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Linear and Non-Linear Rheological Properties of Gluten-Free Dough Systems Probed by Fundamental Methods

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Abstract

Gluten forms a continuous protein network that helps to retain gas produced by yeast fermentation and oven rise. Therefore, gluten-free baked products have poor quality in terms of volume, texture, and shelf life. As a result, manufacturing high-quality gluten-free baked products has become one of the most difficult challenges for manufacturers, cereal technologists, and scientists. Rheological testing of dough has been widely used to predict baked product quality and to adjust processing parameters in the manufacturing of gluten-free baked products. Linear viscoelastic properties are mostly determined by Small Amplitude Oscillatory Shear (SAOS) tests, which provide information without disturbing the 3-D structure of dough significantly, while characterization of the viscoelastic behavior of dough in the non-linear region using fundamental methods such as large amplitude oscillatory shear (LAOS), creep-recovery, and lubricated squeezing flow tests provide a more detailed understanding of dough's viscoelastic response under large deformations. As dough processing involves small and large deformations, characterization of the linear and non-linear rheological properties of gluten-free dough systems might provide a deeper insight into baked product quality. Therefore, the aim of this review was to bring a detailed summary of the viscoelastic properties of gluten-free dough systems probed by fundamental rheological testing methods both in the linear and non-linear regions and their correlations with baked product quality, while providing an overview of the impact of ingredients on viscoelastic properties.

Keywords Gluten-free dough · Rheology · Linear viscoelastic properties · Non-linear rheology

Nomenclature

e	Elastic Chebyshev coefficient
v	Viscous Chebyshev coefficients
G'	Elastic modulus/Storage modulus (Pa)
G''	Viscous modulus/Loss modulus (Pa)
G^*	Complex modulus (Pa)
G_i	Individual relaxation modulus (Pa)
G_e	Pure elastic component (Pa)
G'_M	Minimum strain modulus (Pa)
G'_L	Large strain modulus (Pa)
G'_{rel}	Relaxation modulus (Pa)
$H_{(t)}$	The Heaviside or step function (*is 0 if* $t < 0$; *is 1 if* $t > 0$)
J_e	Steady state compliance (Pa^{-1})
J_R	Recovery compliance (Pa^{-1})
J_v	Viscous compliance (Pa^{-1})
J_e	Elastic compliance (Pa^{-1})
J_0	Instantaneous elastic compliance (Pa^{-1})
J_1	Retarded elastic compliance/viscoelastic compliance (Pa^{-1})
J_{max}	Maximum creep compliance (Pa^{-1})
$J(t)$	Material compliance (%/Pa)
R^2	Coefficient of determination
S	Strain stiffening ratio
T	Shear thickening ratio
t	Time (s)
t_m	Time at which the stress is removed to initiate the recovery test (s)
$\tan\delta$	Phase lag angle/ Loss tangent, [G''/G']
ω	Applied frequency (rad s^{-1})
ω_{rel}	Predicted relaxation frequency (rad s^{-1})

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γ	Shear strain
$\dot{\gamma}$	Shear rate (s^{-1})
γ_0	Amplitude of strain function [$\gamma = \gamma_0 \sin(\omega t)$]
δ	Phase shift/phase angle (rad)
σ	Shear stress (Pa)
σ_0	Amplitude of strain function [$\sigma = \sigma0 \sin(\omega t- \delta)$]
η^*	Complex viscosity (Pa s)
η'_M	Minimum strain rate viscosity (Pa s)
η'_L	Large strain rate viscosity (Pa s)
η_0	Zero shear viscosity (Pa s)
α	Degree of elasticity ($0 < \alpha < 1$)
λ_1	Elastic modulus (Pa)
λ_2	Elastic modulus during creep recovery (Pa)
λ_{rel}	Relaxation time (s)
λ_{ret} (λ)	Retardation time (s)
λ_i	Individual relaxation time (s)

Introduction

Celiac disease, which is known as a severe autoimmune disorder, is a life-long intolerance to gluten that occurs in genetically susceptible people. The only available treatment to help patients recover from their symptoms is strict long-term adherence to a gluten-free diet. Gluten-free diets are not only followed by celiac patients, but also by people who have a gluten allergy or sensitivity, as well as those who believe that a gluten-free diet is healthier [1–3]. Gluten provides a continuous protein network that aids in the retention of gas created by yeast fermentation and oven rise. Hence, gluten-free baked products are of poor quality in terms of volume, texture, and shelf life [4]. Furthermore, they are deficient in vitamins, minerals, and fiber, resulting in a nutritionally imbalanced diet for celiac patients [5, 6]. As a result, one of the most challenging issues for manufacturers, cereal technologists, and scientists is producing high-quality gluten-free foods. Various studies on the rheological characteristics of dough/batter as well as quality parameters of gluten-free baked products have been conducted to date to address the increased demand for high quality products from celiac sufferers [2].

Rheology is the science that measures the deformation and flow of materials. And rheological properties are defined by the relationship between stress and strain or strain rate. Stress is defined as the force acting on a unit area, while strain is a measure of deformation [7]. Deformation (strain), which occurs as a result of a force or stress, is a change in the material's arrangement (response) [8], and it assesses a material's resistance to flow [9]. Even though there are no true elastic solids or liquids in nature, there are complex materials having solid-like and liquid-like behaviors [8], such as most of the food products that are called viscoelastic [7]. If viscoelastic properties are strain and strain rate independent, such materials are called linear viscoelastic materials. However, if the viscoelastic properties of a material are strain- and strain rate-dependent, these materials are referred to as non-linear viscoelastic materials [7]. Most food products, including dough systems, display linear viscoelasticity only when the applied shear strain is low [10]. Linear viscoelastic properties are mostly determined by the Small Amplitude Oscillatory Shear (SAOS) tests, and these tests analyze the material's response by observing the strain and frequency dependence of the elastic modulus and viscous modulus at small strains without disturbing the three-dimensional structure of materials [11].

However, wheat flour dough and gluten-free dough systems have been shown to display non-linear viscoelastic behavior above the strain amplitudes that may range from 0.06% to 1.6% [4, 12–15]. Besides, dough is exposed to large deformations during processing. The strain amplitudes experienced by the dough during breadmaking can range from 100% during sheeting to 1,000% during fermentation and oven rise and up to 500,000% during mixing [16]. Therefore, characterization of the non-linear rheological properties of dough systems may offer a more detailed understanding of their rheological responses under real processing conditions [11].

Studies evaluating dough rheology under large deformations in the non-linear region mostly focused on empirical methods like a Farinograph, Mixograph, or Extensograph, etc. [2]. However, these empirical dough testing methods are designed for wheat flour dough testing [17]. When compared to wheat flour dough, gluten-free dough formulations tend to have higher water levels. As a result, gluten-free dough resembles batter rather than dough, and it can not be shaped in the same way that wheat flour dough can. As a result, mechanical mixing is used, most commonly in a kitchen mixer or a mixer with a batter attachment. Typically, wheat bread production steps involve mixing, bulk fermenting, dividing, proofing, and baking. On the other hand, gluten-free bread is just made by mixing, proofing, and baking. Moreover, gluten-free dough formulations require 40–60% less time for proofing and baking [18, 19]. Due to poor handling properties of gluten-free doughs, quality evaluation on loaf volume or crumb texture of the resulting bread is mostly used to characterize the water absorption capacity of doughs and to define the mixing time, instead of using Farinograph measurements. Furthermore, the CO_2 release rate is known to be higher in gluten-free dough (22 µmol/min) compared to that of wheat dough (5 µmol/min) at 23 °C. For these reasons, to improve gluten-free baked product quality, establishing a link between gluten-free dough functioning and the qualitative parameters of the resultant product is crucial, and yet remains challenging [2].

Empirical dough testing methods were created to evaluate the quality of wheat flour and modifications must be made in order to use them to examine gluten-free doughs. On the other hand, fundamental rheological experiments carried out in both the linear and non-linear areas can offer a complete characterization of the rheological characteristics of gluten-free dough systems by filling the gap. In the literature, the characterization of linear viscoelastic properties of gluten-free dough systems has received much attention. However, there isn't much research evaluating the fundamentals of rheology on gluten-free dough systems in the non-linear region, and recently, limited studies are available on the effects of gluten-free flours or starches, non-gluten proteins, hydrocolloids, and fibers on the non-linear rheological characteristics of gluten-free doughs. Consequently, the aim of this study is to provide a comprehensive overview of the linear and non-linear rheological properties of gluten-free dough systems defined by the fundamental methods by revealing gaps in the literature and their relationship with baked product quality.

Linear Rheological Properties of Gluten-free Dough Systems

Since the linear viscoelastic region is the small range of applied stress where a material's response is independent of the stress applied, it is also critical to determine the rheological behavior of dough within the linear viscoelastic region. The fundamental rheological methods that are used to determine linear rheological methods can be classified as SAOS tests, including stress/strain sweeps, frequency sweeps, and temperature sweeps, and linear creep recovery tests. These tests enable the characterization of various materials without causing structural damage.

Linear Rheological Properties of Gluten-free Dough Systems: Impact of Flour/Starch Type

Most gluten-free products have traditionally been made by substituting alternative flours for wheat flour and adding ingredients to mimic the viscoelastic characteristics of gluten (Table 1). Utilizing starches, hydrocolloids, emulsifiers, enzymes, protein, and/or fiber sources have been used to manufacture gluten-free products to obtain comparable quality to their gluten-free counterparts.

Frequency sweep experiments under linear viscoelastic region have revealed that the elastic modulus is higher than the viscous modulus for gluten-free dough/batter formulations through all the frequency range, and both moduli slightly increase with increasing frequency levels. This behavior shows elastic-like structure; thus, tan δ values, which is calculated as G''/G' is lower than 1 for dough [18, 20, 21]. The viscoelastic measurements of gluten-free dough prepared with the different flours, starches, or their combinations where elastic moduli dominate viscous moduli ($G' > G''$) shows a weak gel-like or solid-like structure.

The elastic and viscous moduli are a function of the applied frequency, particularly in the 1–10 Hz frequency range, and typically follow a linear evolution. The shear stress output produced by a sinusoidal strain input may be written as [9];

$$\sigma = G'\gamma + (G''/\omega)\dot{\gamma} \tag{1}$$

The elastic and viscous moduli can be expressed in terms of the amplitude ratio $\left(\frac{\sigma_0}{\gamma_0}\right)$ and the phase shift

$$G' = \left(\frac{\sigma_0}{\gamma_0}\right)\cos(\delta) \tag{2}$$

$$G'' = \left(\frac{\sigma_0}{\gamma_0}\right)\sin(\delta) \tag{3}$$

The phase lag angle between stress and strain is measured using a sinusoidally oscillating deformation of known magnitude and frequency. In other words, it can be described as energy loss per cycle divided by the energy stored per cycle, and it shows the loss of molecular interaction in a material. Since $0 \le \delta \le \pi/2$, tan δ can vary from zero to infinity and hence highly structured materials generally have low tan δ [9].

The data can also be described by a power-law relationship (Eqs. (4)–(6)),

$$G'(\omega) = G'_{\omega 1}.\omega^{a} \tag{4}$$

$$G''(\omega) = G''_{\omega 1}.\omega^{b} \tag{5}$$

$$\tan\delta(\omega) = \frac{G''(\omega)}{G'(\omega)} = \left(\frac{G''}{G'}\right)_{\omega 1}.\,\omega^{c} = (\tan\delta)_{\omega 1}.\,\omega^{c} \tag{6}$$

are defined at a frequency of 1 Hz. The exponents a, b, and c represent the degree of dependency of these moduli and the loss tangent to the oscillation frequency [22].

The linear rheological properties of dough prepared from gluten free flours (rice, sorghum, moong, water chestnut, and unripe banana) were compared with those of wheat dough [23]. The highest elastic and loss modulus values were obtained for moong flour, followed by wheat, water chestnut, unripe banana, sorghum, and rice flour. Demirkesen et al. [18] stated that rice dough, unlike wheat dough, lacks a protein network, which limits the production of a strong viscoelastic structure. Therefore, ingredients that imitate a gluten network are necessary to produce high-quality gluten-free products. The protein contents of moong, wheat, water chestnut, unripe banana, sorghum, and rice flour were found to be approximately 24, 11, 9, 10, and 8%, respectively [24].

Table 1 An overview of research articles showing the impact of flour/starch type on rheological properties of the gluten-free dough/batter

Flour Type/Product Type	Rheological method	The findings	Reference
Chestnut flour, rice flour/Bread	SAOS test	The desired bread quality with dough prepared in a 30/70 chestnut/rice flour ratio with intermediate elastic (G') and loss (G'') moduli Higher bread quality with dough prepared with 30/70 chestnut/rice flour and xanthan–guar blend-emulsifier diacetyl tartaric esters of monoglycerides (DATEM) blend Lower volume, a harder texture, and a darker color with elevated levels of chestnut flour regardless of gum blend and emulsifier addition	Demirkesen et al. [20]
Chestnut flour, rice flour/Cookie	SAOS test	Higher complex modulus values with the replacement of rice flour with chestnut flour The softest texture with the 40% replacement of rice flour with chestnut flour Increases in hardness values and decreases in the spread ratio of cookies with elevated levels of chestnut flour	Demirkesen [36]
Rice flour, carob flour/Bread	SAOS test	Strengthening of dough structure with fiber addition Increases in elastic character with increasing amounts of carob flour	Tsatsaragkou et al. [33]
Acorn flour, potato starch, corn starch/Bread	SAOS test	A significant increase in the moduli G' and G'' and a decrease in phase shift tangent with the use of acorn flour Improved bread volume and crumb characteristics with the use of certain amounts of acorn flour	Korus et al. [35]
Buckwheat flour, rice flour, potato starch, acorn flour/Bread	SAOS test	Increase in degree of structure in the dough with the addition of acorn flour (23%) Lower G' values in the dough containing 35% acorn flour	Beltrão Martins et al. [34]
Chickpea flour, rice flour/Bread	SAOS test	Higher viscous and elastic moduli and hence a better dough structure with the incorporation of chickpea flour into rice-based doughs	Kahraman et al. [93]
Taro flour/Bread	SAOS test	Increase in the elastic and loss moduli values and strengthening the dough structure with the addition of taro flour to gluten-free doughs Increase in dietary fiber content with the taro flour addition	Arıcı et al. [94]
Fermented cassava, sweet potato and sorghum mixed flours/Bread	SAOS test	Increase in the solid character of the dough (G') with the decreasing amount of cassava flour An optimum crumb property of the fresh and stored breads with 75% fermented cassava, 20% sweet potato flour, and 5% sorghum	Monthe et al. [95]
Rice flour, sorghum flour, moong flour, water chestnut flour, unripe banana flour/ Bread	SAOS test	The differences in moduli values of different gluten-free doughs (rice, sorghum, moong, water chestnut, and unripe banana) and wheat dough by the different composition, protein network, particle size, and particle size distribution	Patil et al. [23]

Table 1 (continued)

Flour Type/Product Type	Rheological method	The findings	Reference
Rice flour, husked buckwheat flour and unhusked buckwheat flour/Bread	SAOS test	Significant decrease in G' and yield stress value with the increasing amount of unhusked buckwheat flour from 10 to 20% No significant rheological impact with the addition of 30% of unhusked buckwheat flour An initial increase in G' with the husked buckwheat flour addition	Torbica et al. [21]
Buckwheat flour, rice flour/ Cookie	SAOS test and Linear Creep Recovery Test	A decrease in storage modulus and an increase in tan δ with an increase in the buckwheat flour addition Increase in dough tenacity and resistance to deformation with the addition of carboxymethyl cellulose Similar strength and extensibility properties to wheat cookie dough with the use of carboxymethyl cellulose and 20 and 30% of buckwheat flour in gluten-free dough	Hadnađev et al. [61]
Whole grain maize flours/Cookie	SAOS test	Increase in the particle size and the water absorption values with the presence of whole-grain flour Decrease in the viscoelastic moduli of the doughs and a higher spread ratio, lower hardness, and lower shelf life of breads with the presence of whole-grain flour	Paesani et al. [96]
Amaranth-oat composite flour/Cookie	SAOS test	Improved viscosity and water-holding capacities of dough with amaranth and its composites Acceptable color, flavor, and texture of the cookies with the use of amaranth-oat composites Enhanced the nutritional value of the cookies with the use of amaranth-oat composites	Inglett et al. [97]
Rice flour, maize flour and potato starch, maize starch, wheat starch/Bread	SAOS test and Linear Creep Recovery Test	Higher specific volume and lower hardness with starch-based breads, especially those made with wheat starch Reinforced continuous phase of the crumb with lower pasting temperature Not a continuous starch-hydrocolloid matrix with the large potato starch granules The lowest specific volume, elasticity, cohesiveness, and resilience, and the highest hardness with the large potato starch granules	Martínez and Gómez [29]
Maize satrch, potato starch, hydroxypropylated distarch phosphate and acetylated di-starch adipate and high amylose corn starch/Bread	SAOS test and Linear Creep Recovery Test	Poor gel behavior of the dough with the use of modified starch The high relationship between the frequency and the storage modulus values The significant change in the viscoelastic characteristics of dough with the use of hydroxypropylated distarch phosphate	Witczak et al. [98]

Table 1 (continued)

Flour Type/Product Type	Rheological method	The findings	Reference
Corn starch, potato starch, waxy corn starch, waxy potato starch/Bread	SAOS test and Linear Creep Recovery Test	An increase in values of storage (G') and loss moduli (G'') and zero shear viscosity with the increased swelling capacity of waxy starch The best bread volume with 10% waxy starch replacement level A good texture and the staling characteristics of bread with the 10–15% waxy starch replacement	Witczak et al. [31]
Corn starch, potato starch, potato flakes/Bread	SAOS test and Linear Creep Recovery Test	Increase in storage and loss moduli and zero shear viscosity with the presence of potato flakes. The strengthening in structure and improvement in water absorption and swelling of solids with the presence of potato flakes The reduction in the staling properties of bread with the presence of potato flakes	Witczak et al. [45]
Rice flour, damage starch/Bread	SAOS test	Increase in viscoelastic modulus and hydration properties of rice batter and decrease in pasting viscosity with the increase in the damaged starch content Better gas retention capability and hence higher specific volume of bread with the use of rice flour with a starch level of 4% and 6%	Qin et al. [32]
Corn starch, wheat starch, potato starch, cassava starch, rice flour, buckwheat flour/Bread	SAOS test	A non-linear relationship between viscosity and ohmic-heated bread characteristics The significantly affected rheological behavior of the gluten-free batter from the starch:water ratio and the starch or flour source and structure	Waziiroh et al. [30]
Rice flour, modified starches (di-starch phosphate and acetylated di-starch adipate starches)/Bread	SAOS test	No effect on G' and G'' moduli with the addition of Di-starch phosphate and acetylated di-starch adipate compared to control Rise in G' and G'' and decrease in tan δ value with pregelatinized acetylated di- starch phosphate Increased water binding capacity, a higher cold-pasting viscosity, and hence a more elastic dough, particularly with a 20% pregelatinized acetylated di- starch phosphate addition	Roman et al. [99]
Quinoa flour, rice flour, potato starch/Cake	SAOS test	Increase in both the elastic and viscous moduli of the batters with quinoa flour substitution. Higher quality of cakes with the substitution of quinoa flour, especially with 50% addition	Bozdogan et al. [25]
Maize starch, tef flour/Bread	SAOS test	Higher viscoelastic moduli and steady-state viscosities and lower tan δ values with the addition of tef Higher quality of a commercial gluten-free bread with the use of tef flour, at a certain level of addition (from 50 to 100% depending on the tef variety)	Villanueva et al. [37]

Thus, the differences in moduli values of dough made from different flour samples could be related to their different protein content.

All the gluten-free doughs and wheat dough had shear dependent behavior, since the increase in frequency led to an increase in viscoelastic moduli values. On the other hand, gentle slopes in the behavior of viscoelastic moduli were obtained for gluten-free dough, which was less sensitive towards frequency change. In contrast to discrepancies at higher frequency levels, the differences in the values of storage modulus between the samples were quite small at low frequency levels. This showed that wheat, rice, sorghum, water chestnut, and unripe banana flour had increased amounts of stored energy as a result of external stresses with the increase in angular frequency. Moong flour, on the other hand, did not retain this energy due to external influences in the higher frequency region. Such a difference in the behavior of the doughs might be related to their different composition. Moong flour might be susceptible to being disrupted at higher shear rates due to the weak contact between the particles [23]. The tan δ for wheat and gluten-free flours, except rice flour, increased monotonically to varying degrees in the whole frequency range. Unlike wheat and other gluten free flours, the tan δ curve in the case of rice dough decreased owing to the presence of effective interfacial bonding. This limited viscoelastic energy dissipation caused the curve to flatten. The flattened region of the curve might be related to the relaxation of the flour particles [23].

Bozdogan et al. [25] studied the effects of substituting rice flour and potato starch with quinoa flour on the rheological properties of batters and their physicochemical, functional, and cake-making properties. The temperature sweep test result showed that G', G'' and G^* were notably affected by the increasing levels of quinoa flour.

Complex modulus may also be used to describe the data obtained from dynamic measurements. It can be expressed as;

$$G^* = \frac{\sigma_0}{\gamma_0} = \sqrt{(G')^2 + (G'')^2} \tag{7}$$

For the entire temperature range (30–120 °C), the contribution of G′ to G* was found to be higher than that of G″. Three stages of change in G', G'', and G^* were detected during measurements. The initial reduction in the firmness of the batters between 30 °C and 60 °C might be related to thermal activation of the molecules, energy absorption by starch molecules, protein expansion, and viscosity reduction. G', G'', and G^* began to rise as a result of protein denaturation and starch swelling, which accelerated structure development beyond the threshold temperature at which G', G'', and G^* minimum occur. Ahmed et al. [26] stated that the higher G' of thermally treated water chestnut samples can be explained by their high inherent amylose content, which may increase the stiffness of the starch granule structure and the amount of amylose leached out throughout heating process.

The higher protein content of quinoa flour compared to rice flour and potato starch may account for the increased flexibility of the batters with quinoa flour substitution. The elevated levels of quinoa flour led to increases in the viscoelasticity of the batters. After reaching a maximum at a given temperature, G', G'', and G^* began to decrease as structural alterations were completed. Quinoa flour significantly increased the maximum G', G'', and G^* values, as well as the associated temperatures. Because the greater protein content of quinoa flour inhibited water mobility, the gelatinization process was slowed in the quinoa flour-added batters. Proteins made starch granules more resistant to breakdown, which was reflected in the decreases in G', G'', and G^* as the amount of quinoa flour increased. As a result, the denatured proteins stabilized the continuous matrix between the dispersed and continuous phases; the inclusion of quinoa flour increased the mechanical strength of the continuous matrix substantially. The physical, chemical, and quality parameters of the cakes were significantly enhanced by quinoa flour substitution as well. The cake made with 50% quinoa flour provided the highest scores in terms of sensory test, and overall acceptability [25].

In addition to the different compositions of dough, the variances in the rheological behavior of dough may be caused by the size of the flour particles, their distribution, and the densities of the flours [23]. Furthermore, water absorption, temperature, and shear rate are also effective on the rheological behavior of dough. Moreira et al. [27] evaluated the rheological characterization of doughs made from different types of maize (white, yellow, and purple maize) and milled with two different sieves (200 and 500 µm). In order to better evaluate the viscoelastic properties of dough, experimental data for G' and G'' vs. ω were fitted by equations;

$$\log G' = \log \mathrm{a}' + \mathrm{b}' \log \omega \tag{8}$$

$$\log G'' = \log \mathrm{a}'' + \mathrm{b}'' \log \omega \tag{9}$$

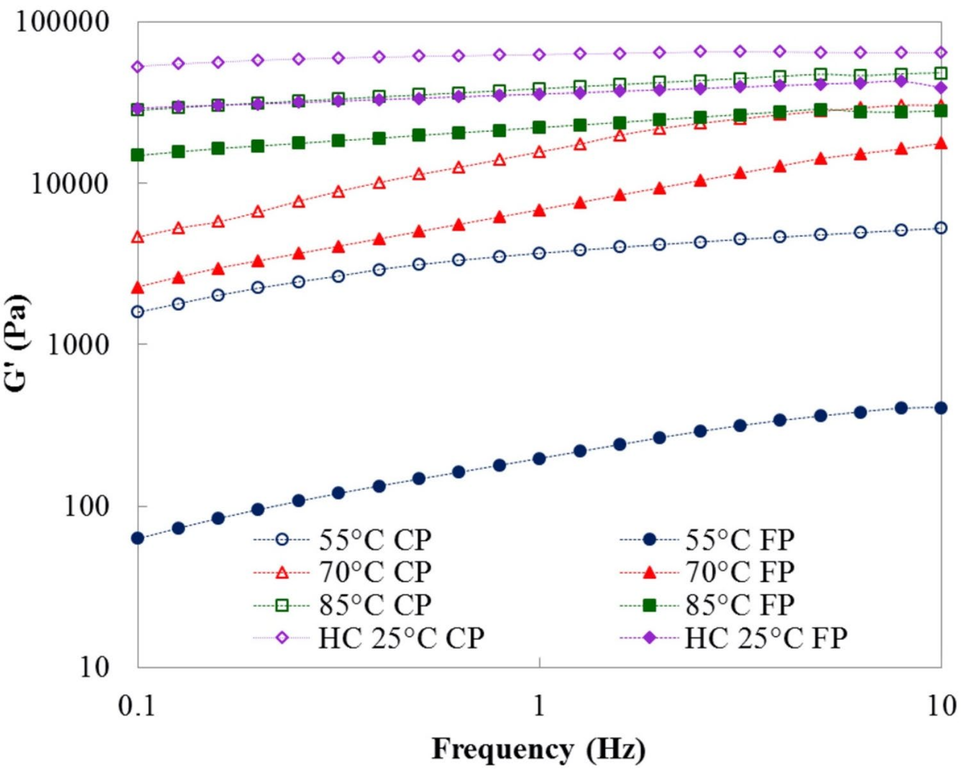
where a′, a″, b′ and b″ are the fitting parameters.

Milling is important for dough rheological properties because a lower average particle size increases the amount of damaged starch. White maize flour milled at 500 µm had the highest a′ and a″ values. This increase might be linked to varied interactions between starch granules with different particle sizes and the integrity of flour particles, which results in firmer doughs [26, 27]. However, doughs made from flours with a smaller average particle size (milled through a 200 µm sieve) had different viscoelastic properties based on their varieties. Among dough made from flours milled with a 200 µm sieve, yellow maize flour had the highest a′ and a″ values, which might be due to the dough's increased water absorption requirements. Water absorption decreased with increasing average flour particle size, resulting in higher viscoelastic moduli values, while water absorption increased linearly with increasing damaged starch. In another study, Ahmed et al. [26] conducted a study to determine the influence of particle size on the compositional, functional, pasting, and rheological characteristics of commercial water chestnut flour. Frequency sweep studies were conducted inside a linear viscoelastic zone under constant strain at specified temperatures based on thermal transitions (e.g., glass transition, pasting properties). Rheological measurements revealed that, regardless of temperature, coarser particles (88 µm) produced stronger mechanical strength than smaller particles (74 µm), resulting in higher G′ (Fig. 1). However, when compared to the findings of Moreira et al. [27], coarser particles absorbed more water, resulting in a greater water holding capacity (2.4–3.5) than smaller particles (1.9–3.3). Furthermore, larger particles had higher sediment volume fraction (ϕ) (31.1–34.4) values than the sediment volume fraction of finer particle fragments (ϕ) (27.4–33.0). The different findings about the water-holding capacity of particles may be explained by the different dough composition as well as their different sizes. According to Scanlon et al. [28], larger particle sizes (91–136 µm) contain greater protein content than smaller particles (less than 91 µm). As a result, the authors hypothesized that the composition of flour (protein, starch, etc.) may play different roles in the rheological behavior of the dough.

Martínez and Gómez [29] investigated mechanistic relations between the evolution of the starch/flour structure, dough rheology, and bread quality using the most common flours (rice flour, maize flour) and starches (potato starch, maize starch, wheat starch) in gluten-free bread-making. In dynamic linear viscoelastic measurements, critical amplitudes of the shear stress and strain for the onset of the nonlinear response were estimated from the normalized plot of *G′* and *G″*, taking as reference the average of their initial values at the lower torques reached by the rheometer. Doughs made with flour showed a much higher shear stress than doughs prepared with starches. Shear strain, on the other hand, showed no apparent changes, highlighting mainly the greater critical amplitude of the shear strain for wheat starch dough. The more uniform structure of wheat starch created higher resistance to strain during the strain sweep. The authors suggested that high stability to shear stress of flour-based doughs can be related to the intrinsic size of the flour particle and hence its resistance to disruption compared to starch granules.

Different viscoelastic behaviors were observed for gluten-free flour- and starch-based dough samples. A crossover between *G′* and *G″* was observed at low frequencies for the doughs made with starch. This crossover marks the end of the plateau region and the start of the terminal zone of the relaxation spectrum. The smaller particle size of starch granules

Fig. 1 Effect of particle size on mechanical spectra of water chestnut flour dispersions during isothermal heating and after heating/cooling (HC); (CP-coarse particles: 88-µm and FP-fine particles: 74-µm). Reproduced from Ahmed et al. [26] with permission from the publisher



compared to flour particles might increase the Pickering stabilization of the dough, shifting the plateau relaxation zone to lower frequencies. However, a larger plateau was observed in potato starch dough at high frequencies. This might be related to the B-type crystalline polymorphism property that has no pores in the granular surface and hence low water absorption capacity. The larger granules of potato starch than cereal starches (wheat and maize starch) might also have played a role in their shifting the plateau relaxation zone. Similarly, higher loss tangent values for potato doughs might also be related to the structural differences in granules. Consequently, higher viscoelastic moduli were obtained from flour-based doughs, which could be attributed to their larger particle size and protein adhesion [29]. Waziiroh et al. [30] attributed the increased complex viscosity of flour dough to its higher starch damage, protein content, and water absorption capacity when compared to starch dough.

Linear creep and recovery test showed that doughs made with gluten-free flours had lower compliance values in both creep and recovery phases, reflecting their higher consistency values [29]. At all three fermentation durations, wheat starch had higher compliance values than maize starch, which was consistent with its low viscoelastic moduli. In the case of potato starch, there was no notable increase in compliance as the fermentation progressed. This might be owing to the larger size of potato granules combined with the lack of superficial pores, making dough less effective in terms of granule packing and continuous phase formation. Higher steady state compliance (J_e) which reflects the elasticity of the dough was obtained from doughs made with wheat starch. Starch-based breads, on the other hand, had a larger specific volume and reduced hardness, particularly those prepared with wheat starch, which had lower viscoelastic moduli, superior packing properties, and the ability to form a continuous homogeneous matrix in the dough. However, the large granules of potato starch did not form a continuous matrix, and hence, breads with potato starch had the lowest specific volume, elasticity, cohesiveness, and resilience, and the highest hardness [29].

For optimal performance in bread dough, a balance of elastic (film formation and gas retention) and viscous (protein absorption into the liquid lamella and flexibility for gas expansion) properties is required [20]. Therefore, several potential approaches have been used to create gluten-free products that are identical to their gluten-containing counterparts though the utilization of starches. The impact of several gluten-free starches, as well as a flour-starch combination, on baked product quality was also investigated. The positive effect of waxy starch on structure formation and staling retardation in corn/potato starch-based gluten-free bread was demonstrated [31]. Viscoelastic properties of dough were determined by frequency sweep and creep and recovery tests.

Experimental data obtained from frequency sweep test were described using power equations:

$$G'(\omega) = K' \cdot \omega^{\mathrm{n}'} \tag{10}$$

$$G''(\omega) = K'' \cdot \omega^{\mathrm{n}''} \tag{11}$$

where; K', K'', n', n'' experimental constants.

Partial replacement of starch mix with waxy starch (5, 10, 15, 20 and 25%) modified viscoelastic properties of the dough leading to an increase in values of G' and G''. There was a rise in storage and loss moduli constants (K' and K'') as the percentage of waxy starch increased until it reached 20%. A considerable positive change was detected at 15% waxy starch level. However, 25% increase in the amount of waxy starch in the dough decreased both constants [31]. Waxy starch has higher swelling ability as compared to its amylose containing counterpart, and hence its use increases water absorption and strengthens the dough structure through swollen starch granules. Thus, it can form a cohesive dough with improved viscoelastic properties. On the other hand, if the waxy starch content is too high, it may interfere with the hydration of non-starch hydrocolloids (in this study, pectin and guar gum), reducing their structural significance. In this study, the changes in the dough's rheological characteristics were not excessive, yet the observed tendency showed that the waxy starch content strengthened the dough [31].

Creep and recovery data, which were described using Burger's model, showed that the participation of waxy starch in the structuring of dough led to a decrease in its compliance towards applied stress, and the addition of 15–25% waxy starch significantly reduced the compliance. The instantaneous compliance (J_0) and viscoelastic compliance (J_1) reduced with an increasing share of waxy starch, although the changes were not statistically significant. The influence of waxy starch on retardation time was found to be statically insignificant. However, the elevated levels of waxy starch significantly increased zero shear viscosity. Strong correlations were determined for parameters describing the sweep frequency test and creep and recovery tests. The results of this study suggested that the optimum level of waxy starch (10%) improved the quality of gluten-free bread. The high-level use of waxy starch damaged the hydration of non-starch polysaccharides of dough such as hydrocolloids, reducing their role in structure formation. Therefore, the excessive (25%) level of waxy starch in the bread formulation significantly reduced the volume and increased the staling of breads [31].

The increases in damaged starch content in rice dough led to increases in the G' and G'' and decreases in tan δ value of the dough [32]. The introduction of damaged starch into the dough system reduces available water, decreasing the batter's tolerance to expanding with gas pressure and, hence, may increase the crumb hardness. Therefore, the observed firmer texture of breads with the addition of damaged starch might be related to the water binding ability of damaged starch. On the other hand, bread made from only dried milled rice flour had poor quality. The network was strongly cross-linked when bread was made from rice flour with a 4–6% damage starch content. This provided a good gas retention capacity, leading to a high specific volume, dense cell structure, and elastic bread texture. According to the findings of these investigations, the optimal level of starch should be used. In order to increase the quality of gluten-free products, the starch/water ratio, starch/flour source, and starch/flour structure should also be evaluated [30].

The addition of fiber-rich flour positively influenced the rheological properties, bringing the gluten-free dough closer to a gel-like material (Table 1). Elevated amounts of carob flour in rice dough led to a shift of $G'(\omega)$ and $G''(\omega)$ towards higher values, whereas tan $\delta(\omega)$ presented lower values [33]. The results suggested that the inclusion of fiber rich flour resulted in a more prominent solid elastic-like behavior. However, the impact of fiber-rich flours on the rheological qualities of dough formulations has also been reported in various manners. The influence of acorn flour on different types of gluten-free dough formulations has also been studied [34, 35]. The viscoelastic functions were found to be lower in the control dough, which was made without the inclusion of acorn flour [34]. Furthermore, at low frequency values, a pseudo-terminal zone was observed, with a tendency for a crossover point at extremely low frequencies. This behavior showed a less structured system of the control dough. The incorporation of acorn flour, on the other hand, increased in the moduli G' and G'', resulting in a reduction in phase shift tangent (tan δ). This finding showed the role of acorn flour in improving the degree of dough structure [34]. The findings of Beltrão Martins et al. [34] suggested that the improvement of rheological characteristics in acorn flour doughs underlined the contribution of the fiber content present in acorn flour. Interestingly, higher levels of acorn flour (35%) significantly reduced G' values. On the other hand, Korus et al. [35], discovered that both the moduli of gluten-free dough prepared with corn and potato starch were proportionally increased with the replacement of acorn flour with starch. These differences between the findings of Beltrão Martins et al. [34] and Korus et al. [35] revealed the significant role of the various dough components in their different rheological behavior.

Demirkesen et al. [20] studied the use of chestnut with the combination of rice flour on the rheological behavior of dough and the resultant product of bread. Both G' and G'' proportionally increased with the increasing chestnut flour content. The authors related such an increase in the viscoelastic structure of dough to the entanglement of fibers in chestnut flour. The formulations with the chestnut/rice flour ratio of 30/70 having the intermediate G' and G'' provided the desired quality parameters to breads. Thus, SAOS experiments demonstrated that for optimal baking results, a gluten-free dough with balanced viscoelastic qualities is required. The breads prepared with 30/70 chestnut/rice flour and xanthan–guar blend-emulsifier blend gave the highest quality. On the other hand, elevated levels of chestnut flour gave low volume, a harder texture, and a darker color regardless of gum blend and emulsifier addition. Similar findings were also observed for gluten-free cookies [36]. Replacement of rice flour with chestnut flour led to higher complex modulus values. The softest texture was obtained from cookie samples prepared with a certain replacement level of rice flour with chestnut flour (40%), and higher levels of chestnut flour increased hardness values and decreased the spread ratio of cookies [36].

Similar to the findings of Tsatsaragkou et al. [33] and Demirkesen et al. [20], in the study of Villanueva et al. [37], higher viscoelastic moduli and steady-state viscosities and lower tan δ values of dough samples were observed with the additional increase of tef in maize-starch based dough. This might be related to the higher water absorption capacity of tef flour due to its higher fiber and protein content. Torbica et al. [21] found that increasing the amount of unhusked buckwheat flour from 10 to 20% resulted in a substantial decrease in G' and yield stress value, whereas adding 30% of unhusked buckwheat flour had no effect. The addition of husked buckwheat flour to the dough, on the other hand, resulted in an initial increase in G'. This might be due to husked buckwheat flour's higher fiber content and starch swelling. As a result of segregative interactions between system components, it has been hypothesized that differences in gel strength are driven by changes in macromolecular organization. The optimum baking quality was again obtained with a certain level of flour (10% and 20% of husked buckwheat flour and 10% of unhusked buckwheat flour).

Linear Rheological Properties of Gluten-free Dough Systems: Impact of Non-Gluten Proteins

Gluten-free bread, particularly that which is made from diverse botanical sources of starch, is often poor in protein. Hence, much research has focused on the possibility of supplementing gluten-free products with proteins.

Batter consistency is primarily affected by the hydration level, the water-binding capacity, and the air entrapment ability of the batter [38]. Lower hydration levels in batters and ingredients with high water-binding capacity can result in higher G' and G'' values than higher hydration levels in batters and ingredients with lower water-binding capacity [39]. In the study of Ozturk and Mert [38], the water holding capacity of protein-rich by product 'corn gluten meal' was enhanced with the microfluidization technique, and then microfluidized corn gluten meal was used instead of gluten in gluten-free bread formulations. The increase in water holding capacity with microfluidization provided higher elastic and viscous moduli values and, hence, higher specific volumes than the untreated samples.

The effect of protein interactions (egg white and pea proteins) and hydration level on protein-enriched gluten-free breads was investigated [39]. The highest elastic modulus was obtained for control dough prepared without the addition of protein, followed by dough enriched with pea protein. Elastic modulus decreased gradually with the elevated levels of egg white protein content as well. The good foaming capacity of egg white provided better air entrapment and the lower water-binding capacity of the ingredients. Similar to the study of Bravo-Núñez et al. [39], Herranz et al. [40] stated that the foam nature and also the higher lipid content of egg white led to lower values of G^*_{max} values and higher tan δ in cake batters made with chickpea flour:corn starch with respect to those made with whole egg alone. The authors stated that replacement of whole eggs with egg white was not found to be a suitable strategy to increase batter functionality. In contrast to the findings of Bravo-Núñez et al. [39] and Herranz et al. [40], Han et al. [41] stated that the addition of egg white protein (5–15%) increased the elasticity of gluten-free batter. In terms of quality, breads with egg white had larger specific volumes and a more homogeneous texture, and egg white addition improved the texture properties of bread during storage. However, Bravo-Núñez et al. [39] reported that the hardness values of breads were increased by the presence of egg white protein, while they decreased with the presence of pea protein.

Different results regarding the effect of egg white protein on dough/batter rheological qualities may be due to changes in the water absorption characteristics of the ingredients in the formulation. Mariotti et al. [42] compared the influence of different levels of corn starch, amaranth flour, pea isolate, and psyllium fiber on the linear rheological characteristics of gluten-free dough. In the presence of psyllium fiber, the higher presence of pea isolate protein did not have any influence on the linear rheological properties of the dough, but the influence of pea isolate was marked in the absence of psyllium fiber. This finding also highlighted the role of the interaction between proteins and other components in the rheological properties of batters. Sahagún and Gomez [43] observed that while the addition of pea and potato protein in gluten-free cookie formulations had no significant effect on rheological characteristics of the dough, egg proteins or whey proteins significantly affected the viscoelastic properties of the dough by lowering the values of G' and G''. This result might be related to the correlation between the water binding capacity of ingredients and the viscoelastic properties of dough [43].

The rheological characteristics of the dough are not only determined by the type of protein added, but also by the type of starch used as the dough base. In order to investigate the influence of protein on the rheological behavior of gluten-free dough in the presence of starch, Mancebo et al. [44] studied the effects of starch and/or protein addition on rice flour gluten-free cookie quality. The use of protein in formulations increased the hydration properties of the mixture and the viscoelastic properties of dough, while maize starch addition reduced hydration properties. Cookies with higher protein content showed higher acceptability than cookies with higher starch content and no protein addition. Witczak et al. [45] evaluated the replacement of rapeseed protein (6, 9, 12, and 15%) as a novel ingredient with starch mix in gluten-free dough. The linear viscoelastic measurements revealed that dough samples behaved as weak gels, and both G' and G'' values were found to be significantly dependent on angular frequency. The introduction of rapeseed protein isolates in dough led to a substantial drop in the values of G' and G'' indicating greater plasticity. These findings were accompanied by an increase in phase shift tangents, which ranged from 0.1 to 1.0. The increases in rapeseed protein content did not create a significant decrease in moduli values, and the drops in moduli values were found to be relatively constant. The authors explained these observations by the hydration properties of proteins, indicating a correlation between water binding capacity of ingredients and G' and G'' values of dough. According to Korus et al. [46], in addition to water binding capacity, rapeseed protein's surface activity may also help to keep the gas bubbles in the crumb structure. Hence, gluten-free breads with higher loaf volume and improved consumer acceptance can be obtained. Sarabhai and Prabhasankar [47] evaluated the replacement of starch and protein with water chestnut flour on gluten-free cookie quality. For this purpose, the influence of whey protein concentrate and potato starch on the rheological properties of water chestnut flour-based gluten-free cookie dough and the quality of gluten-free cookies was studied [47]. Frequency sweep test results indicated that an increase in whey protein concentrate and potato starch increased storage modulus and decreased tan δ suggesting that the presence of whey protein concentrate and potato starch increased the strength and elasticity of gluten free cookie dough. The presence of large starch granules might be responsible for higher G' and G'' values. The results of creep curve analysis in the linear viscoelastic range were in accordance with the oscillation results, which also revealed increases in zero shear viscosity and decreases in maximum creep compliance. However, it was observed that the rheological properties of dough were more affected by replacement quantity than by protein presence. The results of physical and sensory evaluation of gluten-free cookies showed the addition of whey protein concentrate increased cookie hardness, fracturability, spread ratio, and overall acceptability, as evaluated by a trained panelist.

Matos et al. [48] stated that the extent of the effect of protein on rheological properties of dough/batter and quality characteristics of resulted products depends on the source of protein. The role of soy protein isolate, pea protein isolate, egg white protein, casein, and, as a comparison, vital wheat gluten on the rheology and quality of gluten-free rice muffins was investigated. Leguminous proteins induced a major effect on the rheological properties of batter. The presence of all leguminous proteins modified the elastic and viscous component of batter, inducing increases in G' and G''. Batters containing soy protein isolate and pea protein isolate led to the highest increases in G' and G'' values, whereas vital wheat gluten containing batter had very low G' and G'' values, which were slightly higher than those of non-protein containing dough. Casein protein containing dough had slightly higher viscoelastic values than control dough prepared without the addition of protein. However, egg white protein containing dough had the lowest G' and G'' values. Complex modulus significantly improved with the addition of proteins, and it had the same trend observed in G', indicating higher contribution of the elastic component to the viscoelastic properties of the batter systems.

In order to comprehend the influence of protein type in the changes that occurred during the thermal treatment of the rice-based batters, the viscoelastic properties were also studied during the application of a temperature sweep test. The storage modulus values were determined during heating from 25 °C to 95 °C. The addition of vegetable proteins caused differences in the slope of the heating curves, which have been linked to starch gelatinization as well as protein coagulation reactions. The initial increase in the elastic component as the temperature increased resulted in an early onset of starch gelatinization (61–78 °C) in the dough with no protein. The addition of wheat proteins in muffin batter did not influence the rheological behavior at temperatures lower than 70 °C. However, at temperatures higher than 70 °C, the formation of inhibited rice starch 3-D internal structure, as well as denaturation and disassociation of proteins, resulted in a loss in elastic structure [48].

The rheological behavior of batter samples containing soy protein and pea protein isolates showed different responses on heating, which might be attributed to the different thermal stability of their protein fractions. An increase in G' with rises of temperature in egg white protein containing batter was caused by the coagulation of proteins. Casein containing batter had a very high consistency, showing the higher water absorption of this protein but the limited amount of available water for starch gelatinization. In general, large increases in G' values of dough samples containing soy protein isolate, pea protein isolate, and casein were observed with the temperature increases. Concerning muffin quality, pea protein isolate gave the softest texture, while the highest specific volume was obtained from egg white protein containing muffins [48]. Similarly, Ronda et al. [49] stated that proteins from vegetable sources resulted in more structured dough matrices, higher viscoelastic moduli, and lower tan δ. Protein isolates (kidney bean, field pea, and amaranth) enhanced viscoelasticity of gluten-free muffin batters [50]. The introduction of potato protein and hemp protein isolates resulted in enhancements in the viscoelastic characteristics of gluten-free batters [51, 52]. The presence of components, especially protein, which initially absorb water and, swells and at high temperatures denatures, and modifies the viscoelastic properties of the dough. More viscoelastic batters containing various proteins could retain and stabilize the gas bubbles, resulting in a higher aerated structure and more voluminous products.

According to Ziobro et al. [53], except for albumin, all proteins caused significant increases in G' and G'', and the most pronounced effect was obtained from dough containing pea protein, followed by soy protein containing one. As compared to the control, the inclusion of protein preparations resulted in a considerable decrease in tan δ, which correlates to dough structural strengthening. The dough with albumin had the least drop in tan δ. The authors, similar to Korus et al. [46], underlined the role of protein's gas holding capacity on rheological parameters and hence product quality. Despite the fact that albumin had the least effect on tan δ, its capacity to form foam and hold gases resulted in a large increase in bread volume. The addition of lupine protein caused a rise in tan δ at higher angular frequencies, indicating that the dough with lupine protein has a weaker structure and deforms more quickly after stress is applied. While the volume of bread increased with albumin, soy protein and collagen had a negative effect on volume. Generally, the use of proteins in formulations provided a softer crumb and retarded the staling of breads. In terms of sensory properties, pea protein bread was the most acceptable among analyzed samples, while bread containing soy protein had the least sensory acceptance [54]. All these findings suggest that the type and denaturation pattern of protein fractions affect both the rheological characteristics of dough/batter and the quality measurements of the final products.

Tomić et al. [55] tested the substitution of millet flour with 10% of different sources of proteins (pea, rice, and whey protein concentrate) in the presence of an enzyme. The influence of different concentrations of transglutaminase (0.5, 1.0, and 1.5% w/w based on the flour-protein blends) on dough rheological properties and bread textural and sensory quality was investigated. While the incorporation of pea proteins increased viscous and elastic moduli values, the incorporation of rice proteins did not lead to any noticeable modification of the viscoelastic behavior of the dough. Whey protein doughs, on the other hand, showed lower values for both moduli, which might be due to more air being incorporated into the dough during mixing, resulting in higher specific volumes of bread. The influence of transglutaminase was mainly affected by the nature of the used proteins, and it was to a certain extent masked by the high concentration of protein concentrates. Overall, the substitution of millet flour by pea, rice, and whey proteins caused a significant reduction in bread hardness and a complete loss of the bitter taste originating from millet.

Environmental factors such as acidity have additional significant impacts on the direction of changes in the viscoelastic properties of protein-enriched dough. The influence of acidification with an acetic + lactic blend and protein fortification (caseinate or soy-protein isolate) on the rheological properties of wheat, corn, potato and tapioca starch-based gluten-free bread doughs was also studied [56]. Proteins provided structure and strengthened the doughs, especially those containing soy-protein isolate-potato starch and caseinate-wheat starch mixtures. G' and G'' decreased with acidification up to 70% as compared to unacidified dough. The influence was found to be more significant in protein-fortified doughs. The authors proposed that acidification of protein-enriched starch matrices modulates dough rheological properties, which are of relevance in gluten-free product development.

Linear Rheological Properties of Gluten-free Dough Systems: Impact of Hydrocolloids and Dietary Fiber

The impact of hydrocolloids on the G''/G' ratio in gluten-free systems varies depending on the kind and concentration of hydrocolloid. This effect appears to be linked to polysaccharide molecular structure and chain conformation, which define the physical intermolecular interactions of polymeric chains [18, 20].

The molecular structure of hydrocolloids, which determines the intramolecular linkages between polymeric chains, appears to alter their effect on dough rheological qualities. Linear rheological and color characteristics of gluten-free pasta dough made from proso millet dough with the addition of three different types of hydrocolloids (guar gum, xanthan gum, and sodium alginate) were compared with those of wheat dough [57]. As expected, wheat dough had a higher elastic modulus than proso millet dough. The use of all hydrocolloids increased G', but the most pronounced improvement in G' was obtained with xanthan gum, which was followed by guar gum and sodium alginate. It has been suggested that the semi-rigid conformation and relatively strong intramolecular interactions of xanthan gum may contribute to making a strong interaction with cereal proteins [57, 58]. Similarly, Demirkesen et al. [18] observed that xanthan gum provided higher viscoelastic properties to dough samples as compared to guar gum, locust bean gum (LBG), hydroxypropyl methylcellulose (HPMC), and pectin. In the study of Romero et al. [57], the addition of xanthan gum decreased tan δ significantly, while the addition of sodium alginate showed little influence on tan δ. This finding showed the most pronounced contribution of xanthan gum to the elastic properties of dough compared to other gums. A higher concentration of guar gum as well as sodium alginate increased the tan δ value indicating an increase in the viscous properties of dough structure. Therefore, increasing the concentrations of these two gums poorly enhanced the viscoelastic behavior. On the other hand, regarding the quality of pasta, both guar and xanthan gum improved the network strength of pasta, but sodium alginate did not contribute to textural enhancement.

Peressini et al. [59] studied the influences of xanthan gum and propylene glycol alginate (PGA) addition on the linear rheological properties and breadmaking performance of rice-buckwheat batter at different water levels. The addition of both hydrocolloids significantly provoked an upward trend in the storage modulus of batter, but xanthan gum had a superior effect on the viscoelastic properties (G' and G'' moduli) compared to PGA. Such a stronger influence of xanthan gum on the viscoelastic properties was found to be in agreement with previous studies [18, 57]. PGA helped to form elastic films at the gas–liquid interface, which protected gas cells from instability [59]. Therefore, it provided higher improvement in breads in terms of specific volume, crumb firmness, and crumb structure as compared to xanthan. The findings of the study revealed that the rheological properties of batter, which are determined by polymer addition and water content, played a critical role in bread quality, and the high elasticity values inhibited batter expansion during proofing, thereby causing low breadmaking performance.

The impact of tara and xanthan gums on the viscoelastic and textural qualities of gluten-free doughs and breads prepared from maize starch or potato starch was studied by Vidaurre-Ruiz et al. [60]. Xanthan gum provided higher of G' and G'' to dough samples and among all samples, the highest of G' and G'', was obtained from dough containing corn starch and xanthan gum. Tara gum, on the other hand, created lower G' and G'' values in doughs made with corn starch and potato starch. According to Demirkesen et al. [20], very low viscosity and viscoelastic modulus values might cause structural weakness and prevent air bubble entrapment in dough, resulting in low specific volume values of bread. Similarly, the doughs could not hold the gas produced during the fermentation process when they have very high viscoelastic values. In the study of Vidaurre-Ruiz et al. [60], very low viscoelastic properties were obtained for the dough with tara gum and both starches, as well as very high viscoelastic properties of dough containing corn starch and xanthan gum, which gave inferior properties to breads. Xanthan gum with potato starch efficiently balanced the viscoelastic behavior of the dough. Hence, higher quality in terms of texture and volume was obtained for the breads formulated with xanthan gum and potato starch.

The influence of the replacement of buckwheat flour with rice flour (10, 20 and 30%) and the addition of carboxymethyl cellulose (CMC) on the rheological properties and quality parameters of gluten-free cookies was studied by Hadnađev et al. [61]. Both G' and G'' were found to be frequency dependent in a frequency sweep test. In order to express the magnitude of the dependence of storage modulus on oscillation frequency, the curves were fitted to the power law equation and the coefficients were obtained. Rice cookie dough had higher values of K' (storage modulus at 1 Hz) and lower values of tan δ in comparison to other dough samples, reflecting the properties of rigid and stiff material. Furthermore, the value of n' (the coefficient which represents the slope of the curve in a log–log plot of G' versus the frequency) of rice dough was lower than that of wheat cookie dough, reflecting its frequency-independent structural stability. The utilization of buckwheat flour in the dough reduced elastic modulus and increased tan δ, showing that the presence of buckwheat flour lowered the strength and elasticity of gluten-free cookie dough. However, gluten-free dough resembled wheat cookie dough when CMC, which led to a significant rise in storage modulus, was used in the formulation. Gluten-free dough containing CMC and buckwheat flour between 20 and 30% substitution level was found to be easy to handle and strong enough to resist sheeting and maintain an acceptable shape, resulting in an improved quality of cookies.

Zhao et al. [62] tested the effect of the co-supported matrix of HPMC and PGA on enhancing the structure and texture of gluten-free bread in comparison with that of the single hydrocolloids (xanthan gum, CMC, konjac gum, etc.). Dough samples with xanthan gum, CMC, and konjac gum had higher elastic moduli values than those with PGA dough and HPMC dough. The viscoelastic measurements also showed that the increase in hydrocolloid concentration was still less than the critical point of the concentration needed to obtain the desired changes in rheological properties. G' value shows both the elasticity and the rigidity of the dough. While the dough with a higher elasticity performs better during processing, a greater rigidity might prevent the dough from expanding as forementioned above. HPMC gave dough expansion capacity, but PGA produced dough with a stiffer structure, as evidenced by the difference in G' and G''. When the concentration of PGA was increased, a decrease in tan δ was noticed, along with an increase in G', indicating a more elastic dough, as well as a more stable dough structure. The findings showed that PGA probably co-supported with HPMC to improve dough structure by rearrangement of polysaccharide polymers. The use of HPMC improved the specific volume of breads, but the crumb characteristics of the breads had texture defects. These defects were eliminated by the use of HPMC in combination with PGA. The positive synergic interactions between different gums have also been used to improve gluten-free bread texture. Such a synergic effect between xanthan gum, which interacts with the smooth sections of galactomannans like guar gum and locust bean gum, has also been used successfully in gluten-free chestnut bread [20].

As a novel hydrocolloid, bacterial nanocellulose was recently evaluated in gluten-free muffins [63]. Batters containing bacterial nanocellulose had higher G' and G'' than control during and after thermal treatment. The appropriate bacterial nanocellulose levels (0.12–0.18 g/100 g raw batter) led to more air entrapment and hence higher volume for the baked products. The authors stated that great rheological variation within a short bacterial nanocellulose range could be useful to adapt formulations for different baking processes. These studies also reflected the fact that the influence of hydrocolloids on dough is mainly connected to their interactions with dough components. Furthermore, the interaction between different hydrocolloids and other ingredients has also been effective on the rheological properties of dough and hence the quality of products. The effect of the combination of different hydrocolloids and emulsifiers on the rheological properties of rice bread dough and the final quality of gluten-bread as compared to wheat dough was studied by Demirkesen et al. [18]. First, the viscoelastic moduli values of wheat dough samples and gluten-free rice dough samples containing different hydrocolloids (xanthan, xanthan + guar, LBG + xanthan, guar, LBG, HPMC, and pectin) were determined. Then, the viscoelastic moduli values of wheat dough samples were compared with rice dough samples containing different hydrocolloids and the emulsifier Purawave™. Lastly, the viscoelastic moduli values of wheat dough samples and rice dough samples with different hydrocolloids and emulsifier diacetyl tartaric esters of monoglycerides (DATEM) were tested.

In the absence of gum or emulsifier, rice flour dough could not form a homogenous mixture and had very quick phase separation. Therefore, it was not possible to obtain any meaningful results for the rice dough sample. Gluten plays an important role in the cohesive and viscoelastic properties of wheat flour, and thus, wheat dough had the highest elastic and loss modulus values among all dough samples. In contrast to wheat dough, rice flour dough samples displayed strong frequency dependence, indicating that the structure of rice flour dough was not strong enough to provide the same elastic structure as wheat dough. Among all the rice dough samples that were prepared with hydrocolloids, the addition of xanthan created the highest moduli values, which were followed by xanthan–guar and xanthan–locust bean gum containing dough samples [18]. This might be due to the complex aggregates formed by semi-rigid molecules and high-water holding capacity of gum, which reduces the available water that promotes the movement of particles in dough [20]. In comparison to xanthan gum, guar and locust bean gum caused a lesser rise in viscoelastic moduli. Furthermore, HPMC and pectin showed a negligible effect on dynamic viscoelastic behavior [18].

The hydrophilic and lipophilic groups of emulsifiers can interact with the components of rice dough, such as water, oil, etc. Thus, a significant improvement in the viscoelastic moduli was observed when emulsifiers were used in addition to hydrocolloids. When the viscoelastic values obtained from emulsifier DATEM or Purawave™ containing samples were compared, DATEM was found to have a more pronounced influence on viscoelastic moduli. Due to the larger hydrophilic part of emulsifier DATEM, it has a higher HLB value. Thus, it may decrease the surface tension of the dough even in very low concentrations, and a stronger dough structure can be obtained when it is incorporated into the dough. The significant increase in the viscoelastic properties of dough with the use of DATEM resulted in a less sticky and easier-to handle surface. Hence, the functions of DATEM in combination with hydrocolloids provided the most acceptable gluten-free rice breads. A relationship between the rheological qualities of dough samples in terms of viscoelastic parameters and the hardness of rice bread samples was also determined. The discrepancies between the elastic and loss moduli of samples were amplified with increasing frequency. The elastic and loss moduli values obtained at plateau locations (maximum measured frequency, 10 Hz) were selected for correlation. Higher moduli of dough samples resulted in less hardness of bread samples. The findings of this study showed that DATEM can be recommended to be used with different gums to obtain the desired rheological properties and hence acceptable quality values in gluten-free rice breads [18].

Fiber macromolecules with variable water binding and gelling capacities compete for water, resulting in additive, synergistic, and/or antagonistic impacts on main linear rheological properties. The significance of the incorporation of HPMC, and barley β-glucan at different amounts were tested in gluten-free rice-based dough [64]. When there was sufficient amount of water, barley β-glucan decreased significantly tan δ indicating an increasing contribution of the elastic component to dough viscoelasticity. Larger dynamic moduli with lower frequency dependence, lower elastic deformation at constant tension, and higher viscosity at steady state were associated with more consistent doughs [64]. Similarly, increasing levels of added HPMC and sugar beet fiber caused an increase in elastic modulus, while decreases in tan δ and compliance values were observed in the study of Djordjević et al. [65]. Higher levels of HPMC and sugar beet fiber incorporation enhanced specific loaf volume and crumb texture.

It is useful to determine the rheological behavior of dough on a longer timescale, including its relaxation time. Shear rate-controlled frequency sweep tests, which entail significant amplitude oscillation when the shear rate is relatively high and the angular frequency is low, can be used to apply Frequency Superposition (SRFS) to soft materials. On the other hand, gluten-free doughs might not display a prominent structural relaxation peak in the measurable frequency range, which might be attributed to poor stability and short linearity, which affect master curve development. As a result, applying 'Strain-Rate Frequency Superposition' to gluten-free rice doughs might be challenging. Thus, Ren et al. [66] used 'The generalized Maxwell model' to determine the influences of methylcellulose, psyllium seed husk powder (PSY), and water addition levels on gluten free dough rheological properties. The generalized Maxwell model is made up of numerous single Maxwell elements that are connected in parallel and are each defined by G_i and λ_i. In the generalized Maxwell model characterized by G_e, a single spring can be inserted. In this method, frequency sweep tests were performed in a logarithmic decrease manner with a strain of 0.02% which is in the linear viscoelastic region. The slopes of log G' versus log ω and log η^* versus log ω were used to depict the frequency dependences of storage moduli G' and complex viscosity η^* in the middle frequency range (0.881 to 40.9 rad s^{-1}). The dynamic moduli $G'(\omega)$ and $G''(\omega)$ in small amplitude oscillatory experiments can be calculated from the angular frequency (ω by equations;

$$G'(\omega) = \sum_i G_i \frac{w^2\ \lambda i^2}{1 + w^2\ \lambda i^2} + G_e \tag{12}$$

$$G''(\omega) = \sum_i G_i \frac{w\ \lambda i}{1 + w^2\ \lambda i^2} + G_e \tag{13}$$

Individual relaxation modulus G_i were varied to minimize the sum of squared discrepancies between calculated $G'(\omega)$, $G''(\omega)$ and experimentally obtained G', G'' with arbitrarily chosen, individual relaxation times, λ_i. In the model, G_e shows a pure elastic component.

The model fitting resulted in 21 parameters, including 10 predefined λ_i for each Maxwell element and 10 corresponding G_i and G_e for all the samples, which were not included since their values were almost zero, showing an insignificant contribution to the overall viscoelasticity. The storage and loss moduli, complex viscosity, and tan δ at two angular frequencies (1.29 and 60 rad s^{-1}: $G'_{1.29}$, G'_{60}, $G''_{1.29}$, G''_{60},

$\eta^*_{1.29}$, η^*_{60}, t tan $\delta_{1.29}$, and tan δ_{60}), slopes of log G' versus log ω and log η^* versus log ω, ω_{rel}, with corresponding modulus (G'_{rel}) and η^*_{rel}, and R^2 values of the generalized Maxwell model are defined. The addition of methylcellulose and psyllium fiber increased $G'_{1.29}$, G'_{60}, $G''_{1.29}$, G''_{60}, $\eta^*_{1.29}$ and η^*_{60}. It also showed positive contributions to the slope of log G' versus log ω, reflecting less frequency dependence and more solid-like property. On the other hand, the addition of water had negative effects $G'_{1.29}$, G'_{60}, $G''_{1.29}$, G''_{60}, $\eta^*_{1.29}$ and η^*_{60} and insignificant effect on the slope of log G' versus log ω. Higher water levels caused PSY to have a positive effect on G' and PSY and methylcellulose to have a positive effect on G''. The result showed the strengthening effects of hydrocolloids on viscoelastic behavior and the diluting impact of water on both flour and hydrocolloids.

PSY's impact on G'_{60} was more substantial than that of methylcellulose at a low water addition level. Methylcellulose, on the other hand, had a greater influence on G''_{60}, whereas PSY had a greater influence on $G''_{1.29}$. Methylcellulose increases viscosity when it is dissolved in water. As a result, it produces a higher G' at high frequencies and a higher G'' at low frequencies. On the other hand, PSY has a gel-like property. Therefore, the different contributions of PSY and methylcellulose to the elastic and viscous moduli of the doughs at different frequencies were observed. The authors proposed that the variation in rheological characteristics of MC and PSY, as well as their different water-binding abilities, might cause their differences in the counteracting effect of water [66]. In the log G' vs. log ω model, methylcellulose-PSY interaction had a negative coefficient, indicating the negative contribution, which might be related to their competition for water. The higher relaxation frequency of gluten free doughs than wheat doughs reflected their fluid-like characteristics at the deformation rates during proving. The study showed that methylcellulose significantly influenced dough extensibility and work of adhesion, which were good predictors of bread volume and textural properties. Small amplitude oscillatory tests were found to be less significantly correlated to specific volume, but they were sensitive to formulation variations, especially the PSY addition. It gave information about dough structures and stability, related to proving behaviors, and correlated to loaf concavity [66].

The presence of citrus fiber also altered the linear rheological properties of the dough, resulting in an increase in storage modulus and loss modulus values, as well as zero shear viscosity, accompanied by a decrease in J_0 and J_1 to applied stress, indicating dough strengthening due to significantly greater water binding and swelling properties characteristic of citrus fiber. The use of citrus fiber in bread formulations decreased bread volume, porosity, and average pore size. It was found to be effective in retarding the staling of gluten-free bread [67]. Similarly, Ozturk and Mert [38] observed the positive effect of citrus fiber on the quality of gluten-free breads. Kırbaş et al. [68] examined the effects of using different fiber sources (apple pomace powder, carrot pomace powder, and orange pomace powder) on the linear rheological characteristics of dough and the quality characteristics of gluten-free rice cakes. Elastic and viscous moduli of the batters increased with elevated levels of all kinds of pomace powders. Furthermore, the addition of pomace powders increased batter specific gravity and crumb hardness and decreased the specific volume of cakes.

Martínez et al. [69] compared the effects of insoluble fibers (oat and bamboo, fine and coarse, potato and pea), and soluble fibers (nutriose and polydextrose) on gluten-free dough rheology and microstructural features of the resulting bread. Soluble fibers decreased dough consistency, while doughs with insoluble fibers increased consistency, particularly those with potato fiber and, slightly, with pea fiber,which both had larger particle size. Insoluble fibers became more rounded by the presence of starch granules, leading to larger, more irregular structures than in the control dough. Hence, the larger and rounder fibers had a greater effect on the dough structure. Soluble fibers dissolved in the aqueous solution with the hydrocolloid and the other solutes, which created a lubricating effect on the dough. Thus, the quantity of starch available to absorb water decreased, leading to a decrease in dough consistency and elasticity and hence an increase in loss tangent. In addition, more air is incorporated into the dough and a more uniform internal structure and fewer discontinuities are obtained when soluble fibers are used. Soluble fibers increased specific volumes and cell density, lowered hardness and luminosity as compared to control breads. The fine insoluble fibers gave higher specific volumes and lower hardness, while coarser insoluble fibers caused lower specific volumes and higher hardness as compared to controls. Soluble fibers with the hydrocolloid created a film that coated the starch granules and flour particles, providing more stability to the structure, whereas insoluble fibers disrupted the structure. Therefore, producing gluten-free dough with balanced viscoelastic properties is critical for achieving optimal baking results, and this may be accomplished when fiber types (insoluble/soluble) and their quantities are consistent with dough components.

Non-linear Rheological Properties of Gluten-free Dough Systems

The fundamental rheological methods that are commonly used to determine the non-linear rheological methods include lubricated squeezing flow, non-linear creep recovery, and Large Amplitude Oscillatory Shear (LAOS) tests (Table 2). Lubricated squeezing flow tests apply biaxial extension, and they are useful to predict the dough proofing

Table 2 Comparison of the linear and non-linear viscoelastic properties of gluten-free dough systems with different ingredients

Ingredient	Dough system	Rheological method: Linear viscoelastic response	Rheological method: Non-linear viscoelastic response
Gluten-free flour/starch:			
Carob flour:rice flour	bread dough	***SAOS test:*** decrease in tanδ (increase in elasticity) with increasing carob flour[a]	***Non-linear creep recovery test:*** decrease in J_1 (increase in elasticity) with increasing carob flour[a]
Buckwheat flour: rice flour (up to 30:70, w/w)	cookie dough	***SAOS test:*** decrease in G', increase in tanδ with increasing replacement ratio with buckwheat flour[c]	***Non-linear creep recovery test:*** increase in J_{max} and decrease in η_0 (decrease in elasticity) with partial replacement of rice flour with buckwheat flour[c]
Rice flour	cookie dough[c]	***SAOS test:*** lower tanδ values (higher elasticity) when compared to wheat flour dough[c]	-
	bread dough[e,g]	***SAOS test:*** similar apparent viscosity to those of wheat, soy, quinoa, and buckwheat flour doughs[e]	***LAOS test:*** higher degree of strain stiffening ($e_3/e_1 >$ 0) and wider elastic Lissajous-Bowditch curves (more viscous-like non-linear viscoelastic behavior) when compared to wheat, soy, quinoa, and buckwheat flour doughs[e] ***Non-linear creep recovery test:*** increase in the recovery ratio with microwave assisted heat-moisture treatment (up to 170% when blended with native rice flour at 50:50, w/w)[g]
Maize starch:tef flour (0–100:100–0, w/w)	bread dough	***SAOS test:*** lower tanδ values (higher elasticity) with increasing tef flour levels[f]	***Non-linear creep recovery test:*** decrease in J_1 (higher elasticity) when tef flour ratio is $\geq$ 50% (w/w) Maize flour:tef flour (50:50, w/w): improved loaf volume and crumb properties in the resulting bread (positive correlation between J_1 and loaf volume)[f]
Nixtamalized corn flour	corn masa	***SAOS test:*** increase in G' and G'' values as a function of tempering time and increasing $Ca(OH)_2$ concentration (up to 2%, w/w) [m] Solid-like viscoelastic behavior ($G' > G''$)[m]	***LAOS test:*** Type III non-linear behavior (weak strain overshoot), Shear thinning ($T < 0$) and strain stiffening ($S > 0$) behaviors in the non-linear region up to 1000% strain[n]
Non-gluten proteins:			
Extruded zein + rice, maize, potato starches	bread dough	-	***Non-linear creep recovery test:*** the lowest α value (the highest elasticity) for extruded zein-rice starch dough due to the smaller granule size of rice starch[i] Decrease in α value and increase in breadmaking quality with extrusion temperature > 150 °C[i]
Zein:rice starch (1:9, w/w) + co-proteins (5% of total protein, w/w)	bread dough	***SAOS test:*** lower phase angle values for zein:rice starch dough (with or without added co-protein) compared to benchmark gluten dough when mixed at room temperature[k]	***Lubricated squeezing flow test:*** higher extensional viscosity (higher resistance to deformation) for all zein-rice starch doughs compared to benchmark gluten dough when mixed at room temperature. The highest extensional viscosity was with added casein[k]
Caseinate, soy protein isolate + wheat, corn, tapioca, potato starches	bread dough	***Linear creep recovery test:*** decrease in J_{max} (increase in elasticity) with protein addition[h] Similar recovery (%) values for protein-potato starch dough both in linear and non-linear regions (higher stability)[h]	***Non-linear creep recovery test:*** decrease in J_{max} (increase in elasticity) with protein addition[h] Lower recovery values (%) for wheat, corn, and tapioca starch based doughs (higher degree of structural decay) under large deformations[h]

Table 2 (continued)

Ingredient	Dough system	Rheological method: Linear viscoelastic response	Rheological method: Non-linear viscoelastic response
fish actomyosin + mung bean starch	noodle dough	***SAOS test:*** sharp decrease in G' and G'' with increasing level of added actomyosin[j]	***Non-linear creep recovery test:*** increase in J_{max} with fish actomyosin addition (increased fluidity) [j] 30% of actomyosin addition was ideal to improve the extrusion process[j]
Hydrocolloids/fibers:			
HPMC + chestnut flour:chia flour	bread dough	***SAOS test:*** decrease in apparent viscosity, G' and G'' with HPMC addition[b]	***Non-linear creep recovery test:*** increase in J_R/J_{max} (increase in elasticity) with added HPMC[b]
CMC + buckwheat flour:rice flour (20:80 and 30:70, w/w)	cookie dough	***SAOS test:*** increase in G' with CMC addition[c]	***Non-linear creep recovery test:*** similar J_{max}, η_0, and J_R/J_{max} values to those of wheat flour cookie dough[c] Improved sheeting properties with added CMC[c]
Orange pomace powder + buckwheat flour:rice flour (20:80, w/w)	cake batter	***SAOS test:*** increase in G', G'', and apparent viscosity with orange pomace powder addition[d]	***LAOS test:*** increase in the degree of strain stiffening ($e_3/e_1 > 0$) and shear thinning ($v_3/v_1 < 0$) behaviors with orange pomace powder addition[d] increase in cake volume with added fiber up to 16% (on flour weight basis)[d]
HPMC, β-glucan + maize starch:zein (8:2, w/w) dough	bread dough	-	***Hyperbolic contraction flow test:*** increase in elongational viscosity and strain stiffening behavior withHPMC addition (2% on total weight basis, w/w)[l] Higher loaf volume and finer crumb in the resulting bread with HPMC compared to the bread with β-glucan[l]

[a] Tsatsaragkou et al. [33]

[b] Moreira et al. [5]

[c] Hadnađev et al. [61]

[d] Ozyigit et al. [91]

[e] Yazar et al. [4]

[f] Villanueva et al. [37]

[g] Villanueva et al. [76]

[h] Villanueva et al. [56]

[i] Frederici et al. [75]

[j] Mi et al. [83]

[k] Tandazo et al. [3]

[l] Andersson et al. [86]

[m] Contreras-Jiménez et al. [80]

[n] Alvarez-Ramirez et al. [77]

and baking performance (i.e., dough expansion during proofing and oven rise during baking) as biaxial and uniaxial extensions are the main deformations dough is exposed to during processing [3]. The deformation capacity of dough under the applied stress can be evaluated with a creep test [22]. Creep tests indicate the presence of non-linear behavior,however, they cannot provide a quantitative measure of the type and extent of the non-linear behavior [70]. For this purpose, LAOS tests have been recently used to bring a quantitative measure of the non-linear viscoelastic properties of gluten-free dough systems [4] through the meaningful LAOS parameters [G'_M, G'_L, η'_M, η'_L], dimensionless LAOS parameters [S, T], Lissajous-Bowditch curves, and e and v Chebyshev coefficients that cannot be obtained with SAOS testing [11, 71].

Non-linear Rheological Properties of Gluten-free Dough Systems: Impact of Flour/Starch Type

Studies evaluating the non-linear rheological properties of gluten-free dough systems have mostly focused on the impact of blending different gluten-free flours/starches on baked product quality. Tsatsaragkou et al. [33] studied the non-linear creep behavior of rice flour-based gluten-free bread doughs with carob flour added at different percentages (5:95, 10:90, 15:85 carob flour:rice flour, w/w). The water content of dough samples was increased as the carob flour percentage increased and water levels ranging from 70 to 150% (on a flour weight basis, w/w) were used. For the creep tests, a constant stress of 50 Pa was applied for 60 s followed by a strain recovery by the sample in 180 s after removal of load, and the rheological parameters were calculated from the creep curves using the Burger's model [9, 22, 33].

$$J(t) = J_0 + J_1\left(1 - \exp\left(\frac{t}{\lambda}\right)\right) + \frac{t}{\eta_0}, \text{ for the creep phase} \qquad (14)$$

$$J(t) = J_{max} - J_0 - J_1\left(1 - \exp\left(-\frac{t}{\lambda}\right)\right), \text{ for the recovery phase;} \qquad (15)$$

Increasing percentages of added carob flour resulted in an increase in η_0 and a decrease in J_1 for the rice flour doughs with the same level of water, suggesting a decrease in the flowability and an increase in the elasticity of dough samples with carob flour addition, respectively. On the other hand, increasing levels of water resulted in an increase in J_1 suggesting a more viscous-dominant non-linear behavior for the rice flour dough samples with carob flour. Therefore, the simultaneously increasing levels of added carob flour and water were suggested to contribute to the viscoelasticity of rice flour doughs [33]. Since a balance between the viscous (extensibility) and elastic (resistance to extension) components of dough samples is required for improved baked product quality [4, 72], too high and too low J_1 values for dough samples are associated with poor breadmaking quality. Rice flour doughs with carob/water ratios of 10:100, 15:130, and 15:140 (w/v) were found to have medium J_1 values, thus they were suggested to produce gluten-free bread with acceptable loaf volume and crumb characteristics due to their well-balanced viscous to elastic nature [33]. Rice flour dough with 110% water (on flour weight basis, w/v) was found to show a more viscous non-linear behavior compared to soft wheat flour dough obtained at 500 BU Farinograph consistency as evidenced by the wider elastic Lissajous-Bowditch curves (stress–strain loops) obtained for the rice flour dough at large strains [4]. This was the opposite of the viscoelastic behavior characterized for rice flour cookie dough in the linear region by Hadnađev et al. [61], as lower tan δ values suggesting higher elasticity were found for rice flour dough when compared to wheat flour dough (Table 2). This can be attributed to the differences in the formulations of these rice flour-based dough systems and to the differences in the methodologies of fundamental rheological tests conducted in the linear and non-linear regions. When the material enters the non-linear viscoelastic region, its 3-D structure starts to deform due to being exposed to large strains. Therefore, the viscoelastic behavior starts to become more viscous-like in the non-linear region compared to that observed in the linear region [11]. And the degree of viscous decay observed in the viscoelastic behavior during the transition from linearity to non-linearity depends on the networking abilities of the material. Thus, the findings of Hadnađev et al. [61] and Yazar et al. [4] highlighted the weaker networking in rice flour doughs compared to wheat flour doughs. Elastic Chebyshev coefficients obtained by the LAOS testing (γ: 0.01–200%, ω: 0.1, 1, 10 rad/s) pointed out a higher degree of intracycle strain stiffening ($e_3/e_1 > 0$) for rice flour dough compared to soft wheat flour dough and other gluten-free flour (soy, quinoa, buckwheat flours) doughs mixed at their optimum water absorption levels, which explained the lowest loaf volume obtained for rice bread [4]. Strain stiffening is an important phenomenon that affects loaf volume in fermented baked products. During proving, protein-starch matrix surrounding the gas cells expands biaxially to large strains (> 100%) due to increasing pressure in the gas cells by the diffusion of CO_2. This causes the thinning of the gas cell walls, and if the gas cell continues to expand, it may rupture, leading to CO_2 release from the dough and thus to a lower loaf volume. Strain hardening can be defined as the stress response of the gas cell walls or the surrounding protein-starch matrix against deformation, that prevents the gas cells from rupturing. However, a decrease in loaf volume is observed, if the strain stiffening behavior of a dough system is above or below the "optimum" which is basically defined by the balance between the viscous and elastic characteristics of the dough [4, 72, 73]. High strain stiffening of rice flour dough was attributed to starch playing the dominant role in the deformation and stiffening of the dough and to the poor deformation quality of the proteins in rice flour [4]. Therefore, the addition of carob flour into rice flour-based dough systems may improve gluten-free bread quality by contributing to the elasticity of dough systems, as suggested by Tsatsaragkou et al. [33]. On the other hand, partial replacement of rice flour with buckwheat flour (90:10, 80:20, 70:30 rice flour:buckwheat flour, w/w) resulted in an increase in J_{max} and a decrease in η_0 (creep phase: 50 Pa for 300 s, recovery phase: 0 Pa for 900 s), indicating a decrease in cookie dough elasticity [61], in contrast to the non-linear response reported for the rice flour dough with carob flour by Tsatsaragkou et al. [33]. Since high elasticity in cookie doughs was associated with poor spreading during baking, reduced cookie diameter and harder texture [74], partial replacement of rice flour with buckwheat flour was suggested to contribute to gluten-free cookie quality [61]. Lubricated squeezing flow tests revealed an increase in the extensional viscosity of rice flour-based cookie doughs when rice flour was replaced with chestnut flour, suggesting an increased resistance to deformation in cookie doughs with increasing chestnut flour levels. Replacement of rice flour with high levels of chestnut flour, especially above 40% (w/w), was found to decrease the spread ratio of cookies. So, the high extensional viscosity of rice-chestnut flour doughs was associated with a decrease in cookie diameter. The change in the extensional viscosities of cookie doughs was attributed to the higher fiber content of chestnut flour (9.5%) compared to rice flour (2.5%). The use of fibers was suggested to increase extensional viscosity by causing entanglements and increasing water absorption in the dough [36].

Villanueva et al. [37] studied the non-linear rheological properties of maize starch doughs with tef flour added at different percentages (0:100, 50:50, 75:25, 100:0 maize starch:tef flour, w/w) by conducting creep recovery tests (creep phase: 100 Pa for 60 s, recovery phase: 0 Pa for 200 s). J_0 and J_1 values both for creep and recovery phases were lower, while the recovery ratios (%) were higher for the dough samples that had 100% and 75% tef flour, suggesting a more elastic non-linear viscoelastic behavior for the dough samples with high percentages of tef flour compared to dough samples with 100% maize starch and 50:50 (w/w) maize starch:tef flour. Burger's model parameters indicated the lowest elasticity for the dough with 100% maize starch [37]. Similarly, Frederici et al. [75] also applied a stress of 100 Pa for the creep phase and reported a lower elasticity for maize starch based zein-starch dough in the non-linear region, when compared to rice starch based zein-starch dough. Unlike the gluten-free dough systems studied by Villanueva et al. [37], Frederici et al. [75] studied protein-starch based dough systems and they attributed the lower elasticity obtained for the maize starch dough in the non-linear region to the larger particle size of maize starch compared to rice starch, which possibly interrupted the protein-starch matrix under large deformations. On the other hand, Villanueva et al. [37] attributed the higher elasticity obtained in the non-linear region for tef flour-based doughs compared to maize starch-based doughs to the higher water absorption capacity of tef flour due its higher protein and fiber content. The resulting bread samples with 100% and 75% tef flour had lower loaf volumes, while the bread with 100% maize starch had deficiencies in the crumb structure even though it had the highest loaf volume. Dough samples with 50:50 tef flour:maize starch blend resulted in breads with higher loaf volume compared to the breads with higher levels of tef flour and with improved crumb structure compared to 100% maize starch breads. A positive correlation between J_1 obtained in the recovery phase and loaf volume (r = 0.73) was found pointing out to the impact of the balance of elastic to viscous characteristics of the dough on bread loaf volume [37], as also suggested by Tsatsaragkou et al. [33]. Findings of both Frederici et al. [75] and Villanueva et al. [37] indicated the need to pair maize starch with other ingredients to improve its breadmaking quality, as maize starch alone failed to impart the required viscoelasticity to dough.

Alternative heating technologies such as heat moisture treatment, alkaline heating treatment, etc. have been proposed to improve the viscoelastic behavior and breadmaking performance of gluten-free doughs. Villanueva et al. [76] studied the impact of microwave assisted heat-moisture treatment on the non-linear rheological behavior of rice flour doughs with creep-recovery tests (creep phase: 50 Pa for 50 s, recovery phase: 0 Pa for 200 s). Rice flours with initial moisture contents of 20% and 30% (on a flour weight basis) were exposed to microwave heating for 8 min (sample temperature reaches 157.5 °C) and blended with native rice flour at replacement ratios of 30% and 50% (w/w). Rice flour with 30% initial moisture blended at 30% and 50% (w/w) showed the highest elastic non-linear behavior and the recovery capacities of doughs increased 67% and 170%, respectively, when compared to control. Addition of heat-moisture treated rice flours at both concentrations resulted in higher loaf volume and softer crumb texture in rice flour breads, indicating the contribution of increased elasticity to the non-linear rheological properties of rice flour dough to bread quality [76], as also suggested by Tsatsaragkou et al. [33]. Alvarez-Ramirez et al. [77] studied the non-linear viscoelastic properties of nixtamalized corn masa (37% water, on total weight basis) with LAOS tests (γ: 0.01%- 1000%, ω: 0.1 Hz, 1 Hz, 10 Hz). Nixtamalization is a lime-based alkaline heating process that involves the cooking of corn kernels in water with up to 2% $Ca(OH)_2$ (on a corn weight basis) and steeping for 12–20 h. Nixtamalized grains are either washed and stone-milled or extruded to obtain corn masa, or they are dried and ground into nixtamalized corn flour to be used for the production of tortillas, tortilla chips, and tamales [78, 79]. Rheological testing conducted in the linear region defined extruded corn masa as a solid-like ($G' > G''$) viscoelastic material [80]. The poor breadmaking characteristics of corn flour due to its low protein content resulting in a weak viscoelastic network and gas retention capacity were suggested to be improved by the heating process and the presence of calcium as it promoted crosslinking of starch chains and their interaction with proteins and lipids [80, 81]. Alvarez-Ramirez et al. [77] characterized the viscoelastic properties of corn masa in the non-linear region to bring a deeper insight into the viscoelastic behavior defined in the linear region (Table 2 and found the onset of non-linearity for corn masa [nixtamalized corn flour:water (63:37, w/v] to occur at around the strain amplitude of 1%. Decreasing G' along with G'' overshoot at the onset of non-linearity indicated type III non-linear behavior for corn masa [77], which was described as *weak strain overshoot* by Hyun et al. [82]. Positive S ($S > 0$) values obtained throughout the studied strain range indicated strain stiffening behavior for corn masa in the non-linear region, while negative T ($T < 0$) values suggested shear thinning behavior. The degree of strain stiffening behavior started to decrease above the strain amplitude of 60–80% [77]. Similar strain stiffening and shear thinning behavior trends were also found for wheat flour dough with the LAOS testing [14, 15], which suggests a similar viscoelastic response for corn masa under large deformations to that of wheat flour dough. However, the extents of strain stiffening and shear thinning behaviors defined through S and T values for corn masa [77] were higher compared to those determined for wheat flour doughs [14, 15].

Other studies focused on the comparison of the non-linear behaviors of different gluten-free flours. Moreira et al. [27] compared the non-linear rheological properties of white, yellow, and purple maize flour doughs with the creep recovery tests (creep phase: 50 Pa for 60 s, recovery phase: 0 Pa for 180 s, T: 30 °C). Under the same milling conditions, white maize flour had a higher average particle size, higher starch damage, and water absorption capacity, indicating a harder endosperm texture, when compared to yellow and purple maize flours. In the creep recovery tests, white maize flour dough had the highest J_1 among the other maize flours milled under the same conditions. A linear correlation was found between J_1, J_{max} and water absorption values ($R^2 > 0.94$) of maize flour dough. Besides, increasing starch damage in maize flours resulted in increasing J_1, indicating the impact of starch damage on the viscoelastic behaviors of maize flour doughs. The highest J_R/J_{max} value was obtained for white maize flour dough (87.6%), followed by purple maize flour dough (86.5%) and yellow maize flour dough (83.1%), suggesting the lowest elasticity for yellow maize flour dough. A lower J_R/J_{max} value was reported for wheat flour dough (65%), which indicated that the non-linear viscoelastic behavior of maize flour doughs should be improved for better breadmaking quality. Optimization of milling parameters depending on kernel hardness was suggested as a tool to control the non-linear viscoelastic properties of maize flour doughs [27]. Non-linear rheological properties of rice, buckwheat, soy, and quinoa flour doughs were studied with the LAOS technique (γ: 0.01–200%, ω: 0.1, 1, 10 rad/s, T: 25 °C) and compared to those of soft wheat flour dough [4]. For the most accurate comparison, dough samples were obtained at the same viscosity by adding different levels of water (110%, 90%, 85%, and 160% for rice flour, buckwheat flour, quinoa flour, and soy flour, respectively) and this was ensured by the overlapping η^* values on frequency sweeps. The onset of non-linearity was found to occur at around 1.6% of strain for all gluten-free dough samples [4], which was similar to the value (1%) reported for corn masa [77]. Soft wheat flour dough (Fig. 2a) and soy flour dough (Fig. 2b) showed the highest elastic-dominated viscoelastic non-linear behavior, when compared to the rest of the gluten-free doughs (Fig. 2c, d, and e, as evidenced by the narrower trajectories obtained for the elastic Lissajous-Bowditch curves at large strain amplitudes (outer loops. In the nonlinear region, the order of increasing elastic behavior was found to be as follows; rice dough < buckwheat dough < quinoa dough < soy dough < soft wheat flour dough. A similar order was also found for the loaf volumes of the resulting breads (Fig. 3), indicating the impact of dough

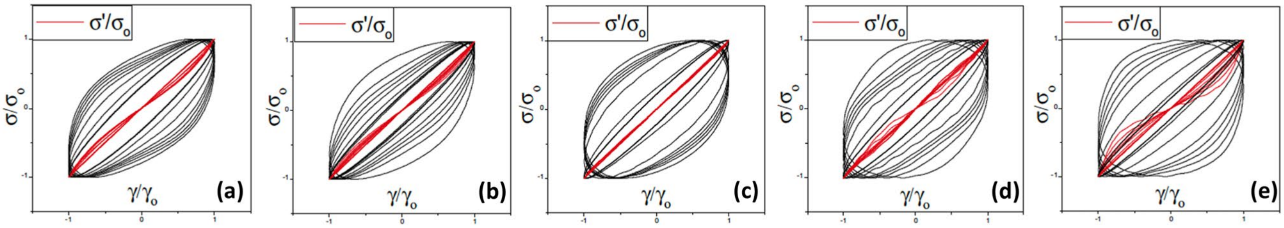


Fig. 2 Elastic Lissajous Bowditch curves (*g*: 0.01–200%, *w*: 10 rad/s) for dough samples with **a** soft wheat flour, **b** soy flour, **c** quinoa flour, **d** buckwheat flour, **e** rice flour. Reproduced from Yazar et al. [4] with permission from the publisher

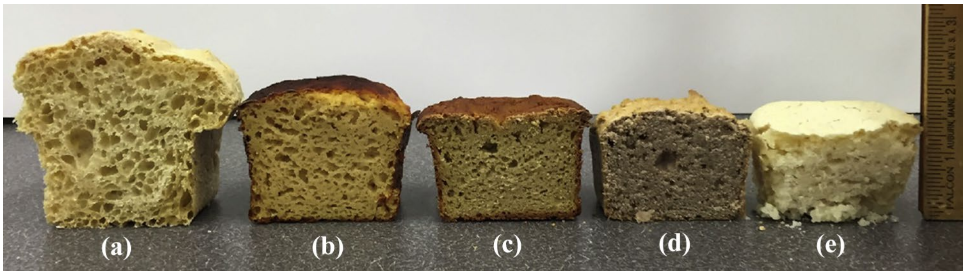


Fig. 3 Cross-sections of gluten-free breads with **a** soft wheat flour, **b** soy flour, **c** quinoa flour, **d** buckwheat flour, **e** rice flour. Reproduced from Yazar et al. [4] with permission from the publisher

elasticity probed by the Lissajous-Bowditch curves in the non-linear region on loaf volume.

The closer elasticity observed for soy flour dough in the non-linear region to that for wheat flour dough was suggested to be due to the similarities between soy (2S, 7S, 11S) proteins and wheat proteins (albumins-globulins, gliadin, glutenin). Besides, the higher elasticity in soy flour dough when compared to other gluten-free doughs was attributed to the higher protein content of soy flour (~46%) than the protein contents of rice (6–8%), buckwheat (~12%) and quinoa (~15%) flours.

LAOS parameters were further used to correlate the non-linear viscoelastic properties of gluten-free doughs to the loaf volumes of the resulting breads. A positive correlation was found between G'_L ($\mathrm{R}^2 = 0.58$), G'_M ($\mathrm{R}^2 = 0.74$) values of gluten-free flour doughs (at γ:200%, ω:10 rad/s) and the resulting gluten-free breads. e and v Chebyshev coefficients, especially e_3/e_1 and v_3/v_1, were also suggested to help predict the loaf volume [4], as the signs of the third-order harmonics indicate the driving cause of the deviation from linearity [11, 71]. Rice flour dough had the highest e_3/e_1 value, indicating the highest strain stiffening behavior (Table 2). Quinoa flour dough had the lowest positive e_3/e_1 values, while buckwheat flour dough showed strain softening ($e_3/e_1 < 0$) at large strains. Thus, the resulting breads obtained from rice flour (Fig. 3e), buckwheat flour (Fig. 3d), and quinoa flour (Fig. 3c) had lower loaf volumes. On the other hand, soy flour dough showed a similar degree of strain stiffening behavior to that of wheat flour dough. However, the strain stiffening behavior of soy flour dough showed a constant increase as the amplitude of strain increased ($e_3/e_1 > 0$), while the increasing strain stiffening behavior of wheat flour dough was followed by a decrease ($e_3/e_1 > 0$) against the increasing deformation. The decreasing strain stiffening behavior of wheat flour dough under large deformations was suggested to be the origin of the higher gas retention capacity of wheat flour doughs that was attributed to the unique viscoelastic properties of gluten network. As a result, the highest loaf volume was obtained for soft wheat flour bread (Fig. 3a), while soy flour bread had the second highest loaf volume (Fig. 3b). These findings highlighted the impact of strain stiffening behavior of viscoelastic dough systems under large deformations on breadmaking quality and suggested LAOS as a tool to develop gluten-free baked products with improved quality [4].

Non-linear Rheological Properties of Gluten-free Dough Systems: Impact of Non-Gluten Proteins

Villanueva et al. [56] evaluated the impact of caseinate, and soy protein isolate on the non-linear rheological properties of wheat starch, corn starch, tapioca starch and potato starch-based bread dough samples. For this purpose, they conducted creep recovery tests in the non-linear viscoelastic region at 25 °C by applying a constant stress of 50 Pa for 60 s and then allowing the dough samples to recover for 180 s after the stress was removed. They reported a decrease in the maximum compliance and an increase in the zero-shear viscosity values of gluten-free doughs with the addition of proteins (5% on a starch + protein weight basis, w/w), especially for corn and potato starch-based doughs with added soy protein isolate [56]. Lower creep compliance is associated with elasticity due to the lack of configurational rearrangements in solid-like materials under deformation [7]. Therefore, the creep recovery tests conducted in the non-linear region revealed an increase in the elasticity of gluten-free doughs with added proteins. The recovery (%) values obtained in the non-linear region were lower than those obtained in the linear region, except for potato starch dough (Table 2). The recovery values remained the same for potato starch dough in both linear and non-linear regions, suggesting higher stability for potato starch dough against the applied deformations when compared to other gluten-free dough samples [56]. On the other hand, Mi et al. [83] conducted creep recovery tests on mung bean starch dough with added fish actomyosin at 25 °C with a shear stress of 50 Pa applied for 50 s followed by a recovery phase for 150 s and reported an increase in J_{max} and a decrease in η_0. These results indicated an increased fluidity of the dough with the addition of fish actomyosin. And this was attributed to the interruption of the starch-gel network [dry starch:water (3:7, w/w) + binder paste (starch mixed with boiling water, 3:2 starch:water w/w)] by added protein (10–50% on total dough weight basis). The increased fluidity and improved softness in the starch dough with added fish actomyosin was suggested to facilitate the extrusion process for starch noodle production. Since improved dough handling properties are achieved with both flow resistance and the ability to recover after deformation, the starch dough with 30% actomyosin (on total dough weight basis, w/w) was suggested to have the ideal non-linear rheological properties. Frederici et al. [75] studied the impact of extruded zein (at temperatures ranging from 90 to 160 °C) on the non-linear rheological properties of rice, potato, and maize starch-based doughs (15:85, zein:starch, w/w) with creep recovery tests conducted at 35 °C. Gluten-free dough samples were prepared with water at 50 °C using the optimum water absorption levels determined for each starch-zein blend (87.5% for the rice starch-zein blend, 70% for the maize starch-zein blend, and 72.5% for the potato starch-zein blend). A constant stress of 100 Pa was applied for 150 s followed by a recovery period for 150 s to compare the non-linear rheological properties of these gluten-free doughs to wheat flour dough. The compliance values were determined and described by the rheological model expressed by the following equation:

$$J(t) = \frac{1}{\Gamma(\alpha+1)}\left[\lambda_1 t^{\alpha} H(t) - \lambda_2 \left(t - t_m\right)^{\alpha} H\left(t - t_m\right)\right] \tag{16}$$

The non-linear rheological properties were evaluated using the parameters α, λ_1, λ_2 [75]. λ_1 and λ_2 are associated with the structure of the sample and the difference between these parameters (λ_1–λ_2) indicates the capacity of the sample to retain viscoelastic properties after deformation. α values range from 0 to 1 and 0 indicates pure elastic behavior, while 1 indicates pure viscous behavior [84]. The lowest α value was obtained for the rice dough with extruded zein, suggesting a higher elasticity for the rice-extruded zein dough that was comparable to that of wheat flour dough under large deformations. This was attributed to the smaller granule size of rice starch (3–8 μm) compared to maize (1–20 μm) and potato (15–110 μm) starches, which might have favored the formation of a more continuous protein matrix leading to higher elasticity. Tandazo et al. [3] also found rice starch to improve the resistance of zein dough to extensional deformation as evident by the high extensional viscosity obtained for rice starch-zein dough that was similar to that obtained for benchmark wheat gluten dough in the lubricated squeezing flow tests (strain rate: 40 s^{-1}, total biaxial strain: 90%). They suggested coupling rice starch-zein doughs with co-proteins (i.e., casein, sodium caseinate) to further improve the viscoelastic properties of rice starch-zein doughs, as co-protein addition (5% of total protein, w/w) increased the elasticity of rice starch (90%, w/w)-zein (10%, w/w) doughs when mixed at room temperature (Table 2). The presence of a co-protein was reported to transform the secondary structure of zein to higher β-sheet content [3] and this change was associated with the formation of a viscoelastic dough system [85]. Therefore, the networking capabilities imparted by the addition of rice starch and co-protein were suggested to improve the gas retention capacity of zein doughs [3].

The temperature used for zein extrusion was also found to affect the non-linear rheological properties of starch-zein doughs, as evidenced by the decreasing α values (increased elasticity) obtained for starch doughs with added zein extruded at 160 °C. This increase in elasticity was linked to increased molecular weight of zein upon extrusion at temperatures above 150 °C and it was suggested to contribute to breadmaking quality as high molecular weight glutenins [75]. Besides the extrusion temperature, the extrusion cooking process itself was suggested to free protein bodies in maize and free α-zein was suggested to form fibrils. These fibrils were found to be responsible for the viscoelasticity of zein-starch doughs [85]. The SEM images obtained for unextruded and extruded zein samples in the study of Frederici et al. [75] indicated fibrous structures in extruded zein. On the other hand, commercial zein that is essentially α-zein is also known to form an extensive network of fibrils when mixed with starch and water at a temperature above its glass transition temperature [85]. Therefore, Frederici et al. [75] stated that both extrusion of zein and starch-zein dough mixing at 35 °C might have contributed to the formation of fibrils.

Studies conducted in the last decade mostly focused on the application of creep recovery tests to evaluate the impact of non-gluten proteins on the non-linear rheological properties of gluten-free doughs. Non-linear creep recovery tests showed that the responses of gluten-free doughs with added proteins to deformation varied depending on the source and particle size distribution of starch granules, type of protein, and processing conditions such as temperature.

Non-linear Rheological Properties of Gluten-free Dough Systems: Impact of Hydrocolloids and Dietary Fiber

The effect of HPMC and oat bran rich in β-glucan (Oatwell, 28% β-glucan instant) on the non-linear rheological properties of maize starch:zein (8:2, w/w) dough was studied by Andersson et al. [86]. The extensional properties of gluten-free doughs with added hydrocolloids (2% on starch-zein weight basis, w/w) were determined with the hyperbolic contraction flow tests (T: 40 °C, $\dot{\gamma}$: 0.55, 1.10, 2.19, 4.39 s^{-1}) and compared with the results obtained for wheat flour dough. The dough samples with HPMC had the highest elongational viscosity, suggesting the highest resistance to extensional deformation (dough stretching). Strain hardening index was calculated using the stress versus time plots and it was above 1 for all dough samples above the strain rate of 1.10 s^{-1} indicating strain hardening behavior. At the highest strain rate applied, gluten-free dough with HPMC showed a higher degree of strain hardening (2.39) compared to the one with β-glucan (2.06), while wheat flour dough (1.38) had the lowest degree of strain hardening [86]. Gluten-free flour doughs with higher degree of strain stiffening compared to that of wheat flour dough were found to result in breads with lower loaf volume [4]. A comparison of the loaf volumes of gluten-free breads and wheat flour bread was not provided by Andersson et al. [86]. Addition of hydrocolloids was suggested to improve the extensional properties of starch-zein doughs, as hyperbolic contraction test could not be conducted on starch-zein dough without hydrocolloids due to its high stiffness. Hydrocolloids were suggested to affect zein microstructure by enabling the formation of finer zein fibrils during mixing [86], which were suggested to contribute to the viscoelasticity of zein doughs [85]. Even though, the extensional properties of starch-zein doughs with HPMC and β-glucan were similar, the resulting breads were significantly different in terms of loaf volume and gas cell size and distribution. The addition of HPMC resulted in higher loaf volume with a finer crumb, and this was attributed to the surface-active characteristics of HPMC that might have contributed to gas cell stabilization in the starch-zein matrix. The higher strain stiffening of starch-zein doughs with HPMC was associated with the finer crumb and even gas cell size distribution in the resulting bread [86]. On the other hand, the addition of HPMC into chestnut flour-based gluten-free dough was reported to soften the dough as evidenced by the decrease in apparent viscosity, G' and G'' values obtained by the frequency sweeps in the linear region; while resulting in an increase in elasticity according to the creep-recovery tests conducted in the non-linear region (σ: 50 Pa for 60 s) [5]. This shows that gluten-free dough samples might develop resistance to deformation under large deformations, even though they had viscous-like properties when the applied deformation was small. In the non-linear creep recovery tests, the ratio of J_R to J_{max} was suggested to give information about the elasticity of dough systems. The addition of HPMC (0.5%, 1%, 1.5%, 2% on a flour weight basis, w/w) into chestnut flour dough with 4% (on a flour weight basis, w/w) chia flour resulted in a gradual increase in J_R/J_{max}, indicating an improved elasticity with HPMC addition. The highest elasticity was obtained with 2% HPMC addition with a J_R/J_{max} value of 64.8%, while chestnut flour dough had a J_R/J_{max} value of 22.3%. The results obtained by Andersson et al. [86] and Moreira et al. [5] pointed out two different resulting effects of HPMC addition on the non-linear rheological properties of gluten-free dough systems. This could be due to the interactions between HPMC and different gluten-free flours and the differences in the responses of different gluten-free flour doughs under large deformations. Starch granules were suggested to adhere to one another in the presence of HPMC, and their mobility was suggested to depend on the surface characteristics, shape, and size. Due to these differences, doughs prepared with different starches (wheat, corn, tapioca, sweet potato, potato starches) and HPMC showed different viscoelastic behaviors in the non-linear creep recovery tests (creep phase: 250 Pa for 300 s, recovery phase: 0 Pa for 300 s). The highest J_{max} was found for potato starch-HPMC dough, followed by sweet potato starch-HPMC, tapioca starch-HPMC, corn starch-HPMC, and wheat starch-HPMC doughs [87]. Potato starch-based gluten-free doughs were also found to show the lowest elastic behavior in the non-linear region by Frederici et al. [75]. Among the chemically synthesized and biosynthetic hydrocolloids, HPMC was found to perform the best in terms of improving the viscoelastic properties of gluten-free dough systems and thus baked product quality [6]. Therefore, studies evaluating the impact of hydrocolloids on the non-linear rheological properties of gluten-free doughs have mostly focused on HPMC. In addition to HPMC, Moreira et al. [5] also studied the impact of guar gum and tragacanth gum additions into chestnut-chia flour doughs on non-linear rheological properties. The elasticity imparted by guar gum started to decrease when added above 1%. Tragacanth gum was only tested at 0.5% and 1% addition levels, and it resulted in similar J_R/J_{max} values to that of chestnut-chia flour dough. So, the lowest elasticity was obtained for the gluten-free doughs with tragacanth gum as a result of creep recovery tests, while HMPC at 2% and guar gum at 1% provided the best results by decreasing the viscosity and increasing dough stability and elasticity. Hadnađev et al. [61] evaluated the impact of CMC addition on the non-linear rheological properties of gluten-free cookie doughs with rice flour-buckwheat flour blends (90:10, 80:20, 70:30 rice flour:buckwheat flour, w/w). The addition of CMC led to a decrease in J_{max} and an increase in η_0 suggesting an increase in dough elasticity. CMC was considered to increase the water absorption level in the dough, which led to an increase in dough consistency. Rice flour cookie doughs with 20% and 30% buckwheat flour and CMC showed similar J_{max}, η_0, and recovered deformation (J_R/J_{max}) values to those of wheat flour cookie dough. Addition of buckwheat flour into rice flour dough resulted in a softer and more deformable dough compared to rice flour dough, while the addition of CMC increased dough strength and produced gluten-free cookie doughs with similar non-linear rheological properties to wheat flour dough that was able to resist sheeting without sticking to rollers and to retain its shape after sheeting [61]. Improved elasticity in this cookie dough with CMC addition was also found in the linear region, as evident by the increase in G' (Table 2). The elasticity imparted by CMC was also maintained under large deformations, indicating the contribution of CMC to cookie dough stability. High elasticity in cookie doughs is known to result in shrinkage after sheeting and to affect cookie diameter and texture [88, 89]. So, the addition of buckwheat flour and CMC was suggested to bring this desired balance between viscous and elastic properties to rice flour cookie doughs, which improved dough handling properties and cookie quality [61]. Pérez-Quirce et al. [90] studied the impact of high- (HMW), medium- (MMW), and low-molecular weight (LMW) β-glucan concentrates on the non-linear rheological properties of rice flour-based gluten-free bread doughs that also contained HPMC in the control formula. For this purpose, they conducted creep recovery tests with a shear stress of 50 Pa applied for 60 s followed by a 180 s of recovery phase and tested the impact of β-glucan concentrates at three different levels (1.3%, 2.6%, 3.9% on rice flour basis, w/w). A decrease was observed in J_{max} as the level of added β-glucan increased; whereas 2.4 kPa.s of η_0 value obtained for control increased to 376 kPa.s for the highest level of added HMW β-glucan. When the stress was released, the recovery of 7.6% obtained for control increased to 73% for the gluten-free dough with the highest level of added HMW β-glucan. These creep recovery data revealed that the addition of HMW β-glucan resulted in the highest elasticity in gluten-free doughs, leading to a decrease in the loaf volume of the resulting bread (Fig. 4d) compared to control (Fig. 4a). Gluten-free dough samples with LMW β-glucan showed higher recovery compared to the samples with MMW β-glucan. Thus, bread with LMW β-glucan (Fig. 4b) had a lower loaf volume compared to the bread with MMW (Fig. 4c). However, the loaf volume of the bread with LMW β-glucan was also lower than that with HMW β-glucan, even though the dough with HMW β-glucan showed the highest elasticity under large deformations. This was attributed to the higher gelation capacity of LMW β-glucan concentrates. Therefore, a negative correlation between the percentage of compliance recovery and bread specific volume ($p < 0.05$; $r = -0.70$) was reported. The use of HMW β-glucan concentrates was found feasible to produce gluten-free baked products due to their hypoglycemic effects and their contribution to dough elasticity that produces gluten-free breads with acceptable quality attributes.

Ozyigit et al. [91] studied the impact of orange fiber and orange pomace powder (at replacement values of 4%, 8%, 12%, and 16% on buckwheat flour weight basis, w/w) on the non-linear rheological properties of rice-buckwheat flour (80:20 rice:buckwheat flour) based cake batter using the LAOS tests (γ: 0.01%–300%, ω: 10 rad/s, T: 25 °C). LAOS sweeps indicated higher G' and G'' values for the batter with orange pomace powder compared to control and the batter with orange fiber, suggesting a higher apparent viscosity for the batter with orange pomace powder. All gluten-free batters showed shear thinning behavior in the non-linear region as evidenced by the viscous Chebyshev coefficients ($v_3/v_1 < 0$). Batter samples with added fibers showed a higher degree of strain stiffening ($e_3/e_1 > 0$) up to 100% strain amplitude when compared to control, which was evident by the lowest magnitude of e_3/e_1 obtained for control. The addition of orange pomace powder resulted in a higher degree of strain stiffening. The transition from strain stiffening to strain softening behavior was observed at higher strain amplitudes for the gluten-free batters with fibers added at 12% and 16%. The highest cake volume was obtained for the gluten-free cake with 16% orange pomace powder (2.52 cm^3/g), while the control cake had the lowest specific volume (1.58 cm^3/g). LAOS sweep data and elastic Chebyshev coefficients seem to be well correlated with cake volume [91], as they are also suggested to be correlated with bread loaf volume [4]. Increased strain stiffening observed under large deformations for gluten-free batters with fibers was associated with the formation of complex microstructures due to the interactions between fibers and gluten-free flour components. And these interactions were suggested to enable the retention of more chemical leavening gases in the batter during baking, which led to higher cake volume [91]. Gas retention capacity and bubble expansion in gluten-free dough systems were suggested to depend on the ingredients and the processing parameters. Several techniques, that monitor dough volume, have been developed to determine the gas retention capacity, as the stabilization of air bubbles in gluten-free dough systems through strain stiffening was unknown [92]. LAOS parameters enabled prediction of specific volume through the strain stiffening behavior of

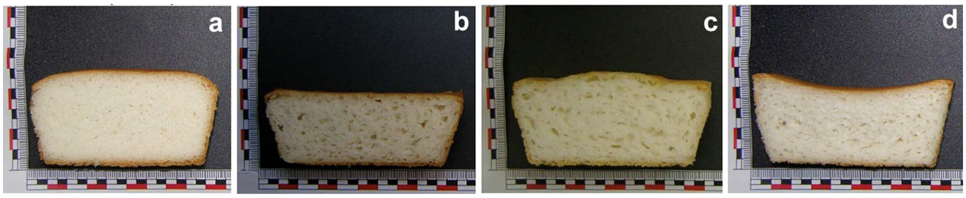


Fig. 4 Cross-sections of gluten-free breads with the highest level (3.9 g/ 100 g rice flour) of added b-glucan concentrates: **a** control (rice flour with 0% b-glucan), **b** LMW b-glucan, **c** MMW b-glucan, **d** HMW b-glucan. Reproduced with permission from Pérez-Quirce et al. [90]

gluten-free dough/batter systems under large deformations [4, 91].

Conclusion

Fundamental rheological tests conducted in the linear and non-linear regions enabled the full characterization of gluten-free dough systems under small and large deformations that are similar to those applied during processing. SAOS tests pointed out a more viscous behavior for rice flour doughs, as evident by the lower G' obtained for rice flour doughs when compared to other gluten-free flour doughs. To improve elasticity in such gluten-free doughs, fiber-rich gluten-free flours were blended with rice flour. On the other hand, LAOS tests indicated the highest strain stiffening behavior for rice flour dough when compared to other gluten-free flour doughs and wheat flour dough. As G' and strain stiffening behaviors of doughs were highly correlated with loaf volume, both SAOS and LAOS parameters were found to collectively explain the low loaf volume obtained for rice flour bread. These linear and non-linear viscoelastic properties determined for doughs with gluten-free flours blended at different ratios indicated the need for an adjustment in the added water level, especially if the baked product was gluten-free bread. The product-specific balance of elastic to viscous response in gluten-free doughs could be achieved by blending different gluten-free flours/starches at different ratios.

Fundamental rheological tests showed that the responses of these dough systems to deformation varied depending on the source and particle size distribution of starch granules, processing conditions such as temperature, and type of protein. Zein proteins, for instance, were reported to contribute to the elasticity of gluten-free doughs when dough mixing was conducted at temperatures above its glass transition temperature (~35 °C) or when added upon being extruded at high temperatures. On the other hand, other non-gluten proteins such as caseinate, and soy protein isolate, were found to increase the elasticity of starch-based gluten-free doughs at room temperature, while fish actomyosin caused a decrease in elasticity. Besides, rice starch was found to promote the formation of a more continuous zein protein matrix under large deformations due to its smaller granule size when compared to corn and potato starches.

The addition of hydrocolloids and dietary fibers was generally found to increase the elasticity of gluten-free dough systems under small and large deformations. However, for zein-based gluten-free dough systems, hydrocolloid addition was suggested to improve extensibility by contributing to viscous flow properties. The addition of chia flour and HPMC was found to soften the chestnut flour doughs in the linear region as evidenced by the decreasing apparent viscosity, G' and G'', while non-linear creep recovery tests pointed out to a higher recovery ratio due to increasing elasticity under large deformations. This shows that the addition of different ingredients to gluten-free doughs might result in different viscoelastic responses under small and large deformations, while the relative viscoelastic response of a certain gluten-free dough system could vary in the linear and non-linear regions due to differences in the networking abilities (stability) of doughs against small and large deformations. Besides, dietary fibers were reported to impart different non-linear rheological behaviors to gluten-free dough systems depending on their molecular weights, leading to differences in the resulting gluten-free baked products' quality.

All these findings unraveled the contribution of different gluten-free flours/starches, or structure-building ingredients such as non-gluten proteins, hydrocolloids, or fibers to gluten-free baked product quality through the fundamental rheological parameters defined in the linear and non-linear viscoelastic region.

Perspectives

- Empirical dough testing methods were designed to measure wheat flour quality, and these methods require adjustments to be made for the analysis of gluten-free doughs. Therefore, fundamental rheological testing methods should be considered as alternatives in future studies to predict gluten-free baked product quality in a more accurate manner.
- Dough processing involves small (i.e., resting) and large deformations (i.e., mixing, proofing, and baking) and the dough's response to these deformations determines baked product quality. For this reason, future studies to improve gluten-free baked product quality should focus on the rheological properties of gluten-free dough systems both in the linear and non-linear regions to get a full characterization of the dough's viscoelastic behavior.
- Further studies should be conducted to unravel if linear or non-linear viscoelastic properties of gluten-free dough systems better correlate with baked product quality.
- There is a vast amount of study in literature regarding the characterization of linear viscoelastic properties of gluten-free dough systems. However, the number of studies conducting fundamental rheological testing on gluten-free dough systems in the non-linear region is limited. Therefore, more studies should be conducted to determine the viscoelastic behaviors of gluten-free doughs under large deformations.
- Studies in literature have mostly focused on the impact of gluten-free flours or starches, non-gluten proteins,

hydrocolloids, and fibers on the non-linear rheological properties of gluten-free doughs. Future studies should focus on the impact of other ingredients (i.e., enzymes, surfactants) on the viscoelastic properties of gluten-free dough systems under large deformations using fundamental rheological methods.

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Declarations

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References

1. Föste M, Verheyen C, Jekle M, Becker T (2020) Fibres of milling and fruit processing by-products in gluten-free bread making: A review of hydration properties, dough formation and quality improving strategies. Food Chem 306:125451. https://doi.org/10.1016/j.foodchem.2019.125451
2. Mert ID, Sumnu G, Sahin S (2016) Microstructure of gluten-free baked products. In: Sozer N (ed) Imaging technologies and data processing for food engineers, 1st edn. Springer, Cham, pp 197–242
3. Tandazo AS, Ozturk OK, Hamaker BR, Campanella OH (2021) Rice starch and co-proteins improve the rheological properties of zein dough. J Cereal Sci 102:103334. https://doi.org/10.1016/j.jcs.2021.103334
4. Yazar G, Duvarci O, Tavman S, Kokini JL (2017) Non-linear rheological behavior of gluten-free flour doughs and correlations of LAOS parameters with gluten-free bread properties. J Cereal Sci 74:28–36. https://doi.org/10.1016/j.jcs.2017.01.008
5. Moreira R, Chenlo F, Torres MD (2013) Effect of chia (*Sativa hispanica* L.) and hydrocolloids on the rheology of gluten-free doughs based on chestnut flour. LWT Food Sci Technol 50:160–166. https://doi.org/10.1016/j.lwt.2012.06.008
6. O'Shea N, Arendt E, Gallagher E (2014) State of the art in gluten-free research. J Food Sci 79(6):1067–1076. https://doi.org/10.1111/1750-3841.12479
7. Duvarci OC, Yazar G, Dogan H, Kokini JL (2019) Linear and non-linear rheological properties of foods. In: Heldman DR, Lund DB, Sabliov C (eds) Handbook of Food Engineering, 3rd edn. CRC Press, Boca Raton, pp 1–152
8. Malkin AY, Isayev AI (2006) Pressure corrections. Rheology: concepts, methods, and applications, 1st edn. ChemTac Publishing, Toronto, pp 253–320
9. Steffe JF (1996) Rheological Methods in Food Process Engineering, 2nd edn. Freeman Press, East Lansing, MI
10. Faubion JM, Hoseney RC (1990) The viscoelastic properties of wheat flour doughs. In: Faridi H, Faubion JM (eds) Dough Rheology and Baked Product Texture, 1st edn. Van Nostrand Reinhold, New York, pp 29–67
11. Yazar G, Caglar Duvarci O, Yildirim Erturk M, Kokini JL (2019) LAOS (Large Amplitude Oscillatory Shear) Applications for Semisolid Foods. In: Joyner H (ed) Rheology of Semisolid Foods, 1st edn. Springer, Cham, pp 97–131
12. Dus SJ, Kokini JL (1990) Prediction of the nonlinear viscoelastic properties of a hard wheat flour dough using the Bird-Carreau constitutive model. J Rheol 34:1069–1084. https://doi.org/10.1122/1.550110
13. Lefebvre J (2006) An outline of the non-linear viscoelastic behavior of wheat flour dough in shear. Rheol Acta 45:525–538. https://doi.org/10.1007/s00397-006-0093-3
14. Yazar G, Duvarci O, Tavman S, Kokini JL (2016) Effect of mixing on LAOS properties of hard wheat flour dough. J Food Eng 190:195–204. https://doi.org/10.1016/j.jfoodeng.2016.06.011
15. Yazar G, Duvarci O, Tavman S, Kokini JL (2016) Non-linear rheological properties of soft wheat flour dough at different stages of farinograph mixing. Appl Rheol 26:1–11. https://doi.org/10.3933/applrheol-26-52508
16. Menjivar JA (1990) Fundamental aspects of dough rheology. In: Faridi H, Faubion JM (eds) Dough Rheology and Baked Product Texture, 1st edn. Van Nostrand Reinhold, New York, pp 1–29
17. Dobraszczyk BJ, Morgenstern MP (2003) Rheology and the breadmaking process. J Cereal Sci 38:229–245. https://doi.org/10.1016/S0733-5210(03)00059-6
18. Demirkesen I, Mert B, Sumnu G, Sahin S (2010) Rheological properties of gluten-free bread formulations. J Food Eng 96(2):295–303. https://doi.org/10.1016/j.jfoodeng.2009.08.004
19. Moore MM, Schober TJ, Dockery P, Arendt EK (2004) Textural comparisons of gluten-free and wheat-based doughs, batters, and breads. Cereal Chem 81(5):567–575. https://doi.org/10.1094/CCHEM.2004.81.5.567
20. Demirkesen I, Mert B, Sumnu G, Sahin S (2010) Utilization of chestnut flour in gluten-free bread formulations. J Food Eng 101(3):329–336. https://doi.org/10.1016/j.jfoodeng.2010.07.017
21. Torbica A, Hadnađev M, Dapčević T (2010) Rheological, textural and sensory properties of gluten-free bread formulations based on rice and buckwheat flour. Food Hydrocoll 24(6–7):626–632. https://doi.org/10.1016/j.foodhyd.2010.03.004
22. Ronda F, Pérez-Quirce S, Villanueva M (2017) Rheological properties of gluten-free bread doughs: relationship with bread quality. In: Ahmed J, Ptaszek P, Basu S (eds) Advances in Food Rheology and Its Applications, Part II. Product Specific Studies in Rheology, 1st edn. Woodhead Publishing Series in Food Science, Technology and Nutrition, Cambridge, pp 297–334
23. Patil S, Sonawane SK, Mali M, Mhaske ST, Arya SS (2020) Pasting, viscoelastic and rheological characterization of gluten free (cereals, legume and underutilized) flours with reference to wheat flour. J Food Sci Technol 57(8):2960–2966. https://doi.org/10.1007/s13197-020-04328-2
24. Patil SP, Arya SS (2017) Nutritional, functional, phytochemical and structural characterization of gluten-free flours. Food Meas 1(3):1284–1294. https://doi.org/10.1007/s11694-017-9506-5
25. Bozdogan N, Kumcuoglu S, Tavman S (2019) Investigation of the effects of using quinoa flour on gluten-free cake batters and cake properties. J Food Sci Technol 56(2):683–694. https://doi.org/10.1007/s13197-018-3523-1
26. Ahmed J, Al-Attar H, Arfat YA (2016) Effect of particle size on compositional, functional, pasting and rheological properties of commercial water chestnut flour. Food Hydrocoll 52:888–895. https://doi.org/10.1016/j.foodhyd.2015.08.028
27. Moreira R, Chenlo F, Arufe S, Rubinos SN (2015) Physicochemical characterization of white, yellow and purple maize flours and rheological characterization of their doughs. J Food Sci Technol 52(12):7954–7963. https://doi.org/10.1007/s13197-015-1953-6
28. Scanlon MG, Dexter JE, Biliaderis CG (1988) Particle-size related physical properties of flour produced by smooth roll reduction of hard red spring wheat farina. Cereal Chem 65(6):486–492
29. Martínez MM, Gómez M (2017) Rheological and microstructural evolution of the most common gluten-free flours and starches

during bread fermentation and baking. J Food Eng 197:78–86. https://doi.org/10.1016/j.jfoodeng.2016.11.008
30. Waziiroh E, Bender D, Saric A, Jaeger H, Schoenlechner R (2021) Ohmic baking of gluten-free bread: role of starch and flour on batter properties. Appl Sci 11(14):6567. https://doi.org/10.3390/app11146567
31. Witczak M, Korus J, Ziobro R, Juszczak L (2019) Waxy starch as dough component and anti-staling agent in gluten-free bread. LWT Food Sci Technol 99:476–482. https://doi.org/10.1016/j.lwt.2018.10.009
32. Qin W, Lin Z, Wang A, Xiao T, He Y, Chen Z, Wang L, Liu L, Wang F, Tong LT (2021) Influence of damaged starch on the properties of rice flour and quality attributes of gluten-free rice bread. J Cereal Sci 101:103296. https://doi.org/10.1016/j.jcs.2021.103296
33. Tsatsaragkou K, Yiannopoulos S, Kontogiorgi A, Poulli E, Krokida M, Mandala I (2014) Effect of carob flour addition on the rheological properties of gluten-free breads. Food Bioproc Technol 7:868–876. https://doi.org/10.1007/s11947-013-1104-x
34. Beltrão Martins R, Nunes MC, Ferreira LMM, Peres JA, Barros AIRNA, Raymundo A (2020) Impact of acorn flour on gluten-free dough rheology properties. Foods 9(5):560. https://doi.org/10.3390/foods9050560
35. Korus J, Witczak M, Ziobro R, Juszczak L (2015) The influence of acorn flour on rheological properties of gluten-free dough and physical characteristics of the bread. Eur Food Res Technol 240(6):1135–1143. https://doi.org/10.1007/s00217-015-2417-y
36. Demirkesen I (2016) Formulation of chestnut cookies and their rheological and quality characteristics. J Food Qual 39(4):264–273. https://doi.org/10.1111/jfq.12209
37. Villanueva M, Abebe W, Collar C, Ronda F (2021) Tef [*Eragrostis tef (Zucc.) Trotter*] variety determines viscoelastic and thermal properties of gluten-free dough and bread quality. LWT Food Sci Technol 135:110065. https://doi.org/10.1016/j.lwt.2020.110065
38. Ozturk OK, Mert B (2019) Characterization and evaluation of emulsifying properties of high pressure microfluidized and pH shifted corn gluten meal. Innov Food Sci Emerg Technol 52:179–188. https://doi.org/10.1016/j.ifset.2018.12.006
39. Bravo-Núñez Á, Sahagún M, Gómez M (2019) Assessing the importance of protein interactions and hydration level on protein-enriched gluten-free breads: a novel approach. Food Bioproc Tech 12(5):820–828. https://doi.org/10.1007/s11947-019-02258-2
40. Herranz B, Canet W, Alvarez MD (2017) Corn starch and egg white enriched gluten-free chickpea flour batters: rheological and structural properties. Int J Food Prop 20:489–506. https://doi.org/10.1080/10942912.2017.1299760
41. Han A, Romero HM, Nishijima N, Ichimura T, Handa A, Xu C, Zhang Y (2019) Effect of egg white solids on the rheological properties and bread making performance of gluten-free batter. Food Hydrocoll 87:287–296. https://doi.org/10.1016/j.foodhyd.2018.08.022
42. Mariotti M, Lucisano M, Pagani MA, Ng PKW (2009) The role of corn starch, amaranth flour, pea isolate, and Psyllium flour on the rheological properties and the ultrastructure of gluten-free doughs. Food Res Int 42(8):963–975. https://doi.org/10.1016/j.foodres.2009.04.017
43. Sahagún M, Gómez M (2018) Assessing influence of protein source on characteristics of gluten-free breads optimising their hydration level. Food Bioproc Tech 11(9):1686–1694. https://doi.org/10.1007/s11947-018-2135-0
44. Mancebo CM, Rodriguez P, Gómez M (2016) Assessing rice flour-starch-protein mixtures to produce gluten free sugar-snap cookies. LWT Food Sci Technol 67:127–132. https://doi.org/10.1016/j.lwt.2015.11.045
45. Witczak M, Chmielewska A, Ziobro R, Korus J, Juszczak L (2021) Rapeseed protein as a novel ingredient of gluten-free dough: Rheological and thermal properties. Food Hydrocoll 118:106813. https://doi.org/10.1016/j.foodhyd.2021.106813
46. Korus J, Chmielewska A, Witczak M, Ziobro R, Juszczak L (2021) Rapeseed protein as a novel ingredient of gluten-free bread. Eur Food Res Technol 247(8):2015–2025. https://doi.org/10.1007/s00217-021-03768-0
47. Sarabhai S, Prabhasankar P (2015) Influence of whey protein concentrate and potato starch on rheological properties and baking performance of Indian water chestnut flour based gluten free cookie dough. LWT Food Sci Technol 63(2):1301–1308. https://doi.org/10.1016/j.lwt.2015.03.111
48. Matos ME, Sanz T, Rosell CM (2014) Establishing the function of proteins on the rheological and quality properties of rice based gluten free muffins. Food Hydrocoll 35:150–158. https://doi.org/10.1016/j.foodhyd.2013.05.007
49. Ronda F, Villanueva M, Collar C (2014) Influence of acidification on dough viscoelasticity of gluten-free rice starch-based dough matrices enriched with exogenous protein. LWT Food Sci Technol 59(1):12–20. https://doi.org/10.1016/j.lwt.2014.05.052
50. Shevkani K, Singh N (2014) Influence of kidney bean, field pea and amaranth protein isolates on the characteristics of starch-based gluten-free muffins. Int J Food Sci 49(10):2237–2244. https://doi.org/10.1111/ijfs.12537
51. Korus J, Witczak M, Ziobro R, Juszczak L (2017) Hemp (Cannabis sativa subsp. sativa) flour and protein preparation as natural nutrients and structure forming agents in starch based gluten-free bread. LWT Food Sci Technol 84:143–150. https://doi.org/10.1016/j.lwt.2017.05.046
52. Witczak T, Juszczak L, Ziobro R, Korus J (2017) Rheology of gluten-free dough and physical characteristics of bread with potato protein. J Food Proc Eng 40(3):e12491. https://doi.org/10.1111/jfpe.12491
53. Ziobro R, Juszczak L, Witczak M, Korus J (2016) Non-gluten proteins as structure forming agents in gluten free bread. J Food Sci Technol 53(1):571–580. https://doi.org/10.1007/s13197-015-2043-5
54. Ziobro R, Witczak T, Juszczak L, Korus J (2013) Supplementation of gluten-free bread with non-gluten proteins. Effect on dough rheological properties and bread characteristic. Food Hydrocoll 32(2):213–220. https://doi.org/10.1016/j.foodhyd.2013.01.006
55. Tomić J, Torbica A, Belović M (2020) Effect of non-gluten proteins and transglutaminase on dough rheological properties and quality of bread based on millet (Panicum miliaceum) flour. LWT Food Sci Technol 118:108852. https://doi.org/10.1016/j.lwt.2019.108852
56. Villanueva M, Pérez-Quirce S, Collar C, Ronda F (2018) Impact of acidification and protein fortification on rheological and thermal properties of wheat, corn, potato and tapioca starch-based gluten free bread doughs. LWT Food Sci Technol 96:446–454. https://doi.org/10.1016/j.lwt.2018.05.069
57. Romero HM, Santra D, Rose D, Zhang Y (2017) Dough rheological properties and texture of gluten-free pasta based on proso millet flour. J Cereal Sci 74:238–243. https://doi.org/10.1016/j.jcs.2017.02.014
58. Benkadri S, Salvador A, Zidoune MN, Sanz T (2018) Gluten-free biscuits based on composite rice–chickpea flour and xanthan gum. Food Sci Technol Int 24(7):607–616. https://doi.org/10.1177/1082013218779323
59. Peressini D, Pin M, Sensidoni A (2011) Rheology and bread-making performance of rice-buckwheat batters supplemented with hydrocolloids. Food Hydrocoll 25(3):340–349. https://doi.org/10.1016/j.foodhyd.2010.06.012
60. Vidaurre-Ruiz J, Matheus-Diaz S, Salas-Valerio F, Barraza-Jauregui G, Schoenlechner R, Repo-Carrasco-Valencia R (2019) Influence of tara gum and xanthan gum on rheological and textural properties of starch-based gluten-free dough and bread. Eur

Food Res Technol 245(7):1347–1355. https://doi.org/10.1007/s00217-019-03253-9

61. Hadnađev TRD, Torbica AM, Hadnađev MS (2013) Influence of buckwheat flour and carboxymethyl cellulose on rheological behaviour and baking performance of gluten-free cookie dough. Food Bioproc Tech 6:1770–1781. https://doi.org/10.1007/s11947-012-0841-6
62. Zhao F, Li Y, Li C, Ban X, Cheng L, Hong Y, Gu Z, Li Z (2021) Co-supported hydrocolloids improve the structure and texture quality of gluten-free bread. LWT Food Sci Technol 152:112248. https://doi.org/10.1016/j.lwt.2021.112248
63. Marchetti L, Andres SC, Cerruti P, Califano AN (2020) Effect of bacterial nanocellulose addition on the rheological properties of gluten-free muffin batters. Food Hydrocoll 98:105315. https://doi.org/10.1016/j.foodhyd.2019.105315
64. Ronda F, Pérez-Quirce S, Angioloni A, Collar C (2013) Impact of viscous dietary fibres on the viscoelastic behaviour of gluten-free formulated rice doughs: A fundamental and empirical rheological approach. Food Hydrocoll 32(2):252–262. https://doi.org/10.1016/j.foodhyd.2013.01.014
65. Djordjević M, Šoronja-Simović D, Nikolić I, Dokić L, Djordjević M, Šereš Z, Šaranović Ž (2018) Rheology and bread-making performance of gluten-free formulations affected by different levels of sugar beet fibre, hydroxypropylmethylcellulose and water. Int J Food Sci Technol 53(8):1832–1837. https://doi.org/10.1111/ijfs.13797
66. Ren Y, Linter BR, Linforth R, Foster TJ (2020) A comprehensive investigation of gluten free bread dough rheology, proving and baking performance and bread qualities by response surface design and principal component analysis. Food Func 11(6):5333–5345. https://doi.org/10.1039/D0FO00115E
67. Korus J, Juszczak L, Witczak M, Ziobro R (2020) Effect of citrus fiber on the rheological properties of dough and quality of the gluten-free bread. Appl Sci 10(19):6633. https://doi.org/10.3390/app10196633
68. Kırbaş Z, Kumcuoglu S, Tavman S (2019) Effects of apple, orange and carrot pomace powders on gluten-free batter rheology and cake properties. J Food Sci Technol 56(2):914–926. https://doi.org/10.1007/s13197-018-03554-z
69. Martínez MM, Díaz Á, Gómez M (2014) Effect of different microstructural features of soluble and insoluble fibres on gluten-free dough rheology and bread-making. J Food Eng 142:49–56. https://doi.org/10.1016/j.jfoodeng.2014.06.020
70. Melito HS, Daubert CR, Foegeding EA (2012) Creep and large-amplitude oscillatory shear behavior of whey protein isolate/κ-carrageenan gels. Appl Rheol 22(6):63691. https://doi.org/10.3933/applrheol-22-63691
71. Ewoldt RH, Hosoi AE, McKinley GH (2008) New measures for characterizing nonlinear viscoelasticity in large amplitude oscillatory shear. J Rheol 52(6):14271458. https://doi.org/10.1122/1.2970095
72. Sroan BS, Bean SR, MacRitchie F (2009) Mechanism of gas cell stabilization in bread making. I. The primary gluten–starch matrix. J Cereal Sci 49(1):32–40. https://doi.org/10.1016/j.jcs.2008.07.003
73. Yazar G, Kokini JL, Smith B (2022) Effect of endogenous wheat gluten lipids on the non-linear rheological properties of the gluten network. Food Chem 367:130729. https://doi.org/10.1016/j.foodchem.2021.130729
74. Pareyt B, Delcour JA (2008) The role of wheat flour constituents, sugar, and fat in low moisture cereal based products: a review on sugar-snap cookies. Crit Rev Food Sci Nutr 48:824–839. https://doi.org/10.1080/10408390701719223
75. Frederici E, Jones OG, Selling GW, Tagliasco M, Campanella OH (2020) Effect of zein extrusion and starch type on the rheological behavior of gluten-free dough. J Cereal Sci 91:102866. https://doi.org/10.1016/j.jcs.2019.102866
76. Villanueva M, Harasym J, Muñoz JM, Ronda F (2019) Rice flour physically modified by microwave radiation improves viscoelastic behavior of doughs and its bread-making performance. Food Hydrocoll 90:472–481. https://doi.org/10.1016/j.foodhyd.2018.12.048
77. Alvarez-Ramirez J, Escarela-Perez R, Vernon-Carter EJ, Carrillo-Navas H (2019) Large amplitude oscillatory shear (LAOS) rheology of nixtamalized corn masa. J Cereal Sci 88:31–37. https://doi.org/10.1016/j.jcs.2019.05.004
78. Amador-Rodríguez KY, Silos-Espino H, Valera-Montero LL, Perales-Segovia C, Flores-Benítez S, Martínez-Bustos F (2019) Physico-chemical, thermal, and rheological properties of nixtamalized creole corn flours produced by high-energy milling. Food Chem 283:481–488. https://doi.org/10.1016/j.foodchem.2019.01.044
79. Ramírez-Araujo H, Gaytán-Martínez M, Reyes-Vega ML (2019) Alternative technologies to the traditional nixtamalization process: Review. Trends Food Sci Technol 85:34–43. https://doi.org/10.1016/j.tifs.2018.12.007
80. Contreras-Jiménez B, Gaytán-Martínez M, Morales-Sánchez E, Figueroa-Cardenas JDD, Pless R, González-Jasso E, Méndez-Montealvo G, Velazquez G (2017) Effects of tempering time, Ca (OH) 2 concentration, and particle size on the rheological properties of extruded corn flour. Cereal Chem 94(2):230–236. https://doi.org/10.1094/CCHEM-03-16-0058-R
81. Guadarrama-Lezama AY, Carrillo-Navas H, Vernon-Carter EJ, Alvarez-Ramirez J (2016) Rheological and thermal properties of dough and textural and microstructural features of bread obtained from nixtamalized corn/wheat flour blends. J Cereal Sci 69:158–165. https://doi.org/10.1016/j.jcs.2016.03.011
82. Hyun K, Kim SH, Ahn KH, Lee SJ (2002) Large amplitude oscillatory shear as a way to classify the complex fluids. J Nonnewton Fluid Mech 107(1–3):51–65. https://doi.org/10.1016/S0377-0257(02)00141-6
83. Mi G, Wang T, Li J, Li X, Xie J (2021) Phase separation affects the rheological properties of starch dough fortified with fish actomyosin. R Soc Chem Adv 11:9303–9314. https://doi.org/10.1039/D0RA10236A
84. Spotti MJ, Tarhan Ö, Schaffter S, Corvalan C, Campanella OH (2017) Whey protein gelation induced by enzymatic hydrolysis and heat treatment: Comparison of creep and recovery behavior. Food Hydrocoll 63:696–704. https://doi.org/10.1016/j.foodhyd.2016.10.014
85. Taylor JRN, Taylor J, Campanella OH, Hamaker BR (2016) Functionality of the storage proteins in gluten-free cereals and pseudocereals in dough systems. J Cereal Sci 67:22–34. https://doi.org/10.1016/j.jcs.2015.09.003
86. Andersson H, Öhgren C, Johansson D, Kniola M, Stading M (2011) Extensional flow, viscoelasticity and baking performance of gluten-free zein-starch doughs supplemented with hydrocolloids. Food Hydrocoll 25(6):1587–1595. https://doi.org/10.1016/j.foodhyd.2010.11.028
87. Zhang D, Mu T, Sun H (2017) Comparative study of the effect of starches from five different sources on the rheological properties of gluten-free model doughs. Carbohyd Polym 176:345–355. https://doi.org/10.1016/j.carbpol.2017.08.025
88. Demirkesen I, Mert B (2020) Recent developments of oleogel utilizations in bakery products. Crit Rev Food Sci Nutr 60(14):2460–2479. https://doi.org/10.1080/10408398.2019.1649243
89. Tarancón P, Salvador A, Sanz T (2013) Sunflower oil–water–cellulose ether emulsions as trans-fatty acid-free fat replacers in biscuits: texture and acceptability study. Food Bioproc Technol 6:2389–2398. https://doi.org/10.1007/s11947-012-0878-6

90. Pérez-Quirce S, Lazaridou A, Biliaderis CG, Ronda F (2017) Effect of β-glucan molecular weight on rice flour dough rheology, quality parameters of breads and in vitro starch digestibility. LWT Food Sci Technol 82:446–453. https://doi.org/10.1016/j.lwt.2017.04.065
91. Ozyigit E, Eren I, Kumcuoglu S, Tavman S (2020) Large Amplitude Oscillatory Shear (LAOS) analysis of gluten-free cake batters: The effect of dietary fiber enrichment. J Food Eng 275:109867. https://doi.org/10.1016/j.jfoodeng.2019.109867
92. Elgeti D, Jekle M, Becker T (2015) Strategies for the aeration of gluten-free bread- A review. Trends Food Sci Technol 46:75–84. https://doi.org/10.1016/j.tifs.2015.07.010
93. Kahraman G, Harsa S, Lucisano M, Cappa C (2018) Physicochemical and rheological properties of rice-based gluten-free blends containing differently treated chickpea flours. LWT Food Sci Technol 98:276–282. https://doi.org/10.1016/j.lwt.2018.08.040
94. Arıcı M, Özülkü G, Kahraman B, Yıldırım RM, Toker ÖS (2020) Taro flour usage in wheat flour bread and gluten-free bread: Evaluation of rheological, technological and some nutritional properties. J Food Process Eng 43(9):e13454. https://doi.org/10.1111/jfpe.13454
95. Monthe OC, Grosmaire L, Nguimbou RM, Dahdouh L, Ricci J, Tran T, Ndjouenkeu R (2019) Rheological and textural properties of gluten-free doughs and breads based on fermented cassava, sweet potato and sorghum mixed flours. LWT 101:575–582. https://doi.org/10.1016/j.lwt.2018.11.051
96. Paesani C, Bravo-Núñez Á, Gómez M (2020) Effect of extrusion of whole-grain maize flour on the characteristics of gluten-free cookies. LWT 132:109931. https://doi.org/10.1016/j.lwt.2020.109931
97. Inglett GE, Chen D, Liu SX (2015) Physical properties of gluten-free sugar cookies made from amaranth–oat composites. LWT Food Sci Technol 63(1):214–220. https://doi.org/10.1016/j.lwt.2015.03.056
98. Witczak M, Juszczak L, Ziobro R, Korus J (2012) Influence of modified starches on properties of gluten-free dough and bread. Part I: Rheological and thermal properties of gluten-free dough. Food Hydrocoll 28(2):353–360. https://doi.org/10.1016/j.foodhyd.2012.01.009
99. Roman L, Reguilon MP, Martinez MM, Gomez M (2020) The effects of starch cross-linking, stabilization and pre-gelatinization at reducing gluten-free bread staling. LWT Food Sci Technol 132:109908. https://doi.org/10.1016/j.lwt.2020.109908

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