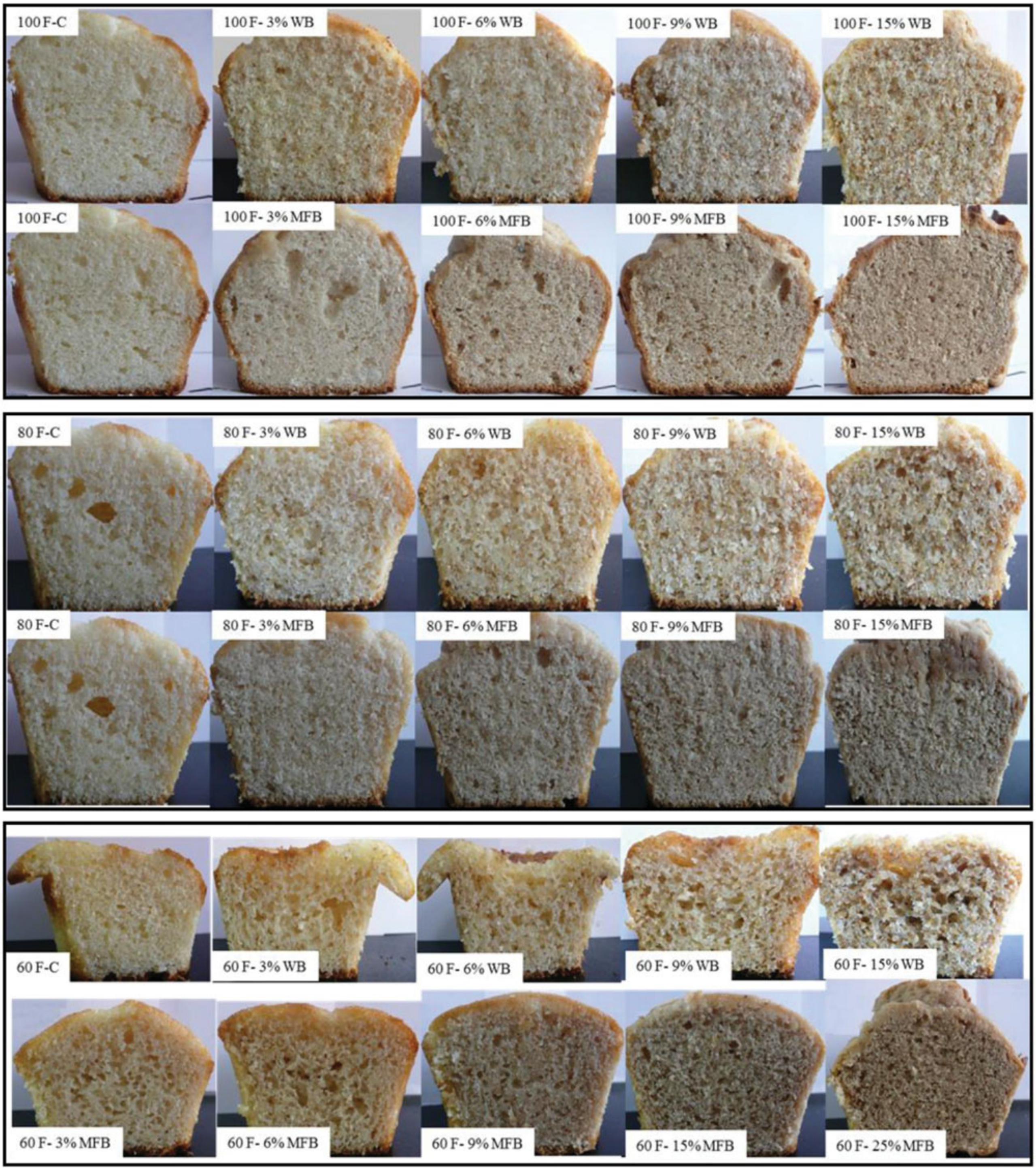

Figure 6. Pictures of cake samples containing various amount of (100, 80, and 60 g) wheat flour and prepared with addition of wheat bran or wheat bran fiber at different percentages. F, gram of four in the formulation; C, control; WB, wheat bran; MFB, microfluidized wheat bran. Reproduced from Mert et al. (2014) with the permission from the publisher.

size of wheat bran fiber having 20 and 30% dry matter instead of fat gave more viscous and elastic moduli values and higher creep resistance values in biscuit dough samples as compared to wheat bran with 10% dry matter. The use of wheat bran instead of fat prevented dough hardening caused by fat reduction. On the other hand, harder doughs were obtained with the increasing amount of wheat bran fiber and decreasing fiber size. It has been suggested that as the amount of shortening was reduced the greater the amount of wheat bran fiber could be added in the dough formulas. The dough must be softer with increasing amount of water in the dough formulation and the amount of water in the formula could be increased with the use of wheat bran fiber. However, it was found that the use of 20 and 30% dry fiber did not allow softening of the dough since the water was retained by the fibers. Results showed that wheat bran fiber with bigger particle size (long fiber) was found to be more favorable in terms of textural properties of the dough and the quality parameters of biscuits whereas the fibers with smaller particle size (Medium Fiber and Small Fiber) enhanced viscoelastic properties of dough. This study indicated that the texture of biscuits was greatly influenced by the texture of the dough. Authors also mentioned that although the use of these fibers in the production of low-fat biscuits were found to be suitable in terms of workability of dough samples, increasing fiber content and/or reducing fiber size resulted in harder biscuits with lower spreading ratio.

Hazelnut skin is often considered as waste product by industry even though it is a valuable by-product of hazelnut industry since it is rich and inexpensive source of natural antioxidant. Due to the fast growing in food industry, many by-products obtained during processing are generally disposed in environmental and economical terms. Considering that in our recent studies, we have used milled and microfluidized hazelnut skin as an ingredient in cake and cookie formulations. The different size reduction techniques (hammer milling, ball milling and microfluidization) were also used to produce a functional food ingredient from hazelnut skin (Cikrikci, Demirkesen, and Mert 2016; Yildiz, Demirkesen, and Mert 2016). The entangled structures of microfluidized hazelnut skin resulted in much higher consistency index, yield stress and viscoelastic moduli values in batter samples than conventionally milled hazelnut skin. The resulted products had higher hardness, finer crumb structure, darker color and longer shelf life. Moreover, the resulted products had higher hardness, finer crumb structure, darker color, longer shelf life and lower water activity at comparable moisture contents. Outcomes of these studies suggested that microfluidization can be applied as a novel milling technology to produce fibrous hazelnut skin samples with improved physical properties, which could be potentially used in bakery products. Furthermore, these studies showed that microfluidization can be applied to incorporate more water in bakery products without having unacceptably high water activity. We proposed that functionalization through microfluidization can be applied as a prospective method for the production of fibrous structures not only from hazelnut skin but also from other common agro by-products such as wheat bran, corn bran, citrus pulp, etc.

The microfluidization process has also been applied in order to improve the functional properties of different gluten-free products as well as to create alternatives to meet with the nutritional requirements of celiac patients. Recently, corn gluten meal received much attention for production of gluten-free formulations. Ozturk and Mert (2018a) conducted a study to present the potential of microfluidization as a value adding process to corn gluten meal, which is generally used as animal feed and hence is underutilized in food industry. They also aimed to improve water holding ability of corn gluten and to investigate the possibility of using this zein-rich by product as the main ingredient in gluten-free bread formulations. Therefore, they analyzed the features of corn gluten meal with hydrocolloids and pH modifications. They also tested the effects of microfluidization, pH modifications, and hydrocolloids on the rheological properties of bread dough and final quality parameters of gluten-free bread samples to develop a product with improved dough stability and enhanced baking characteristics. SEM images of untreated and treated corn gluten meal samples indicated that the hydrophobic amino acids in corn gluten meal showed a tendency to hide inside the structure to reduce their energy by folding and agglomeration resulting in the aggregation tendency and non-uniformity of untreated samples. Aggregation was decreased by the use of colloidal mill treatment as a result of formation of smaller particle sizes but complete uniformity was not obtained. On the other hand, the application of microfluidization completely changed the appearance of samples by producing micro and nanoparticles with its combined forces. Hence, more homogenous particle distribution was obtained. The effects of pH modification on the microstructure of corn gluten meal revealed that in addition to microfluidization pH modifications created more open structures. Furthermore, smooth surfaces were modified into branchy network by producing more tissues, micropores, and cavities. This result might be attributed to deformation within the protein structure such as breakages of bonds, unfolding of hydrophobic amino acids, and hydrolysis due to pH modifications with microfluidization. The transmission profiles indicated unstable and rapid sedimentation of the corn gluten meal particles (Figure 7). The untreated samples had very rapid phase separation. Microfluidization process had significantly lower light transmitting area than other treated and untreated samples reflecting the improved physical stability in water and higher water holding ability of microfluidized samples. pH treated samples on the other hand presented better stability profiles than the untreated sample, but their stability was not as good as that of microfluidized samples. Rheological measurement of corn bread dough samples based on strain sweep measurement indicated that in the lack of gum, untreated samples could not form a homogenous structure because of their incapability to hold water within the structure. According to frequency sweep test, microfluidized samples had the highest moduli values compared to other treatments. Moreover, the addition of hydrocolloids to gluten-free dough formulations further increased moduli values of microfluidized samples. The frequency dependence of the samples increased with the addition of hydrocolloids indicating formation of stronger dough structures because of its improved gas and water holding capacity. The decreasing trend in viscoelastic moduli values with the application of pH shifting might be attributed to destruction of structure due to over-processing of samples. Furthermore, elevated pH levels removed proteins away from their isoelectric point by the denaturation and unfolding of proteins resulting in reduces in the adhesion capability of dough. Consequently, the elastic and viscous moduli values were further reduced with the extreme alkaline conditions giving less strong dough structure. Moisture content analysis of breads showed that water in microfluidized and microfluidized and pH treated samples interacted with other ingredients by overcoming the hydrophobicity of corn gluten meal. Color measurement of bread samples

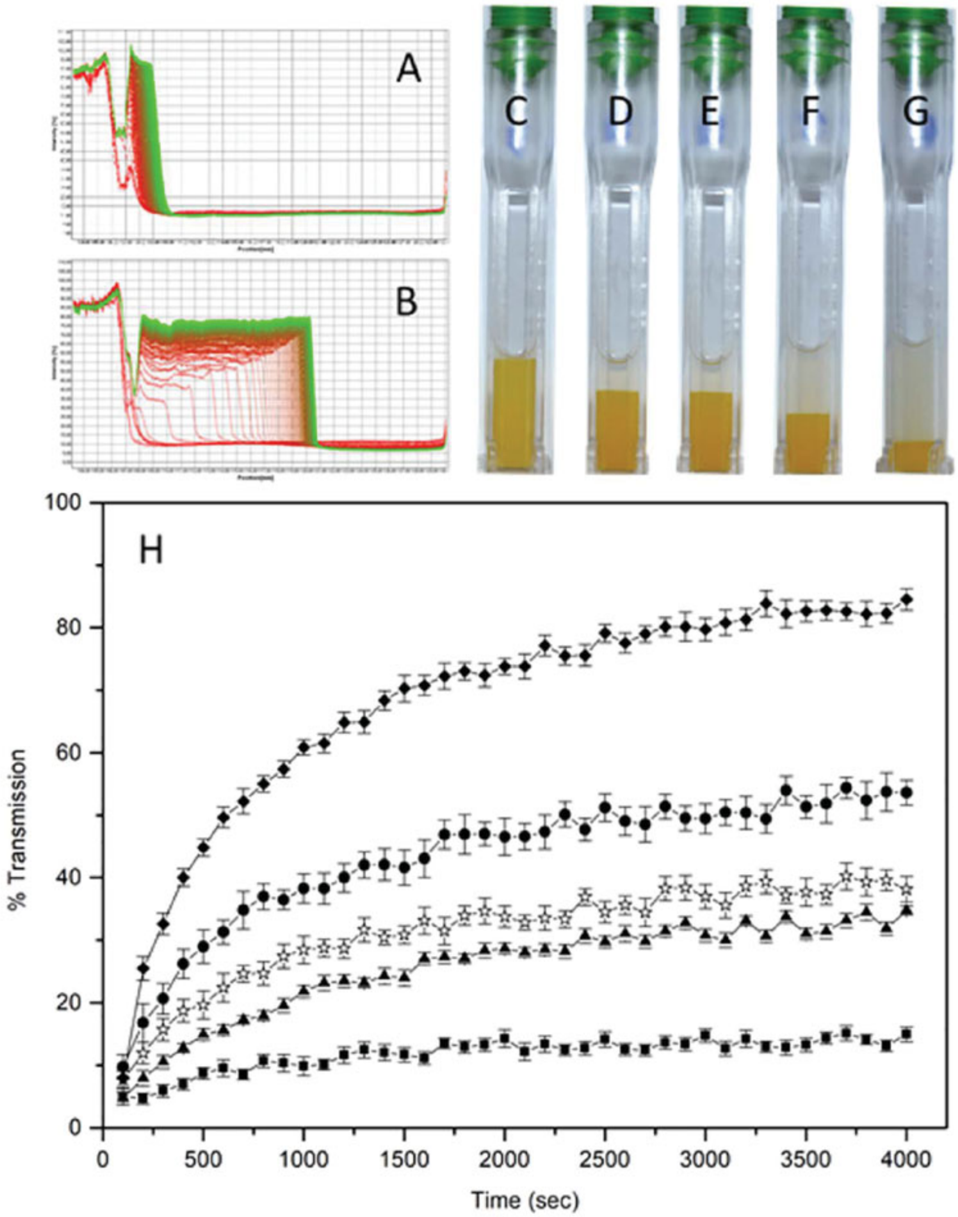

Figure 7. Dispersion analyzer results of the zein suspensions. A: Time course of the light transmission profiles of the microfluidized corn gluten meal suspension under centrifugal force. B: Time course of the light transmission profiles of the untreated corn gluten meal suspension under centrifugal force. C, D, E, F, G: The sample cells after centrifugation for microfluidized, microfluidized -pH 6, microfluidized -pH 8, microfluidized-pH 10, and untreated sample, respectively. H: integrated transmission values of the samples, where ◆ - untreated sample, ■ - microfluidized, ▲, ⋆, and ● - pH shifting + colloidal mill + microfluidizer (microfluidized -pH 6, microfluidized-pH 8, and microfluidized-pH 10, respectively). Reproduced from Ozturk and Mert (2018a) with the permission from the publisher.

presented that brighter yellow crumb color was observed in microfluidized and microfluidized and pH treated samples. When microfluidized and pH treated samples were compared, microfluidized-pH 6 had brighter yellow crumb color, which was followed by microfluidized-pH 8, microfluidized, microfluidized-pH 10, and untreated samples, respectively. This finding was related to revealing more of lutein and zeaxanthin carotenoids, which are the carotenoids responsible for the yellow color of corn gluten meal and corn, due to the reduction in particle size. Therefore, the color of corn gluten meal became brighter with microfluidization and with slight pH modifications (microfluidized-pH 6 and microfluidized- pH 8) a result of improved uniformity by breaking corn gluten meal molecules. On the other hand, excessive pH modification (MF pH 10) caused to a deterioration of these carotenoids giving darkener the crumb color. Although specific volume of bread samples slightly decreased with microfluidization process, these breads had a much closer cell grain through the structure with apparently fewer pores. On the other hand, the combination of microfluidization and pH treatment led to increased pore sizes and even devastation of some crumb cell structure compared to microfluidized samples in addition to further decrease in specific volume. The addition of hydrocolloids clearly improved the quality of breads giving a more aerated, round top, elastic, and fine crumb structure. Texture profile of breads indicated that the lowest hardness values were obtained from microfluidizatied breads and the decrease in hardness values was found to be more obvious in hydrocolloid containing formulations. This might be related to more solubilized structure by breaking the bonds and separating the hydrophobic molecules inside creating more possible interactions among dough constituents, especially between protein and starch. On the other hand, pH modification in addition to microfluidization resulted in the destruction of materials and reduced compatibility and therefore higher pH shifting led to a big increase in hardness. Microfluidization and the addition of gums increased springiness and cohesiveness values of breads. Staling analysis results had higher correlation with the hardness values of breads and therefore, breads produced with microfluidization process and having hydrocolloids had longer shelf life. Therefore, the authors concluded that the use of microfluidization as a milling process for corn gluten meal was found to be an efficient operation and therefore, this process can be applied to bring this underutilized material to a valuable one in food industry for the production of gluten-free products. The same authors also evaluated the utilization of microfluidization process as a physical modification method on corn gluten meal in order to convert corn gluten meal into a valuable substance and they also examined the potential use of xanthan gum and citrus fiber in bread dough formulation (Ozturk and Mert 2018b). Microfluidization process increased stability, surface area, and water holding capacity of dough through its modification effect creating compatible and homogeneous dough structure as opposed to untreated samples. Higher moduli values were obtained with the addition of xanthan and citrus fiber and this could be associated to stronger dough network with increased water holding and gas entrapment capacities. Much brighter crumb color was observed with microfluidization treatment due to revealing of carotenoids responsible for the yellow color of corn gluten meal. Both microfluidization treatment and the addition of supplements improved specific volume and texture of breads giving higher loaf volume, lower hardness, and higher cohesiveness and springiness values. Overall, the result of this study indicated microfluidization could be used as a milling technique to modify corn gluten meal.

Conclusions

Recent researches have deal with the use of cereal and cereal based by-products due to the nutritional, functional and health benefits of fiber. However, it has been reported that a high level of dietary fiber adversely affects the quality of products such as color, texture, volume, sensory and storage time. Furthermore, most of bound phenolic compounds in cereal grains are not accessible to attack by enzymes in the human gastrointestinal tract, leading to low bioavailability. On the other hand, recent scientific experiences have revealed that microfluidization as a novel mean of size reduction method enhanced physiochemical, nutritional and functional properties of fibers obtained from various types cereals. During microfluidization, food are exposed to intense shear rates, high velocity impact forces, ultrahigh pressure, instantaneous pressure drop and hydro-dynamic cavitation hence leading to highly efficient droplet disruption and the formation of uniform distribution of particles/emulsions. Thus, microfluidization has been reported to cause to the disintegration of large particles into flaky and fibrous structures of which higher surface areas, water holding capacity, swelling capacity, porosity, oil-holding capacity and cation-exchange capacity resulted in noticeably different texture and rheological properties in dough/batter and bakery products. Microfluidized bran has also been used to produce bakery products with much less flour content. Moisture content of bakery products may be increased without water activity exceeding the required limits in the products. Incorporation of the novel fibers into bakery products may slow down retrogradation rate during the storage period. This technology has also released some of the phenolic compounds which were previously trapped within the structures enhancing their bioavailability. Microfluidization has been also applied to formation of a new functional resistant starch ingredient with increased viscosity and water-holding properties. The research performed in the literature reflects the potential of microfluidization process over traditional milling/grinding techniques, therefore this process can be easily scaled up and many different, usually wasted, agro by-products can be used and recycled to obtain value added novel ingredients.

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