Rheological Characterization of the Dough with Added Dietary Fiber by Rheometer: A Review

Alina CULEȚU*, Gabriela MOHAN, Denisa Eglantina DUȚĂ

National Institute of Research and Development for Food Bioresources - IBA Bucharest, 6 Dinu Vintila, 021102 Bucharest, Romania
*corresponding author: alinaculetu@gmail.com; alina.culetu@bioresurse.ro

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Abstract

Dietary fibers represent a group of food components approved for use in functional foods as they offer health benefits such as a lower risk for coronary heart disease, type 2 diabetes, obesity and constipation. The enriched bread with different sources of fiber is important in the actual market situation, with an increasing consumer aware of health benefits. This paper reviews recent studies dealing with bread dough rheological characterization by rheometer. The focus is on wheat-based dough and gluten-free dough with added dietary fiber, also. Rheological analysis by rheometer is a useful approach to study the effects of dietary fibers on dough behavior showing that fiber incorporation in bread formulation reduces the elasticity of bread and enhances the mechanical properties of bread.

Keywords: dietary fiber, dough viscoelastic properties, rheometer

Introduction

The rheological behavior of dough is linked to baking properties and bread quality. The relationship between rheological behavior of dough and baking performance and quality of the final product is described in many studies for each phase of the processing flow. Dough rheology is in good correlation with baking qualities on various stages of dough development, i.e. dough mixing parameters correlate with loaf volume, and regarding the proofing stage, as much as dough expands, rheological changes occurred continuously (Chin and Martin, 2014).

The rheology knowledge applied for bakery products through instrumental measurements is classified as fundamental and empirical approach. Fundamental methods provide defined experimental conditions of physical properties (stress and strain) that allow a better interpretation of results, useful for performing process and engineering calculations. The empirical methods of measuring dough rheology are used extensively for flour characterization and quality control, and they are simpler and faster, but unclear about what is being measured. According to Weipert (2006), rheologists state that “with the empirical methods, they do not know what is being measured but it works, whereas with the fundamental methods, they know exactly what they are measuring, but it doesn’t work”.

The dough formation is an essential step in the technological process of flour-based products; the development of a gluten network leads to create viscosity and elasticity, as important properties of doughs.
The design of fiber-enriched baked goods is facing up to the consumer resistance to accept breads with reduced loaf volume, hard crumb and possible accompanied by particular flavors, despite the link between the intake of dietary fiber and several health benefits. Dietary fiber incorporation into wheat dough interferes with protein association and its further aggregation during heating, perhaps because the fibers take up the space of the proteins in the gluten network. In addition, the resultant fiber-rich doughs have high water absorption and reduced fermentation tolerance. Rheology of the dough with added dietary fiber is performed in order to understand the mechanism of action of dietary fiber in the dough, providing useful information about dough behavior in the different processing steps.

This review aims to present research studies about the characterization of dough with different fiber sources using the analysis with rheometer.

**Analysis with rheometer**

Rheology is the study of the horizontal flow and vertical deformation of matter; both being associated to the structure of sample. Rheology measurements by the use of a rheometer bring information about the rheological properties of viscoelastic materials (Song and Zheng, 2007).

A rheometer is a laboratory device used to measure the way in which a fluid (liquid, suspension or slurry) flows in response to applied forces, especially for those fluids which cannot be defined by a single value of viscosity and therefore require more parameters to characterize than in the case of a viscometer. Generally, there are two different types of rheometers: rotational or shear rheometers (rheometers that control the applied shear stress or shear strain) and extensional rheometers (rheometers that apply extensional stress or extensional strain) (Ahmed et al., 2017).

Some examples of measurement procedures employed in order to determine rheological properties using the rheometer (ThermoScientific): (1) Controlled Stress Creep-test which provide information regarding the viscoelastic properties of a substance. A constant shear stress is applied instantaneously and the resulting deformation is measured as a function of time. An analysis of the creep-curve enables the determination of: zero-shear viscosity, the elastic deformation and the steady-state compliance. (2) Controlled Stress Recovery test which is usually linked to a creep step. The shear stress is set to zero. With this measurement the recoverable elastic portion of the deformation can be determined. (3) Oscillation Time Sweep which is used to observe how material changes over time. (4) Oscillation Stress Sweep is used to determine a material’s linear viscoelastic range. (5) Oscillation Temperature Sweep is very similar to the Oscillation Time Sweep test, with the only difference that the temperature is changing in accordance to the settings made.

As a viscoelastic system, the elastic component of bread dough is measured by storage modulus ($G'$), the viscous element by loss modulus ($G''$), while the loss tangent (tan δ) which is related with the overall viscoelastic response describes the increase in $G''/G'$ ratio (change from solid to liquid-like behavior) of the dough.

The storage (elastic) modulus $G'$ (in Pa) of a material refers to the deformation energy stored in the material after oscillation is removed and represents a measurement of the elastic properties of the material. It represents the elastic portion of the viscoelastic behavior and describes the solid-state behavior of the sample. The higher the value is, the more elastic the material will be. The loss (viscous) modulus $G''$ (in Pa) of a material refers to the energy lost from the sample during oscillation, and after the energy is lost, the sample cannot recover the original shape, therefore shows a viscous behavior. It characterizes the viscous portion of the viscoelastic behavior, namely, the liquid-state behavior of the sample (Ahmed et al., 2017).

The dough is a food matrix characterized as being a non-Newtonian material, which during dough rest presents thixotropic properties and fluid while mixed. Rheological tests are performed applying through various methods stresses and strains on the sample, monitoring the time scale of the deformation as well as the flow history. There are two different rheological behavior which can be assigned to the food systems, depending on the before mentioned tests: the thixotropic model - what describes a material where its apparent viscosity decreases with time of flow and the rheoplectic or antithixotropic model - its apparent viscosity increases with time of flow. For the study of the ageing of solid doughs, there are two useful tests: the stress relaxation test at constant strain
- for evaluation of stress decrease with time, and the creep test at constant stress - assessment of strain increase with time (Chin and Martin, 2014).

Generally, the fiber effect on dough viscoelastic properties could be direct or indirect. Direct effect means a contribution of the fiber to dough elasticity, and the indirect effect is related to variation of water absorption. The dynamic moduli $G'$ and $G''$ are very sensitive to water content, increasing as water content decreases (Peressini and Sensidoni, 2009).

Physicochemical properties of fibers vary depending on the source and the type and degree of processing, those characteristics have great impact on the functional quality of the products obtained in every step of the technological flow and end products when obtained by conventional bread-making processes. Rheological tests on dough can predict its behavior during mixing, fermentation and baking, dough being subjected to different shear and extensional large deformations (including fracture), which are largely affected by temperature and water hydration, where the bread dough behaves as a viscoelastic material. It is generally accepted that the presence of fibers limited the water availability for starch pasting and that the fiber incorporation into the dough matrix induces the disruption of the viscoelastic system leading to weaker doughs. The effect over dough viscoelastic characteristics during dual mixing and heating constraint depends on the extent of flour substitution in the first place and on the nature of the fibers in the blend, in the second place (Rosell et al., 2010). Moreover, the additions of certain soluble fibers strengthen the structure of dough and improves the quality of bread, meanwhile higher amounts of insoluble dietary fibers have an unfavorable effect on the formation of the gluten network because of gluten-fiber interaction, leading to lower quality of bread.

**Dietary fiber in bakery products and rheometer analysis**

According to the Codex Alimentarius Commission (2008), dietary fiber is defined as “carbohydrate polymers with 10 or more monomeric units, which are not hydrolyzed by the endogenous enzymes in the small intestine of humans.” Dietary fiber is represented by the edible portion of plants, mainly carbohydrates, that are resistant to the digestion and the adsorption in the human small intestine with complete or partial fermentation in the large intestine (Kendall et al., 2010). Dietary fibers are mainly obtained from cereal grains (44%), vegetables (21%), fruits (13%) and legumes (10%). Example of some rich sources of dietary fiber include: outer pericarp of cereal grains, endosperm cell walls, seed coat and cotyledons of legumes, psyllium husks, and fruit and vegetable skins (Bultosa, 2016).

Dietary fiber intake is generally accepted as having an important impact on human health and a quantity of 25–30 g daily intake has been associated with prevention or treatment of some widespread affections such as cardiovascular diseases and hypertension, diabetes, regulation of the intestinal tract, and decrease in the incidence of several types of cancer (Martins et al., 2017). Although fiber is easily available in a wide variety of plant foods, western diet frequently presents an intake lower than the recommended, therefore fiber supplementation of foods consumed on a regular basis, such as bread, is advisable. The addition of dietary fiber incorporated in bakery products is performed at the levels required for the nutrition claims “source of fiber” and “high in fiber” that means 3 and 6 g dietary fiber /100 g fresh bread, respectively (European Commission, 2006).

Table 1 shows research studies evaluating the rheological properties of dough formulated with a diversity of fiber sources from the usual raw materials such as cereals, to peas, potato and by-products from different food technological flow stages. The diversity of fiber sources underlines the complexity of the food matrix. The need to explain such a great variety of food matrix behavior has led to a multitude of interpretation tools; therefore, there are many mathematical models and methods applied in order to better express the mechanism of action of the fiber in the dough.

The rheological behavior of the dough was studied with different types of rheometers. Table 2 presents some examples of rheometers used in bread dough rheological characterization.

**Wheat-based dough with added dietary fiber**

In a recent study, Liu et al. (2019) have analyzed the influence of bran dietary fiber on dough rheological properties and provided
theoretical reference for the utilization of wheat bran. Dynamic rheological properties of the dough were determined using a rotational rheometer (Table 2) through different tests: strain sweep, frequency sweep and creep-recovery. The addition of wheat bran dietary fiber adversely influenced the proper formation of doughs, regardless of the level of addition (between 3 and 12%). Regarding the strain sweep, the results for wheat bran dietary fiber enriched doughs, showed that $G'$ and $G''$ were higher than control group. The increase of $G'$ and $G''$ with increase of wheat bran dietary fiber addition indicated a more elastic behavior of doughs. Both moduli were influenced by the quality and content of flour protein, and by the water content of the dough. The frequency sweep results also showed that $G'$ and $G''$ increased in the dough when the level of wheat bran dietary fiber increased. Creep-recovery curves of the dough with or without wheat bran dietary fiber revealed a typical viscoelastic behavior combining both viscous fluid and elastic components and the strain of dough system presented continuously modification with time. The maximum strain

### Table 1. Research studies using the rheometer analysis for the characterization of dough with different fiber sources

<table>
<thead>
<tr>
<th>Product</th>
<th>Raw material</th>
<th>Fiber source</th>
<th>Dosage (%)*</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bread</td>
<td>Sweet potato flour, glutinous rice flour, <em>Agaricus bisporus</em> polysaccharide, inulin</td>
<td>3; 6; 9</td>
<td></td>
<td>Sulieman et al. (2018)</td>
</tr>
<tr>
<td>Sweet pan breads</td>
<td>Wheat flour</td>
<td>Chia</td>
<td>5; 10; 15; 20</td>
<td>Zettel and Hitzmann (2016)</td>
</tr>
<tr>
<td>Bread</td>
<td>Wheat refined flour</td>
<td>Oat</td>
<td>6; 12</td>
<td>Kurek et al. (2017)</td>
</tr>
<tr>
<td>Bread</td>
<td>Wheat flour 550 type</td>
<td>Oranges, elderberries, spent beer yeast</td>
<td>4; 8</td>
<td>Martins et al. (2017)</td>
</tr>
<tr>
<td>Bread</td>
<td>Rice flour</td>
<td>Concentrate enriched in β-glucan from oat and barley</td>
<td>1.3; 2.6; 3.9</td>
<td>Pérez-Quirce et al. (2017)</td>
</tr>
<tr>
<td>Bread</td>
<td>Corn starch, rice flour</td>
<td>Wheat, maize, oat, barley</td>
<td>3; 6; 9</td>
<td>Sabanis et al. (2009)</td>
</tr>
<tr>
<td>Bread</td>
<td>Rice flour, native corn starch</td>
<td>Bamboo, oat, pea, potato, Nutriose®, polydextrose</td>
<td>10</td>
<td>Martínez et al. (2014)</td>
</tr>
<tr>
<td>Bred rolls</td>
<td>Wheat flour</td>
<td>Fiber fractions of prickly pear cactus (nopal)</td>
<td>3.6; 2.18; 0.36</td>
<td>Guevara-Arauza et al. (2015)</td>
</tr>
<tr>
<td>Dough</td>
<td>Wheat flour</td>
<td>Wheat dietary fibers</td>
<td>0.5 – 10</td>
<td>Bonnand-Ducasse et al. (2010)</td>
</tr>
<tr>
<td>Bread</td>
<td>Wheat flour</td>
<td>Inulin extracted from Jerusalem artichoke tubers</td>
<td>2.5; 5</td>
<td>Rubel et al. (2015)</td>
</tr>
<tr>
<td>Bread</td>
<td>Wheat flour</td>
<td>Carboxymethylcellulose, locust bean gum, fructo-oligosaccharide, gluco-oligosaccharide</td>
<td>10</td>
<td>Angioloni and Collar (2011)</td>
</tr>
<tr>
<td>Bread</td>
<td>Wheat flour</td>
<td>Fruits pectin and polyphenolic extracts</td>
<td>3; 6</td>
<td>Sivam et al. (2011)</td>
</tr>
<tr>
<td>Bread, batter</td>
<td>Wholegrain oat flour</td>
<td>Oat</td>
<td></td>
<td>Hüttner et al. (2010)</td>
</tr>
<tr>
<td>Bread</td>
<td>Hard wheat flour</td>
<td>Wheat bran, aleurone bran</td>
<td>15</td>
<td>Adams et al. (2017)</td>
</tr>
<tr>
<td>Bread</td>
<td>Corn starch, potato starch</td>
<td>Debittered acorn flour</td>
<td>20; 40; 60</td>
<td>Korus et al. (2015)</td>
</tr>
<tr>
<td>Bread</td>
<td>Wheat flour</td>
<td>Inulin (fructans with different degree of polymerization)</td>
<td>2.5; 5; 7.5</td>
<td>Peressini and Sensidoni (2009)</td>
</tr>
<tr>
<td>Dough</td>
<td>Wheat flour</td>
<td>Wheat bran</td>
<td>3; 6; 9; 12</td>
<td>Liu et al. (2019)</td>
</tr>
<tr>
<td>Bread</td>
<td>Wheat white flour</td>
<td>Pea pod, broad bean pod</td>
<td>0.25; 0.5; 0.75; 1</td>
<td>Fendri et al. (2016)</td>
</tr>
<tr>
<td>Bread</td>
<td>Wheat flour</td>
<td>Inulin, sugar beet, pea cell wall, pea hull</td>
<td>6 to 34</td>
<td>Rosell et al. (2010)</td>
</tr>
<tr>
<td>Steamed bread</td>
<td>Wheat flour</td>
<td>Pineapple core</td>
<td>5; 10; 15</td>
<td>Shiau et al. (2015)</td>
</tr>
</tbody>
</table>

* with respect to the raw material
showed that the control group presented less resistance to deformation than fiber enriched dough, the results keeping the same trend in the strain sweep test. The dough with wheat bran dietary fiber showed higher mechanical strength than the control sample, being much stiffer than control sample due to the high water-binding capacity of wheat bran fiber that limited hydration of starch and protein in dough system (Liu et al., 2019). The authors concluded, in general, that the addition of wheat bran dietary fiber caused important increase in the elastic nature of doughs, the dough being more brittle upon strain, perhaps as a result of water redistribution in gluten as well as the physical damage to gluten matrix induced by fiber.

Bread, generally made from different type of flours (the most important groups being wholegrain and refined flours), is a product with high nutritional value when is based on wholegrain flours and in the same time with much appreciated taste and physical properties when the product is based on refined flours. However, wholegrain bread could have also a negative effect on human health due to the presence of a phytic acid, which decreases the bioaccessibility of some microelements, therefore it is necessary to use special technological measures to decrease this effect.

Kurek et al. (2017) evaluated the rheological properties of dough and final bread quality made from refined wheat flour, enriched with oat dietary fiber (percentage of 6% and 12%, respectively), spelt flour and two types of wholegrain flour: wholegrain (full milling of entire kernel) and wholemeal (one-step milling). The elastic modulus was higher in all dough than the viscous modulus showing that all dough was more elastic than viscous. The highest \( G' \) values were observed in dough with 6% oat dietary fiber addition and the lowest in the wholegrain sample. The rheological measurements revealed that the highest instantaneous compliance (\( J_0 \)) was observed in the wholemeal sample and the lowest was in the mixture with 6% oat dietary fiber addition. The lowest specific volume was observed in the wholegrain bread (0.82 cm\(^3\)/g), while the highest was observed in the control white bread sample (1.60 cm\(^3\)/g) (Kurek et al., 2017).

Bonnard-Ducasse et al. (2010) used several fractions of wheat fibers isolated from starchy endosperm, aleurone layer and bran, with characterized hydration properties and arabinoxylans content on bread dough development. The influence of the wheat fiber addition to standard flour was studied through rheological tests, using dynamic frequency sweep test and creep and creep recovery tests. The effect of insoluble arabinoxylans on dough development was evaluated through their capacity to retain water, and it was found that the addition of insoluble arabinoxylans increased the viscoelastic modulus. The addition of soluble and insoluble arabinoxylans to the dough did not modify the overall dough flow behavior in shear, characterized by a Newtonian plateau at low shear rates followed by shear-thinning behavior at larger shear rates. Water soluble arabinoxylans modified the Newtonian viscosity value, meanwhile the insoluble arabinoxylans addition increased dough consistency, due to a filler-like action in the dough matrix (Bonnand-Ducasse et al., 2010).

The effect of addition of commercial wheat aleurone and bran (pre-hydrated) on rheological properties of frozen dough and final bread quality was studied by Adams et al. (2017). Dough dynamic rheological analysis was performed using a controlled stress rheometer (Table 2). The dynamic rheological data indicated that fresh dough samples with added wheat fiber from bran were significantly more elastic and firmer (higher \( G' \)) than samples with refined flour. By wheat aleurone and bran addition, \( G' \) increased compared to fresh dough sample made from refined flour. The incorporation of wheat fiber into refined wheat flour produced dough with minimum alterations in its rheological properties during 9 weeks of frozen storage (−18 °C) compared to refined and 100% wheat flour dough samples. The study underlined the positive role of pre-hydration treatment of wheat aleurone or bran to enhance the quality of the final products as compared to non-hydrated fiber.

Hüttner et al. (2010) studied commercial wholegrain oat flours from different countries (Finland, Ireland and Sweden) to evaluate the bread potential with the objective of finding predictive relationships between flour physicochemical properties and bread quality. Wholegrain oat flours are high in dietary fiber content, and, especially, soluble fiber as \( \beta \)-glucan. Small amplitude oscillatory shear measurements within the linear viscoelastic region were used to
study the rheological properties of the wholegrain oat doughs using a controlled stress and strain rheometer (Table 2). Regardless of the wholegrain flour used, storage modulus was higher than loss modulus, indicating elastic-solid-like behavior of the doughs. Dough made from wholegrain oat flour from Finland was more elastic (higher values for $G'$) than the others flours. Variations in the wholegrain flour composition were responsible for differences in the water hydration capacity and consequently influenced dough and bread making properties. Water hydration capacity

Table 2. Types of rheometers used in bread dough rheological characterization

<table>
<thead>
<tr>
<th>Rheometer type</th>
<th>Company</th>
<th>Geometry</th>
<th>System</th>
<th>Diameter (mm) / gap (mm)</th>
<th>T (°C)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>MARS 40 dynamic rheometer</td>
<td>Termo-Haake, Karlsruhe, Germany</td>
<td>plate-plate</td>
<td>- / 2</td>
<td>20</td>
<td></td>
<td>Iuga et al. (2019)</td>
</tr>
<tr>
<td>RheoStress 6000 rotational rheometer</td>
<td>Thermo Fisher Haake, Germany</td>
<td>plate-plate</td>
<td>20 / 2</td>
<td>25</td>
<td></td>
<td>Liu et al. (2019)</td>
</tr>
<tr>
<td>DHR3</td>
<td>TA Instruments, West Sussex, England</td>
<td>parallel plate</td>
<td>40 / 1</td>
<td>25</td>
<td></td>
<td>Sulilman et al. (2018)</td>
</tr>
<tr>
<td>Mars III</td>
<td>Thermo Fisher Scientific Inc., USA</td>
<td>plate-plate</td>
<td>20 / 2</td>
<td>15</td>
<td></td>
<td>Kurek et al. (2017)</td>
</tr>
<tr>
<td>AR-G2</td>
<td>TA instruments, New Castle, USA</td>
<td>plate-plate</td>
<td>40 / 2</td>
<td>-</td>
<td></td>
<td>Martins et al. (2017)</td>
</tr>
<tr>
<td>RheoStress 1</td>
<td>Thermo Haake, Karlsruhe, Germany</td>
<td>serrated parallel plate</td>
<td>60 / 2</td>
<td>25</td>
<td></td>
<td>Pérez-Quirce et al. (2017)</td>
</tr>
<tr>
<td>MCR 302 rotational rheometer</td>
<td>Anton Paar, Graz, Austria</td>
<td>parallel plate</td>
<td>25 / 2</td>
<td>-</td>
<td></td>
<td>Zettel and Hitzmann (2016)</td>
</tr>
<tr>
<td>Controlled stress oscillatory rheometer</td>
<td>Rheoplus, AntonPaar, Germany</td>
<td>serrated plate-plate</td>
<td>- / 1.5</td>
<td>25</td>
<td></td>
<td>Guevara-Arauza et al. (2015)</td>
</tr>
<tr>
<td>MARS II</td>
<td>Thermo Haake, Germany</td>
<td>parallel plate</td>
<td>35 / 0.5</td>
<td>25</td>
<td></td>
<td>Korus et al. (2015)</td>
</tr>
<tr>
<td>MCR301 Physica rheometer model</td>
<td>Anton Paar GmbH, Austria</td>
<td>parallel plate</td>
<td>50 / 2</td>
<td>25</td>
<td></td>
<td>Rubel et al. (2015)</td>
</tr>
<tr>
<td>RheoStress 1 controlled strain rheometer</td>
<td>Thermo Fisher Scientific, Schwerte, Germany</td>
<td>serrated parallel plate</td>
<td>60 / 3</td>
<td>25</td>
<td></td>
<td>Martínez et al. (2014)</td>
</tr>
<tr>
<td>RS1 stress rheometer</td>
<td>Thermo Haake, Karlsruhe, Germany</td>
<td>plate-plate</td>
<td>35 / 1</td>
<td>25</td>
<td></td>
<td>Angioloni and Collar (2011)</td>
</tr>
<tr>
<td>MCR 301</td>
<td>Physica, Graz, Austria</td>
<td>plate-plate</td>
<td>25 / 2</td>
<td>-</td>
<td></td>
<td>Sivam et al. (2011)</td>
</tr>
<tr>
<td>MCR 301 controlled stress and strain rheometer</td>
<td>Anton Paar, Germany</td>
<td>corrugated plates</td>
<td>- / 2</td>
<td>30</td>
<td></td>
<td>Hüttnner et al. (2010)</td>
</tr>
<tr>
<td>RC 1 rotational rheometer</td>
<td>Rheotec Messtechnic GmbH, Raderburg, Germany</td>
<td>-</td>
<td>-</td>
<td>25</td>
<td></td>
<td>Sabanis et al. (2009)</td>
</tr>
</tbody>
</table>
was found to be the main reason for increased elasticity of wholegrain oat batters, due to the physicochemical properties of the flours. Small flour particle size, damaged starch granules and high protein and fiber content were identified as the key factors causing increased water hydration capacity. The authors suggested that flours with coarse particle size, limited starch damage and low protein content result in superior oat bread quality. Positive effects on oat bread quality were observed for low batter viscosity and high deformability.

Some studies reported the influence of various fibers on the dough matrix, such as: addition of apple pomace and insoluble wheat fiber leading to a stiffer dough, probably through a filler-like effect in the dough matrix (Sudha et al., 2007; Bonnand-Ducasse et al., 2010); dough incorporated with insoluble date fiber exhibited solid-like behavior (Ahmed et al., 2013); potato fiber, with a high level of insoluble dietary fiber, increased the hardness and gumminess of bread (Kaack et al., 2006).

Comparative studies were conducted by Sivam et al. (2011) to investigate the effects of added dietary fiber – apple pectins and/or phenolic antioxidants – fruit phenolic extracts, on the chemical and rheological properties of bread dough and finished bread. Rheological properties of bread doughs measured during kneading, fermentation and baking were tested using a rheometer (Table 2) and the rheological parameters were measured every 20 min under the same temperature as bread dough. Storage and loss modulus of the bread dough only with apple pectins added were higher than those of control dough. The $G'$ and $G''$ of the treated breads with a combination of pectin and fruit phenolic extract, depended on the type of phenolic extract (apple and blackcurrant extracts behaved differently from kiwifruit extract). The $G'$ and $G''$ at the final baking step were higher than those of other stages, indicating an increase in cross-linking among polymeric molecules and bread particles of high molecular weight.

Shiau et al. (2015) studied the pineapple core, the high-fiber part of the pineapple fruit, as potential dietary fiber in steamed bread. The findings showed notable correlations between the rheological properties of dough and textural parameters of steamed bread, the 5% substitution being optimum to increase dietary fiber intake without modifying the quality of steamed bread. Pineapple core fiber had a higher swelling power and water-holding capacity than wheat flour. Also, the pineapple core fiber with a small fiber size had a lower swelling power and water-holding capacity than pineapple core fiber with larger fiber size (Shiau et al., 2015).

Chia (Salvia hispanica L.) is another source of dietary fiber (polysaccharides, oligosaccharides, lignin) with a content between 18 and 60 g/100 g depending on the cultivar and growth conditions, which was used in sweet pan breads. Zettel and Hitzmann (2016) have evaluated the effects of incorporating chia to the doughs through rheological measurements, using a rotational rheometer (Table 2). Chia fiber was used as hydrocolloid due to its water holding and water absorption capacity in order to obtain specific rheological behaviors (Zettel and Hitzmann, 2016). Moreover, the gel from ground chia was used as a fat replacer in sweet pan breads. The rheological characterization of the dough revealed that the replacement of fat, resulted in softer doughs with decreasing values for storage and loss moduli with increasing chia content. The yeast activity was increased with incorporated chia gel compared to the control and the best results for the baking experiments were obtained with 25% fat replacement with ground chia gel.

Recently, Martins et al. (2017) have used fiber extracted from four types of agroindustry by-products (elderberry, orange, pomegranate and yeast) to prepare functional breads in order to fulfill the requirements for the nutrition claims “source of fiber” - 3 g dietary fiber /100 g fresh bread and “high in fiber” - 6 g dietary fiber /100 g fresh bread. There were evaluated the properties of dough (mechanical, microstructure and fermentation) and bread (volume, texture and image analysis) and correlations between fiber addition and dough/bread characteristics with the help of regression models. The impact of dietary fiber fortification on dough properties was proportional to the extract origin and amount added and also consequently affected bread parameters. The addition of 4% extract had less impact than higher extract concentrations. Multivariate regression analysis highlighted relevant information about the relationship between dough and bread data. For all the samples, regardless of extract and replacement level used, the overall viscoelastic
response (tan δ) was always below 1, indicating a solid, elastic-like behavior of the doughs. The rheological measurements concluded that fiber incorporation had no effect on gelatinization temperature, but reinforced blended dough mechanical strength (Martins et al., 2017).

Different dietary fiber fractions (i.e. total fiber, insoluble fiber and soluble fiber) obtained from prickly pear cactus (Opuntia ficus-indica var. Milpa Alta) with high dietary fiber content of 40–60 g/100 g dry weight were added to formulate the different dough. Dynamic oscillatory tests were performed on a controlled stress oscillatory rheometer (Table 2) and the results showed that all dough samples had a higher storage modulus than loss modulus indicating that dough presented an expected solid, elastic-like behavior. Before proofing, the modulus did not show significantly different among treatments; the total fiber dough showed a significantly higher value of the overall viscoelastic response (tan δ), showing that this dough is softer, less adhesive, more cohesive and with a less elastic behavior (i.e. more viscous) than the other samples, characteristics that are lost after proofing. After proofing, the dough with insoluble fiber had the most viscoelastic behavior, while the dough with soluble fiber showed the lowest values in all modulus and tan δ, indicating that this sample had the less viscoelastic (softer) behavior (Guevara-Arauza et al., 2015).

The effect of addition of inulin-rich carbohydrate powder extracted from Jerusalem artichoke tubers to wheat flour on the viscoelastic properties of dough was investigated by Rubel et al. (2015). Addition of lower concentration (i.e. 2.5 g/100 g flour) did not produce significant changes in dough rheology and bread quality parameters, meanwhile the higher addition of inulin extract produced significant changes in dough viscoelastic properties and bread physical properties. The elastic modulus was higher than viscous modulus, indicating a predominant solid behavior of the doughs. 𝐺′ showed a higher correlation with bread properties.

The effect of inulin was evaluated in the experimental work of Peressini and Sensidoni (2009), investigating the rheological properties of wheat dough and bread quality. Dough rheological properties were investigated using dynamic rheological measurements using a controlled stress rheometer (Table 2). Inulin with high degree of polymerization determined large changes in linear viscoelastic properties of dough. The storage modulus increased and tan δ decreased with increasing levels of inulin which impacted to the overall dough elasticity and strength. A higher 𝐺′ and a lower tan δ was correlated to a more elastic and solid-like material. The increase in solid-like behavior with dietary fiber content prevented expansion of wheat dough during the fermentation stage.

The effects of dietary fiber such as: carboxymethylcellulose, locust bean gum, fructo-oligosaccharide and gluco-oligosaccharide on bread in terms of technological, functional and nutritional properties were studied by Angioloni and Collar (2011). Few technological functional and most nutritional bread properties were found to depend on dietary fiber molecular characteristics as mean particle diameter, 𝐺′, 𝐺″, complex viscosity. Fibers with high viscoelasticity 𝐺′, 𝐺″ and complex viscosity in concentrated solutions determined breads with better sensory perception, lower digestible starch and higher resistant starch contents.

Often, dietary fibers are incorporated into bakery products to prolong freshness due to their capacity to retain water (Fendri et al., 2016). Different types of fiber have been used in bread making and they alter volume, firmness and springiness of bread loaf, and the softness of the bread crumb. Addition of some soluble fiber at a low level strengthened the structure of dough and improved the quality of bread, but excess amounts of insoluble fiber had an adverse effect on the formation of gluten network, reducing the quality of bread due to gluten dilution effect or gluten-fiber interaction (Fendri et al., 2016). However, the study of Fendri et al. (2016) concluded that the addition of extracted pea and broad bean pods fibers improved considerably the texture profile of bread, with a clear decrease in hardness and a slight perfection in adhesion and cohesion, therefore fibers from pea pods and broad bean pods could be recommended as improver in the bread making industry.

The fiber greatly interferes with protein association and behavior during heating and cooling of the dough using the Mixolab device (Rosell et al., 2010). The incorporation of sugar beet fiber into the dough matrix induced the disruption of the viscoelastic system. Therefore, weaker doughs were obtained, due to fiber-starch
competition for water, affecting pasting and gelling. Conversely, inulin seemed to integrate into the dough increasing its stability.

**Gluten-free dough with added dietary fiber**

The enrichment of gluten-free baked products with dietary fiber is proven to be necessary; since it has been reported that coeliac patients have generally a low intake of fiber due to their gluten-free diet.

Sulieman et al. (2018) evaluated rheological and thermal properties of a sweet potato (80.5-89.5%) and glutinous rice flour (10%) gluten-free dough bread fortified with *Agaricus bisporus* polysaccharide flour (3-9%) and inulin (3-9%) as natural and novel substitutes, to enhance the nutritional, sensorial and health attributes. Compared to control dough, incorporation of *Agaricus bisporus* flour in the dough exhibited a significant decrease in both rheological moduli (\(G'\) and \(G''\)) and an increase in rheological tangent (\(\tan \delta\)); while, the addition of inulin instead of *Agaricus bisporus* flour in the same dough revealed a reversible effect (i.e. increased \(G'\) and \(G''\)) and increase in the values of \(\tan \delta\). In case of *Agaricus bisporus* flour addition, the reduction in moduli especially \(G''\) could be attributed to higher protein and fiber contents and a decrease in the starch level. The difference could be also based on the different water absorption capacity: the addition of *Agaricus bisporus* flour required an increased level of water absorption (proteins and \(\beta\)-glucan of polysaccharide flour compete with starch in water availability), that is not the case of inulin with a lower water absorption capacity. In addition, the decrease of \(G'\) and \(G''\) with increasing water level in gluten-free dough could be attributed to the dilution of components and additives of the dough. The interaction among multiple components, which includes protein, dietary fibers, and xanthan gum during the mixing of dough led to a higher water intake and weakened the dough structure, resulting a decreased dough viscosity (Sulieman et al., 2018).

Pérez-Quirce et al. (2017) investigated the effect of three different concentrated \(\beta\)-glucan samples with different molecular weight and originating from oat and barley of similar controlled purity, on dough rheology and physical and nutritional quality of gluten-free rice breads. The rheological measurements included oscillatory and creep-recovery tests with rheometer (Table 2). Creep tests were performed by imposing a step of shear stress of 50 Pa, exceeding the linear viscoelastic region, for 60 s, and for the recovery phase, the stress was removed and the sample was allowed for 180 s to recover the elastic part of the deformation. Creep data were described in terms of creep compliance, \(J\), which was defined as the strain divided by the stress applied. The data from creep and recovery tests were modelled with Burger’s models. A set of calculated parameters were used for analyses and interpretation, as: \(J_0\): instantaneous compliance, \(J\): retarded elastic or viscoelastic compliance, \(\lambda\): retardation time, \(\eta\): steady viscosity (estimated from the creep step), \(\eta_0\): the maximum creep compliance obtained at the end of the creep step, \(J_{\text{steady}}\): the steady-state compliance in the recovery step (calculated by subtracting the compliance value at the terminal region of curve, where dough recovery reached equilibrium, from the \(J_{\text{max}}\) (Pérez-Quirce et al., 2017). For the dough formulations, \(G'\) was higher than \(G''\), and the values for \(\tan \delta\) were lower than 1. Both moduli slightly increased with frequency, and the dependence became less pronounced with \(\beta\)-glucan addition level. The viscoelastic behavior of all doughs corresponded to solid-like materials, as it is characteristic for gluten-free doughs. Both viscoelastic moduli \((G'\) and \(G''\)) increased with \(\beta\)-glucan addition to the doughs, the changes being dependent on the molecular weight of \(\beta\)-glucan. The increase of moduli was larger for high molecular weight concentrates than medium and low molecular weight concentrates compared to the control dough. The behavior was probably due to the large increase of water absorption capacity of the dough when larger quantity of various types of \(\beta\)-glucan are included in the bread formulation.

The study of Pérez-Quirce et al. (2017) demonstrated the feasibility for production of \(\beta\)-glucan-enriched gluten-free breads with acceptable quality attributes that could fulfill the EFSA claim (cholesterol lowering effect for daily consumption of 3 g \(\beta\)-glucan in ~200 g of fortified bread).

Sabanis et al. (2009) evaluated the influence of wheat, maize, oat and barley dietary fibers (added at 3, 6 and 9 g/100 g level) to corn starch and rice flour-based bread. Doughs were evaluated based on consistency, viscosity and thermal properties. Rheological behavior of the gluten-free dough was
determined using the Power low model. The flow behavior index of doughs was influenced by the type of fiber and not by the level of addition, the dough presenting a shear thinning (pseudoplastic) behavior. The highest flow behavior index was showed by the barley fiber, followed by maize and oat fibers.

Martínez et al. (2014) investigated the microstructural features of insoluble (oat, bamboo, potato and pea) and soluble (Nutriose® and polydextrose) fibers and their effect on gluten-free dough rheology and bread-making. The addition of soluble fiber, lowered the dough consistency and elasticity compared to that of the control dough. On the other side, doughs with insoluble fibers presented increased consistency, in case of potato fiber and, decreased consistency, for pea fiber. The effect was less noticed with the coarse bamboo fibers, coarse oat fibers and finally the fine oat and bamboo fibers. The overall viscoelastic response of the doughs with potato, pea and coarse bamboo fibers was lower than that of the control dough, indicating a higher elasticity. The study concluded that the enrichment of gluten-free breads with soluble fibers improved not only nutritional quality but also the physicochemical characteristics; these changes occur due to a modification of internal dough structure, the fiber solubilization and the generation of a homogeneous mixture with water and the type of hydrocolloid used. In the case of breads enriched with insoluble fibers, such as bamboo or oat, longer fibers with a smaller particle size are the most suitable, as rounded or voluminous fibers such as pea or potato will produce breads with a lower volume and greater hardness than fiber-free breads (Martínez et al., 2014).

Korus et al. (2015) have studied the influence of debittered acorn flour as a source of fiber on rheological properties of the dough and quality and staling of gluten-free bread. The analysis of rheological properties of gluten-free dough based on corn and potato starch, supplemented with acorn flour, exhibited significant increase in the moduli $G'$ and $G''$ and a decrease in phase shift tangent (tan $\delta$), which denotes firming (strengthening) of dough structure. As consequence of a diminished starch retrogradation, the bread samples presented a slower staling and improved sensory acceptance. Supplementation of bread with acorn flour at the level of 20 % had positive impact on bread volume and physical properties of the crumb. Factors that influence rheological characteristics of the dough with acorn flour are the high level of fibers (which are characterized by high water absorption) and other non-starch structure forming components.

**Importance of dough formulation in the analysis with rheometer**

To obtain adequate dough characteristics through the rheological analysis with the rheometer, careful dough preparation should be taken into account. Usually, the rheological measurements are done using a standard dough preparation, without addition of baker’s yeast in order to avoid the influence of fermentation (or dough leavening) on the results (Sulieman et al., 2018; Kurek et al., 2017; Pérez-Quirce et al., 2017; Rubel et al., 2015; Korus et al., 2015; Martínez et al., 2014; Hüttner et al., 2010). Thus, the aim is to have a better control of the dough, because the formation of bubbles (avoiding CO$_2$ evolution) during the measurement is an undesirable process. In case that the yeast is used, cold water (4 °C) is employed to stop yeast activity and the dough is covered with a plastic film to avoid dehydration and let to rest for 15 min at 4 °C (Guevara-Arauza et al., 2015).

To prevent dough dehydration during the measurements, different treatments are applied on the external surface of sample: mineral oil (Guevara-Arauza et al., 2015; Peressini and Sensidoni, 2009), paraffin oil (Zettel and Hitzmann, 2016; Korus et al., 2015; Bonnand-Ducasse et al., 2010), vaseline oil (Martínez et al., 2014), silicon oil (Rubel et al., 2015).

The dough samples are prepared just before the rheological experiments. Before measurements, dough sample is placed in the rheometer measuring system and after adjusting to the chosen gap, the excess dough is removed with a spatula. Then, the dough is allowed to rest a sufficient time (between 5 and 30 min) between plates to attain thermal equilibrium and dough relaxation (Liu et al., 2019; Sulieman et al., 2018; Guevara-Arauza et al., 2015; Korus et al., 2015).

As it can be seen, in Table 2, different surfaces for the plate measuring geometry of the rheometer were used in order to obtain the optimum results; the parallel concentric disks geometry seems to be the most versatile among the geometries used in dough rheology, being easier to vary the gap. The selected technique depends on the specific conditions of the study.
product and their functional characteristics. The corrugate plates are used to avoid slippage for wholegrain dough, meanwhile the inertia effects are decreased by teflon coat.

**Conclusions**

The actual trend in the bakery industry, to enrich the baked products with valuable dietary fibers, needs research studies for the already consecrated raw materials as well as for new and sustainable solutions.

Due to their capacity to retain water, the dietary fibers are often used to prolong freshness of baked products, but the main challenge of addition of fiber in cereal based products is the negative effect on the final product quality.

The viscoelastic properties are important information on the suitability of the flour mixture in the baking process as a raw material for bakery products, and also could provide measure to be taken in order to decrease the effect of the added ingredients on rheological behavior of the dough.

The dough rheology, technological and also the physicochemical and textural bread properties are different for fiber enriched bread, wholegrain bread or refined bread.

Dough quality is directly influenced by the gluten network structure and the effect of dietary fiber on dough gluten network structure is both improved and deteriorated due to the different type, structure, size, and amount of dietary fiber used.

Results from the dough rheology analysis by rheometer, give useful information about dough behavior in the different processing steps.

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**References**


