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The Effect of the Relative Amount of Ingredients on the Rheological Properties of Semolina Doughs

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Abstract: "Pani carasau" is a traditional Sardinian bread, made with re-milled durum wheat semolina, with a long shelf-life. The production process is highly energy consuming, but its automation can make it more energy-efficient and sustainable. This requires a deep knowledge of the rheological parameters of the doughs. This study investigated the rheological properties of doughs—prepared by mixing semolina with water, yeast, and salt—as a function of the relative amount of the ingredients. The rheological measurements were carried out by an Anton Paar MCR 102 rheometer, equipped with a plate–plate fixture. In more detail, frequency sweep and creep tests were performed. It was found that doughs obtained with different amounts of ingredients showed significant differences in the rheological responses. The addition of water led to a significant decrease in the viscosity and improved the deformability of the dough. In addition, the yeast addition produced a viscosity decrease, while the presence of salt produced an improvement of the three-dimensional gluten network characteristics and, consequently, of the strength of the dough. In addition to the production process of pani carasau, this work contributes to improving the general performance of the doughs used in the production of flour-and-semolina-based foods.

Keywords: breadmaking; Burgers model; dough rheology; water; ingredients; kneading; salt; semolina; sustainability; yeast

1. Introduction

Bread is one of the most common foods in all diets all over the world. Common wheat is generally used to prepare leavened and flatbreads, while durum wheat is preferred for the production of pasta and of some kinds of traditional bread in many parts of Italy and, more generally, of the Mediterranean area. Although durum flours usually produce a smaller loaf volume than those of common wheat flour, durum wheat bread guarantees several advantages like a yellowish color, appreciated characteristic taste and odor, a fine uniform crumb structure, a higher content of proteins, and a more prolonged shelf-life, all of which are creating an increasing interest in consumers around this specialty [1]. Additionally, durum wheat bread has also been reported to present less gluten toxicity to people with gluten intolerance, which is another good reason to make bread from durum wheat [2]. "Pani carasau" is a traditional Sardinian bread, made with re-milled durum wheat semolina. This kind of bread is produced in very thin sheets (less than 1 mm thick), which give it a particular crispy texture, really appreciated by consumers, and it has a very low moisture content, so it is characterized by a longer shelf-life if compared to all the classic bread kinds. These characteristics, obtained by means of a production process that has consolidated over the centuries, make it a very particular product with

a high added value. Nowadays the market demand for Sardinian bakery products from Italy, the rest of Europe, and also from Asian countries is increasingly growing [3]. Most of the production of pani carasau still occurs in a semi-artisanal way, but some manufacturers have taken the path of controlled industrial production. The challenge is supplying the market with high-quality products, combining tradition with technology, to meet consumer needs, and following the market trends. For these reasons, the carasau bread producers are trying to overcome the drawbacks which are connected to the traditional production process, such as empirical monitoring and manual control, that are currently based only on the knowledge and experience of the operators [4,5]. The main objective is to reach a remarkable level of automation in their bakeries, allowing for real-time suitable modifications of the recipe and the production process parameters to obtain the best dough workability and, consequently, to optimize the energy and raw material consumption.

Taking into account all these aspects, the rheological characterization of the dough is fundamental to understand how the structure and the texture of the material change of its composition and, therefore, how to optimize the production process according to the quality attributes required by the final product. The consensus is that a high protein content, which leads to a strong gluten network, combined with the high extensibility of the dough, is an important property for durum wheat-based products (especially regarding the loaf volume definition). Despite this, accurate research to establish which dough characteristics should be achieved to obtain the required final product texture has not been conducted [6].

The interactions among the ingredients are influenced by their amount and by the kneading operation parameters [7]. In particular, this stage of the production allows the formation of a homogeneous mass and promotes the protein hydration, which is fundamental because it leads to the building of the so-called "gluten network", the microstructure giving the mechanical properties to the dough. An increase in the mixing time leads to an increase in the viscosity of the dough [8]. The gluten network building process is influenced by the presence of other chemical species like carbohydrates (i.e., polysaccharides) in the flour, the water amount, and the presence of the other main ingredients of the bread dough—salt and yeast first of all. All these components compete with each other to bind with water and these interactions produce the different kinds of bind that are established in the network, making the ingredient relative amounts a critical factor [9]. According to this, water, salt, and yeast, in different quantities, can modify the tenacity, extensibility, and strength of the dough. The interactions among these components, proteins, and water are very important in developing the viscoelastic characteristics of the mixed dough [10].

Water quantity in the dough is a critical factor [11]. Indeed, due to the polarity of its molecule, water acts both as a solvent and as a medium for liquid-phase reactions of other components. Since gluten is mostly, but not completely, hydrophobic, the role of the water-soluble fraction is very important for the distribution of water and to obtain dough with the required elasticity. Water also determines the conformation of the components which are based on hydrophobic interactions [12]. Moreover, water is a mobility enhancer: according to its low molecular weight, as the water content is increased, the volume of inclusions increases and viscosity decreases [13]. The effect on the rheological properties is a decrease of the complex shear modulus (G^*) and elasticity, and an increase of the dough creep compliance when the water content increases [14,15].

Salt is essential to improve the taste of the bread and the sensorial properties, but it also plays an important role in the definition of the technological properties of the dough. The addition of salt increases the mixing resistance of dough, improves the extensibility, decreases the stickiness, helps to stabilize the yeast fermentation rate, leads to a more attractive crust color, improves the bread texture, delays the bread staling, and inhibits microbial growth during bread storage [16]. The effect of salt has been investigated in the literature, by means of farinograph, mixograph, extensograph measurements, and baking studies [17–20]. Salt anions, in a flour-water system, bind with the positive charges on the proteins, eliminating the repulsion among the protein chains, which can more easily interact with each other. This phenomenon leads to a modification in the gluten protein network microstructure, promoting the presence of elongated protein strands, instead of less connected protein particles, which

results in slower hydration of the proteins and, consequently, in an increase of the dough optimal mixing time [18], and also in a stronger gluten network [21]. Regarding the rheological properties, the research on the salt effect has shown conflicting results. Some studies documented a decrease in the storage (G′) and loss (G″) modules with an increase in the amount of added NaCl [22,23], for example, when salt increases from 0% to 3% (based on the semolina weight) [7]. Some studies reported an increase in the storage modulus when NaCl is added to the dough [24], but others observed a significant decrease for the same modulus and in the same conditions [25]. It has been hypothesized that these differences in the dough rheological behavior as a function of the salt amount might be due to the use of different flour varieties [17]. In a recent work [16], it is reported that the optimal mixing time increased from 2.75 min for the dough without salt to 4.75 min for the dough with 2.4% (based on the weight of the wheat flour) salt, stating that the addition of this component influences strength, resistance, and mixing stability. On the side of human health, the consumption of high amounts of sodium has been linked to hypertension. This has spurred interest in reducing the sodium chloride content or in the complete or partial replacement of it with alternative salts. Another paper [26] reported that a reduction of the salt content from 1.2% to 0.3% (based on the dough total weight) does not significantly affect the rheological properties and the bread-making performance, but adding no salt at all, however, brings a significant reduction in the dough and bread quality, with a substantial decrease of G′ module and an important negative influence on the sensorial properties. Regarding creep rheological characterizations, in the literature [24,27] it is reported that high levels of salt (2% or more) produce stiffer and slightly deformable doughs, because of the higher complex modulus and the lower creep compliance; moreover, an increase in the dough stickiness was measured when using NaCl.

Yeast is another component playing a crucial role in dough manufacturing. Indeed, yeast fermentation produces CO_2 and, besides, a lot of metabolites that can influence the final product quality, the flavor attributes, and the rheological properties of the dough [28]. All major yeast metabolites were found to produce a softening effect on unfermented doughs, while glycerol merely has a diluting effect; ethanol, succinic acid, and glutathione fundamentally modify the structure of the gluten network [29]. Despite the great importance that fermentation and yeast have on the dough structure, the number of fundamental rheological studies dealing with fermented doughs is limited because of the difficulty to characterize a material which is constantly evolving. The few articles addressing this problem reported a decrease in the dough viscosity and of both G′ and G″ modules, due to the yeast incorporation of polysaccharides and proteins, and to the three-dimensional network gassing [30].

All the previous studies are extensively focused on the influence of the different ingredients used in common bread making, such as water, yeast, salt, and other additives, on the dough rheological properties, but none of these presents a complete characterization from a technological point of view. Moreover, the specific characteristics of pani carasau and the automation of its production process require a deep knowledge of the rheological parameters of the doughs to correctly drive the unit operations such as the lamination, forming, and baking, the latter being carried out in two successive steps.

The aim of the present study was a thorough rheological characterization of doughs with different composition in terms of water, salt, and yeast, in order to address an empirical description of their influence on the dough properties, in view of the future automation of the production process. The study focused on a commercial durum wheat semolina and on the recipe which is currently used in the production of pani carasau, to find the best formulation for the production process. Two important rheological tests were performed and the trend of some parameter measurements was modeled and studied as a function of the dough recipe.

1.1. Dough Rheology

The dough is a viscoelastic material, meaning that the stress experienced during the application of deformation is a function of both applied strain and strain rate [31]. This is mainly due to

its microscopic internal structure that appears as a three-dimensional network supported by the intermolecular weak interactions. The most common rheological tests, which are applied to the dough, are: (i) small deformation dynamic shear oscillation, (ii) small and large deformation shear creep and stress relaxation, (iii) large deformation extensional measurements, (iv) flow viscosimetry [32].

1.1.1. Frequency Sweep Tests and Cox-Merz Rule

Dynamic oscillation measurements, and in particular small amplitude oscillatory shear (SAOS) tests, are ideal to characterize the structural properties of viscoelastic materials [33]. These tests usually operate in the linear viscoelastic deformation regime with low strain values, up to 1% [34]. Frequency sweep measurements can give useful insights into the differences in the dough network characteristics among samples with different compositions. During these tests, the frequency of the deformation is varied while the amplitude of the strain is kept constant. The data at low frequencies describe the behavior of the samples at slow changes of stress while the answer to a fast load is expressed at high frequencies. The measured values are the storage and the loss modulus as a function of the frequency. The storage (G′) modulus in viscoelastic materials represents the elastic portion of the material response after a deformation, while the loss (G″) modulus is related to the energy dissipated as heat, representing the viscous component of its behavior. In addition, one can define the complex viscosity as a frequency-dependent function that contains both real and imaginary parts. The empirical Cox–Merz rule (CMr) [35] states that values of the complex viscosity (η^*) and of the steady shear viscosity (η) must have equal magnitudes at equal values of frequency (ω) and shear rate $\left(\dot{\gamma}\right)$ [36]:

$$\eta\left(\dot{\gamma}\right) = \left.\eta^*(\omega)\right|_{\dot{\gamma}=\omega} \tag{1}$$

However, this rule has some restrictions: in the literature, for example, it can be applied only to fluids without a "structure" that can be disrupted by large strain [37]. Some researchers [38] obtained good results just for cases showing liquid-like behavior. The first work [39] that experimented with the application of the CMr to foodstuff material found that, in some cases, η^* is much larger than η, suggesting a nonlinear nature of the biomaterial response. However, for some food applications, a linear relationship was also appreciated [38]. The conclusion is that one can obtain a measure of the steady shear viscosity by means of the complex one, and this makes frequency measurements even more informative and powerful, due to the importance of this parameter.

1.1.2. Creep Tests and Burgers Model

In a creep test, constant stress is applied to the sample and the corresponding deformation is measured over time. When subjected to constant stress, deformation of a purely elastic material is constant; on the other hand, an ideally viscous material should show a constant flow, producing a linear response to stress [40]. Viscoelastic materials, such as bread doughs, present a non-linear response to deformation, due to their ability to partially recover their initial structure [41]. When a viscoelastic material is subjected to constant stress, it tends to continuously deform over time until it reaches a final deformation, valid for viscoelastic solid materials, called "creeping", while a viscoelastic fluid reaches a regime of flow [42]. The stiffness of the material, i.e., the ratio between the applied stress and the achieved deformation, depends on the rate of application of the load. On the other hand, when a viscoelastic material undergoes constant deformation over time, the effort required to maintain it decreases over time. Creep results are often presented by means of the compliance parameter (J), defined as the ratio between the strain, $\varepsilon(t)$, function of time, and the constant stress (σ_0) that is applied [42].

To describe the trend of this parameter as a function of the time it is common, in the literature, to resort to mechanical models composed by elements with simple mechanical behavior, such as springs and dampers, which are useful to conceptualize the rheological behavior. The most common and basic mechanical models are the Maxwell and the Kelvin–Voigt models [43]. Most of the complex models,

used in the literature to describe the compliance over time, originate from a combination of these basic models. One of the most used is the Burgers model, which is a Kelvin and a Maxwell model placed in series. Mathematically, it can be written as [43]:

$$J(t) = J_0 + J_m\left(1 - e^{-\frac{t}{\tau}}\right) + \frac{t}{\eta_0} \tag{2}$$

The model parameters are the material viscosity η_0, the delay time τ, and the instantaneous and delayed compliance, respectively J_0 and J_m. The compliance characterizes the material based on its deformability, while the viscosity gives information on the material's ability to flow, and the delay time indicates how long the material takes to settle in deformation. Many applications of this model to food characterization, including bread dough, can be found in the literature [24,44,45].

2. Materials and Methods

The dough samples were prepared by using the following ingredients: commercial semolina (its basic chemical parameters are reported in Table 1); distilled water; commercial fresh brewer's yeast (*Saccharomyces cerevisiae*); and commercial sea salt. The semolina protein content was determined with the nitrogen combustion method [46] by using a Leco FP528 nitrogen analyzer (LECO, Stockport, UK). Gluten content and the gluten index of semolina were determined following the ICC standard method No. 158 [47] by using the Glutomatic 2200 system (Perten Instruments AB, Huddinge, Sweden). The dough preparation was performed by using a 10 g capacity mixograph (National Manufacturing, Lincoln, NB). For the investigation of the salt influence, the tested samples were composed of 10 g of semolina, 5 g of distilled water, and a variable amount of salt: 0.5%, 1.5%, and 3.0% (based on the semolina weight); no yeast was added in the samples. For the study of the yeast impact, instead, 10 g of semolina was mixed with 5 g of distilled water and with 0.5%, 1.5% and 3.0% yeast (based on the semolina weight), without adding any salt. These amounts were chosen considering that the dough of pani carasau is nowadays commercially obtained with 50% water, 1.5% yeast, and 1.5% salt (all based on the semolina weight), so a change of the amount of each ingredient to half or twice the amount of the basic recipe was considered. Regarding the amount of water, samples with 55% and 60% (without salt and yeast) were prepared to investigate just the contribution on the rheological properties of the water amount, with increments of 5%. To clearly understand the impact of these components, a sample obtained by mixing just semolina and water in the same amounts as before (reference sample) was tested. Each sample was mixed for a fixed time before starting the measurement (10, 20, and 40 min) at the fixed velocity of 88 rpm. These long mixing times were chosen to study the effect of overmixing on the dough properties and to understand how the addition of the different ingredients influences this phenomenon. Thus, the analysis was carried out on seven different samples (one blank, three with yeast addition, and three with salt addition) and, for each of them, three kneading times were applied, for a total of 21 experimental conditions. This was done to assess, if any, differences in the development of the dough structure when the previous factors are varied by means of rheological measurements. The rheological experiments were performed using an MCR 102 Anton Paar rheometer (Anton Paar GmbH, Austria) equipped with a 25 mm parallel plate geometry. A piece of dough, after kneading by the mixograph, was loaded on the rheometer, compressed to a gap of 2 mm, and then left at rest for 15 min, to allow the material relaxation, as suggested in the literature [48]. To prevent evaporation and, consequently, the drying of the sample, a layer of silicon oil was applied to the edge of it. The measurement temperature in the rheometer was kept constant at 25 °C using a Peltier effect based control temperature system. Frequency sweep tests were performed with frequency ranging from 0.1 to 100 rad·s^{-1} with a constant strain of 0.1% that was well within the linear viscoelastic limit (LVE) that was evaluated through preliminary amplitude sweep tests. The dependence of the measured complex viscosity data on the frequency was established in terms of a power-law model [49,50]:

$$\eta^*(\omega) = A\omega^{n-1} \tag{3}$$

In Equation (3), *A* is the so-called consistency coefficient, whereas the exponent *n* is the power-law index, measuring the degree of non-Newtonian behavior [51]. For Newtonian fluids, *n* is equal to 1; when dealing with non-Newtonian fluids exhibiting a viscosity decreasing with the shear rate (shear-thinning behavior), the power-law index is smaller than 1.

Creep tests were performed applying to the sample a 50 Pa constant stress for 150 s. Compliance data, obtained from these experiments, were modeled as a function of time using the Burgers model (Equation (2)), and the values of the model parameters (J_0, J_m, η_0, and τ) were calculated. Each one of the 27 experimental conditions was replicated three times, for a total of 81 runs, and for each parameter, the average value was taken as the result.

Table 1. Basic chemical parameters of commercial semolina under study.

	Carbohydrates (%)	Fats (%)	Proteins (%)	Gluten (%)	Gluten Index (%)
Commercial Semolina	71 *	1.5 *	11.7 **	8.7 **	88.00 **

* reported on the product label; ** experimentally determined.

3. Results

3.1. Complex Viscosity and Power-Law Modeling

Figure 1 reports the values of the complex viscosity as a function of the frequency for the samples with different amounts of water mixed for 10 min. A visual inspection of the data suggests that linear dependence of the viscosity on the frequency is evident, thus the power-law model is proper to describe the rheological properties of the dough under investigation. It is possible to observe the same trend for the samples with salt (Figure 2), while the samples with the highest content of yeast slightly deviate from the linear trend at small frequencies, i.e., at ~0.1 rad·s^{-1} (Figure 3). However, the modeling with the power-law function was achievable in all the cases: the adjusted R^2 for these regressions was always higher than 0.999, except for the samples with a high content of yeast (1.5–3.0%) in Figure 3, for which it was around 0.990.
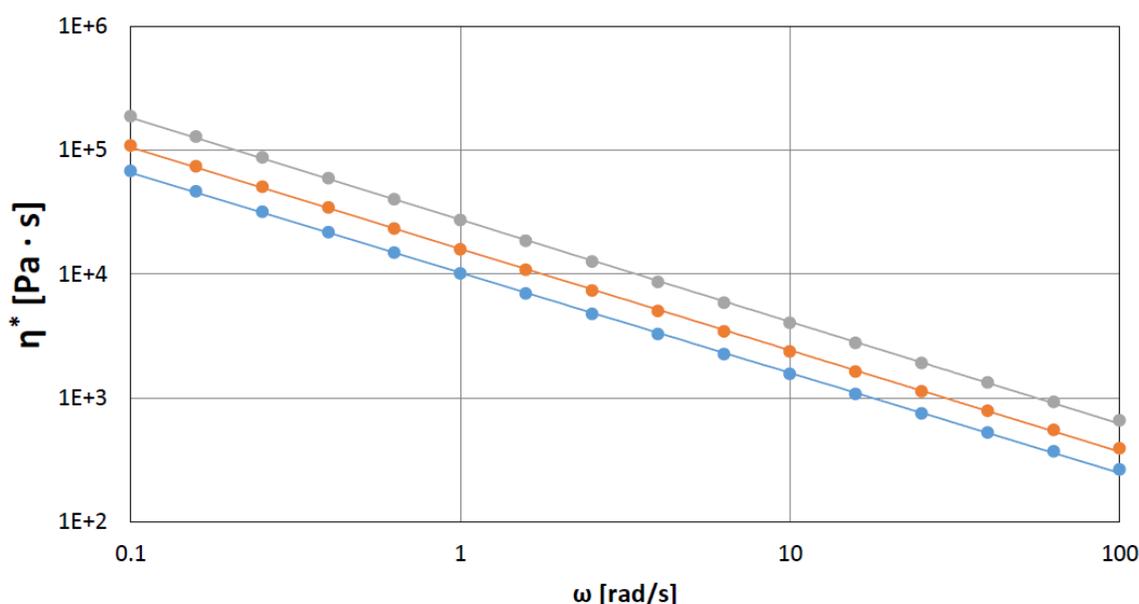

Figure 1. Complex viscosity (points) and power-law curves (lines) of dough mixed for 10 min, reported as a function of frequency for three different water contents: 50% (•), 55% (•), and 60% (•) (percentages based on the semolina weight).
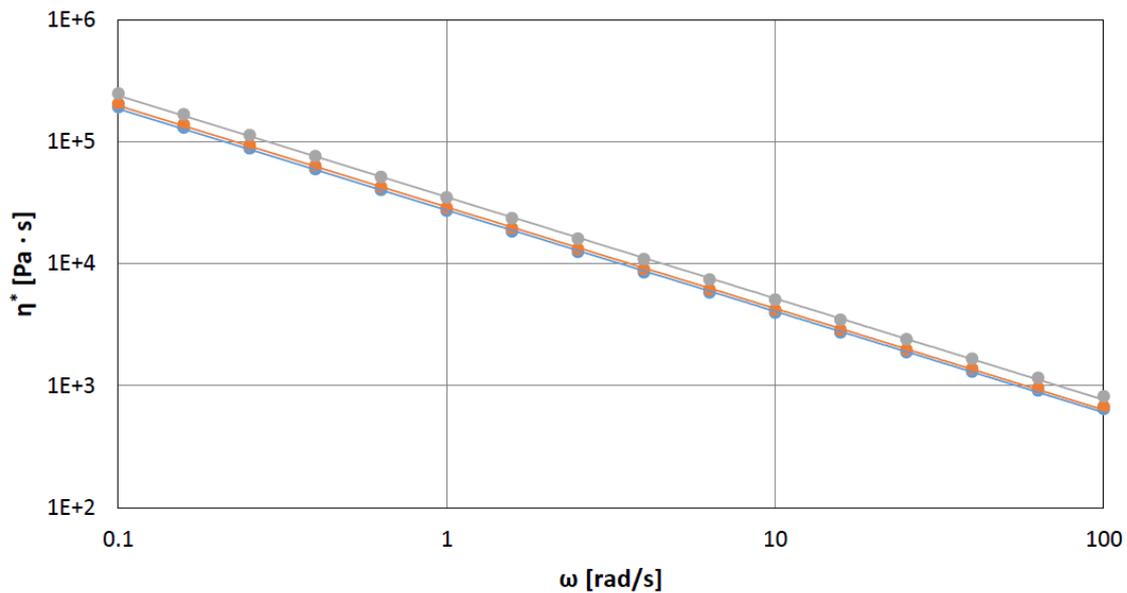
Figure 2. Complex viscosity (points) and power-law curves (lines) of dough mixed for 20 min, reported as a function of frequency for three different salt contents: 0.5% (•), 1.5% (•), and 3.0% (•) (percentages based on the semolina weight).
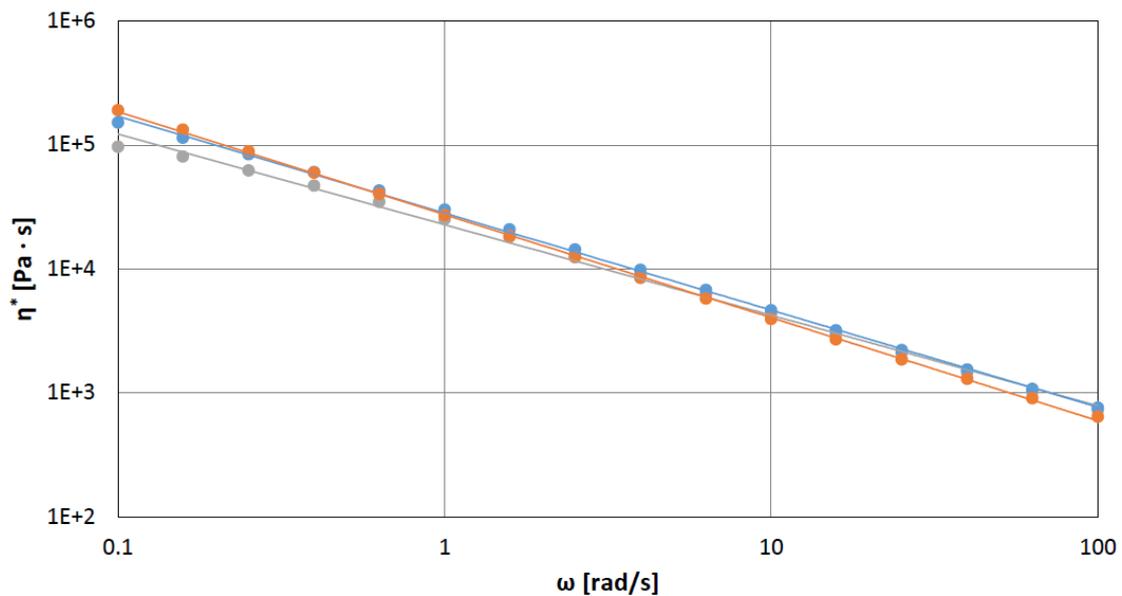

Figure 3. Complex viscosity (points) and power-law curves (lines) of dough mixed for 40 min reported as a function of frequency for three different yeast contents: 0.5% (•), 1.5% (•) and 3.0% (•) (percentages based on the semolina weight).

Taking the previous discussion into account, the regression parameters A and n of the power-law model were calculated: in Figure 4 the parameters for the samples with different amounts of water are reported, in Figure 5 the impact of salt is investigated, while in Figure 6 the effect of yeast on the parameters is analyzed. Figure 4 shows a decay of the complex viscosity when the water content increases, deductible from the decrease of the A parameter and due to the presence of a higher amount of free water in the system, as the binding ability of semolina proteins is limited [52]. A visual inspection of Figure 4 suggests that there is no significant impact of the water content and the n parameter curves overlap around a very restricted range ($-0.83 \div -0.86$).

In addition, the salt effect is more evident for the *A* parameter, with an increase in the viscosity when the salt amount is higher than 1.5% (Figure 5). This increase is explainable by the fact that adding salt results in a less free water amount in the dough, which causes a decrease in its elasticity properties [44].
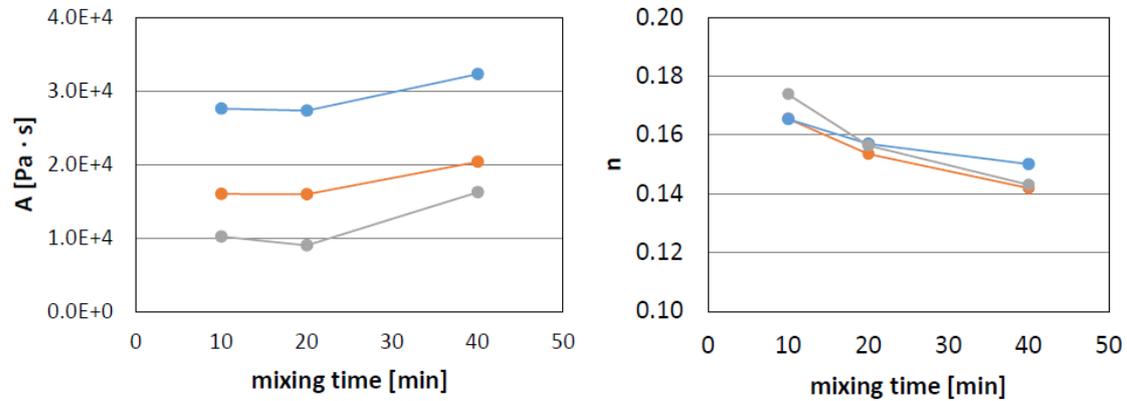

Figure 4. *A* (**left**) and *n* (**right**) parameters as a function of the water content: 50% (●), 55% (●), and 60% (●) (percentages based on the semolina weight).
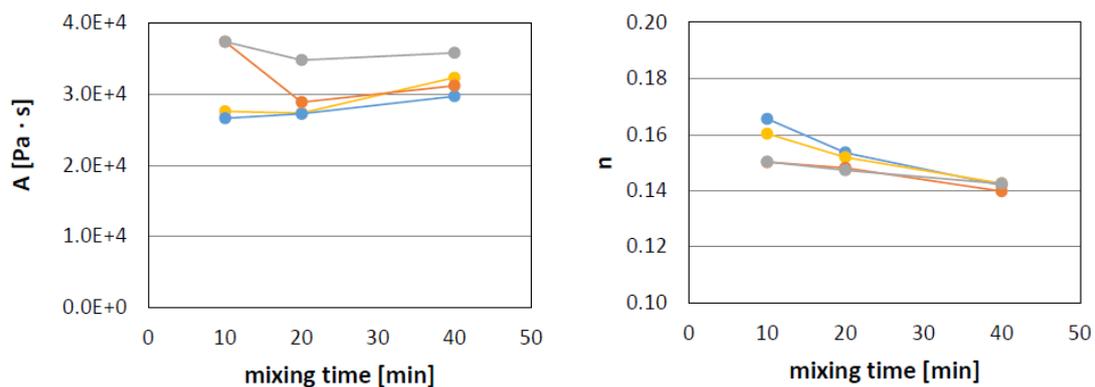

Figure 5. *A* (**left**) and *n* (**right**) parameters as a function of the salt content: 0% (●), 0.5% (●), 1.5% (●), and 3.0% (●) (percentages based on the semolina weight).
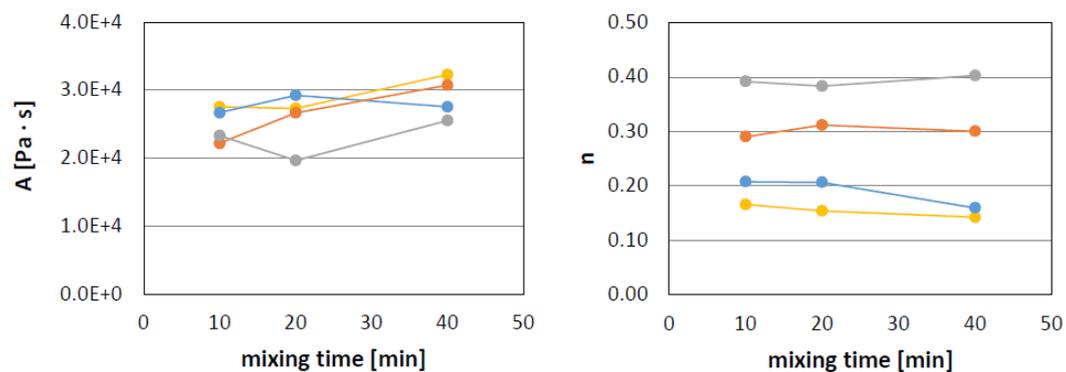

Figure 6. *A* (**left**) and *n* (**right**) parameters as a function of the yeast content: 0% (●), 0.5% (●), 1.5% (●), and 3.0% (●) (percentages based on the semolina weight).

Considering the yeast impact on the power-law parameters (Figure 6), besides a slight increment on *A* parameter, mostly visible for high concentrations (3.0%), it is very interesting to observe how the *n* parameter is influenced by the yeast amount. In this case, the change in the trend of the complex viscosity with the frequency is more pronounced, as already shown in Figure 3. These results are

consistent with the change in the complex shear modulus (G*), observed by Fanari et al. [7] when yeast is added to the dough in different amounts.

The effect of mixing time is an increase of the *A* parameter for all the samples when the time is higher than 20 min, while the *n* parameter is only slightly affected (just a small decrease in most cases). This phenomenon is due to the dough overmixing that results in a strain-hardening of the structure and a loss of elasticity in the dough [53]. By adding salt, this phenomenon is attenuated.

3.2. Creep Test and Burgers Model

In Figure 7, the measured values of compliance from the creep tests are shown together with the Burgers model curve for the samples with the highest additive amount of ingredients that, for this reason, are supposed to be the most far away from the ideal trend which is described by the Burgers model. The Burgers model is able to quantitatively describe the data trend and the adjusted R^2 is always around 0.990. From Figure 7, one can also deduce that yeast has the strongest impact on dough compliance compared to water, and especially to salt, which has an inverse effect indeed, while the yeast and water addition causes an increase of the compliance and salt produces a decrease of this parameter. On the other hand, the Burgers model fails to describe the experiments carried out at the highest yeast content, confirming that the rheological response observed in these experimental conditions significantly deviates from the other ones.
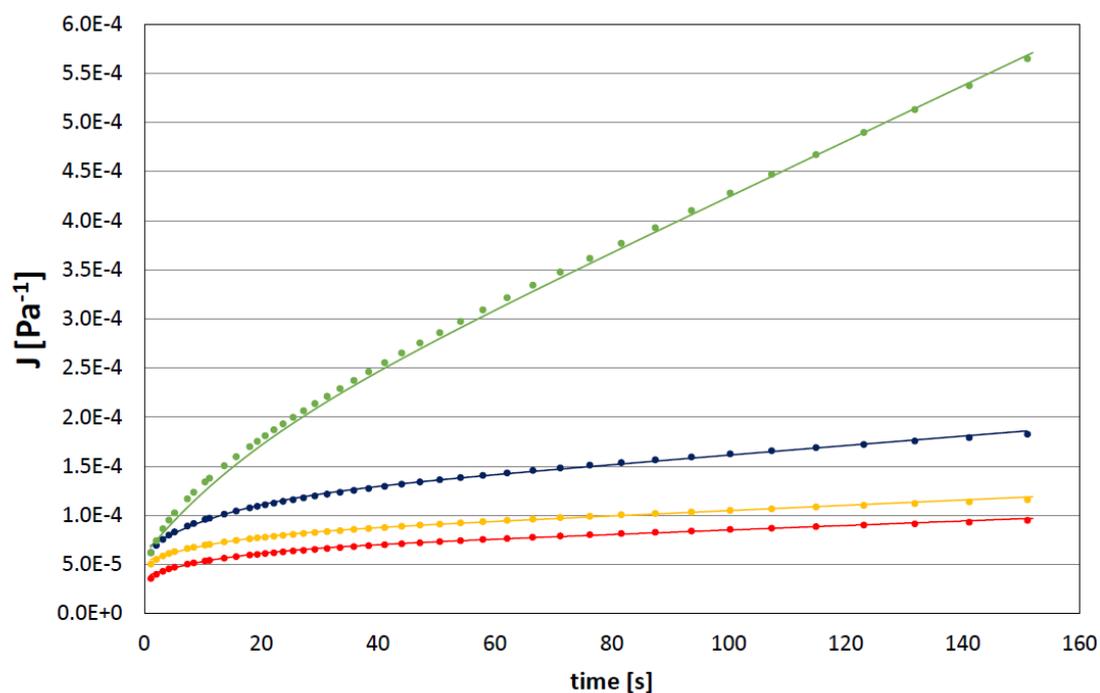
Figure 7. Compliance (points) and Burgers model curves (lines) of samples mixed for 40 min with different water content (60% (●)), salt content (3.0% (●)), and yeast amount (3.0% (●)), compared to the blank sample (50% of water, no salt and yeast (●)) (percentages based on the semolina weight).

In Figures 8–10, the values of the Burgers model parameters are shown. Analyzing the J_0 and J_m parameters, representative of the compliance (deformability of the material), it is noticeable that their trend is opposite to the trend of the η_0 parameter: (i) as the water content increases, J_0 and J_m increase, while η_0 decreases (Figure 8), confirming the results obtained in the previous section; (ii) the increasing of the salt amount results in lower deformability (J_0 and J_m decrease) and higher viscosity η_0, but only when salt is added in a concentration higher than 0.5% (Figure 9); and (iii) the impact of yeast (Figure 10), instead, is similar to that of water (J_0 and J_m increase, while η_0 decrease). Quantitatively speaking, the addition of yeast and water produces a bigger modification to the material properties

compared to the ones appreciated with the salt addition. The effect of water on J_0 and J_m is an increase, compared to the control sample (flour and 50% water) of about 50%–80% when water is increased to 55%, and of about 250%–300% when water is increased to 60%, while η_0 decreases up to 40–60%. The yeast is able to decrease J_0 and J_m about 40–50% and to decrease η_0 up to 100%. Conversely, salt produces an increase (40–60%) on J_0 and J_m when added in small quantities (0.5%) and a decrease of up to 30% when it is added in higher amounts. The influence on η_0 is about the same, with an increase of up to 45% when the salt amount is 3.0%.
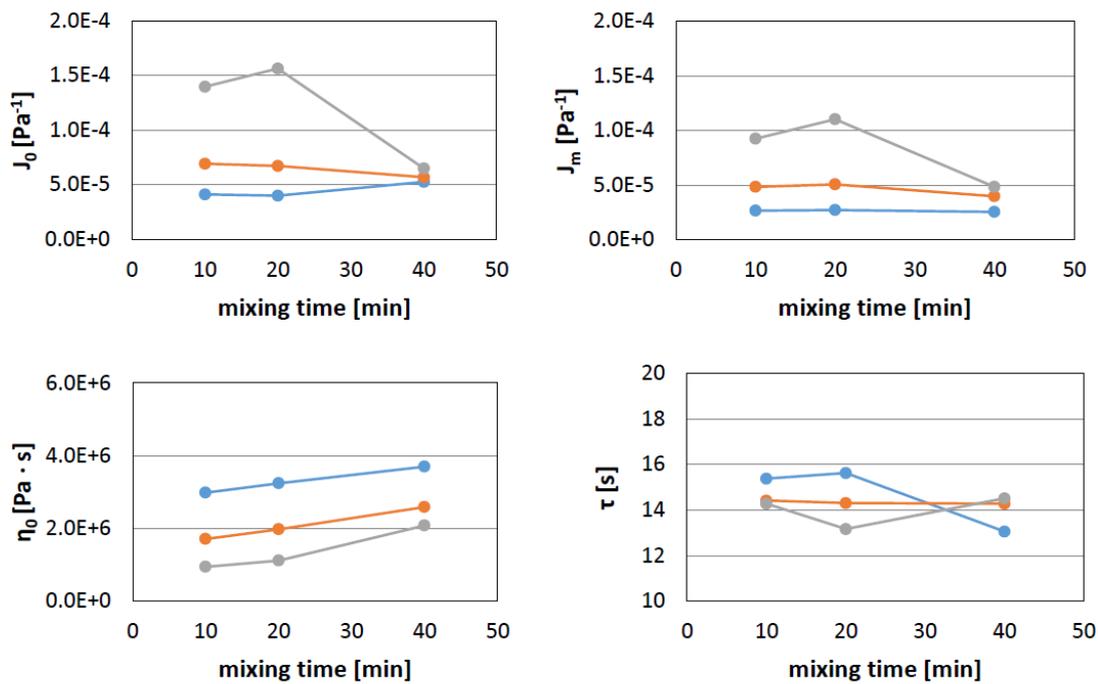

Figure 8. Burgers parameters J_0, J_m, η_0, and τ as a function of the mixing time for three different water contents: 50% (•), 55% (•), and 60% (•) (percentages based on the semolina weight).
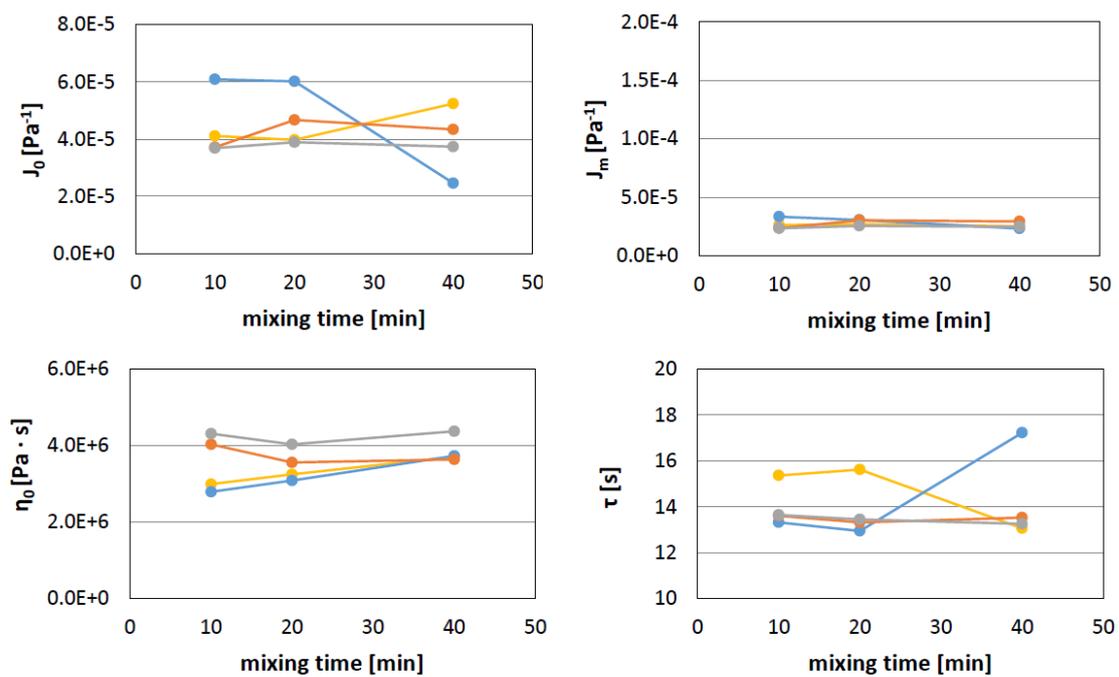

Figure 9. Burgers parameters J_0, J_m, η_0, and τ as a function of the mixing time for four different salt contents: 0% (•), 0.5% (•), 1.5% (•), and 3.0% (•) (percentages based on the semolina weight).
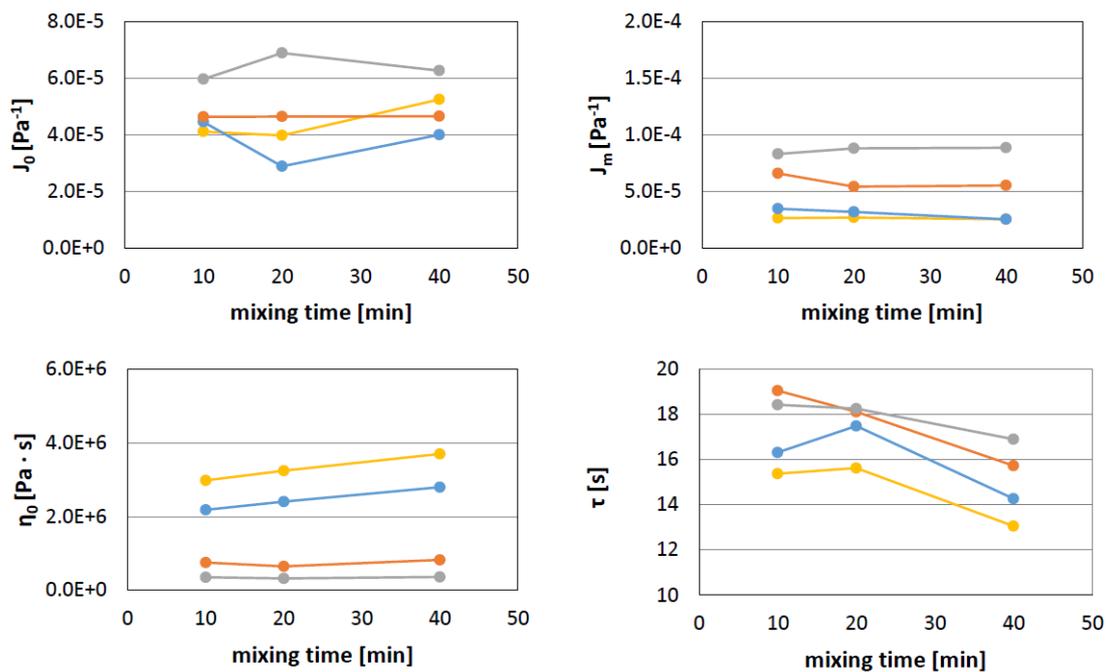
Figure 10. Burgers parameters J_0, J_m, η_0 and τ as a function of the mixing time for four different yeast contents: 0% (●), 0.5% (●), 1.5% (●), and 3.0% (●) (percentages based on the semolina weight).

Regarding τ, the trend of this parameter is not so clear, the effects are low varying the water or salt amount (Figures 8 and 9), while a clearer variation can be observed as a function of the yeast content, with a decrease of the parameter when the yeast is increased (Figure 10).

Another variable considered in this study was the mixing time. Generally speaking, it is noticeable that, for an overmixed dough, J_0 and J_m decrease, η_0 decreases and τ decreases, but in a significant manner just when the yeast content is changed (Figures 8–10). In addition, these results are consistent with the one discussed in Section 3.1: by overmixing, the dough becomes stiffer, so it is less elastic and its machinability decreases. Overmixing is able to reduce the impact of the ingredient amounts up to 50–60%.

4. Discussion

This work aimed to find the impact of the amounts of water, salt, and yeast on the rheological properties of the dough for pani carasau production, in order to acquire a deeper knowledge of the production process finalized to its control and optimization. This study could be very helpful, from an industrial process improvement point of view, also for all the semolina-based foodstuffs manufacturers.

The rheological properties, fundamental in the definition of textural and mechanical properties of the dough, were analyzed through mathematical modeling. Regarding the power-law modeling, a linear dependence of the viscosity as a function of the frequency was detected, with a slight divergence in the case of high yeast contents. Similar results were observed for Burgers modeling, with a good description of the trend as a function of time and just a small deviation when yeast content increases. The model regressions were, for all cases, able to accomplish a very good explanation of the experimental data. Taking into account the power-law model, the most representative parameter in the description of the impact of these ingredients was the *A* parameter, while *n* resulted to be influenced just in the case of yeast addition, influencing also the slope of the straight line and not just its intercept. As it concerns the creep-recovery experiments modeled with the Burgers model, it was found that η_0 is the parameter which is most affected by the effect of the ingredients, and to a lesser extent also J_0 and J_m, while τ is significantly influenced just in case of yeast addition, as it was noticed for *n* parameter of the power law.

From the obtained insights, it is possible to say that water has critical importance in the definition of the dough properties, mainly reducing its viscosity and increasing its compliance by incrementing the amount of free water inside the material. Salt is able to strengthen the dough structure and to reduce the impact of the overmixing phenomena, due to its ability to shield the charges on the surfaces of the gluten proteins and then to increment the interactions among them [27]. Despite this, when salt is added in high amounts (more than 1.5%), it stiffens the dough, reducing its elasticity and machinability. Regarding the yeast addition, instead, a reduction in the viscosity and an increase in the deformability of the dough is observed when the yeast content increases: this is likely due to the yeast incorporation of polysaccharides and proteins and to a lesser extent the three-dimensional network gassing (because the dough had little time to leaven). Moreover, the effect of mixing time was an increase in the viscosity for all the samples when it was higher than 20 min. This phenomenon was due to the overmixing of the dough that results in a breakdown of the S-S covalent cross-links and in a decrease of the network water-binding capacity, due to the disaggregation, or even de-polymerization, of the gluten proteins [53]; these changes translate into a strain-hardening of the structure and a loss of elasticity in the dough.

For the future work development, it could be interesting to compare these results with those obtained by means of other characterization techniques, like thermal analysis [54] or microscopic observation of the molecular structure, and to better study the interactions among the dough ingredients and their influence on the dough structure and properties, trying to correlate these phenomena with the observed rheological behavior. In addition, a study of the joint effects of these parameters can be useful to complete the characterization, maybe considering the effect of different flour properties. Moreover, testing the properties after the leavening of the dough could help to understand the rheological properties' modification during this important phase of the breadmaking process.

References

1. Liu, C.Y.; Shepherd, K.W.; Rathjen, A.J. Improvement of durum wheat pastamaking and breadmaking qualities. *Cereal Chem.* **1996**, *73*, 155–166.
2. Troncone, R.; Auricchio, S.V. Gluten-sensitive enteropathy (celiac disease). *Food Rev. Int.* **1991**, *7*, 205–231. [CrossRef]
3. Cavone, G.; Dotoli, M.; Epicoco, N.; Franceschelli, M.; Seatzu, C. Hybrid Petri Nets to Re-design Low-Automated Production Processes: The Case Study of a Sardinian Bakery. *IFAC-PapersOnLine* **2018**, *51*, 265–270. [CrossRef]
4. Baire, M.; Melis, A.; Lodi, M.B.; Tuveri, P.; Dachena, C.; Simone, M.; Fanti, A.; Fumera, G.; Pisanu, T.; Mazzarella, G. A wireless sensors network for monitoring the Carasau bread manufacturing process. *Electronics* **2019**, *8*, 1541. [CrossRef]
5. Baire, M.; Melis, A.; Brunolodi, M.; Fanti, A.; Mazzarella, G. Study and Design of a Wireless Sensors Network for the Optimization of Bread Manufacturing Process. In Proceedings of the 2018 26th Telecommunications Forum (TELFOR), Belgrade, Serbia, 20–21 November 2018.
6. Fois, S.; Sanna, M.; Stara, G.; Roggio, T.; Catzeddu, P. Rheological properties and baking quality of commercial durum wheat meals used to make flat crispy bread. *Eur. Food Res. Technol.* **2011**, *232*, 713–722. [CrossRef]
7. Fanari, F.; Desogus, F.; Scano, E.A.; Carboni, G.; Grosso, M. The rheological properties of semolina doughs: Influence of the relative amount of ingredients. *Chem. Eng. Trans.* **2019**, *76*, 703–708.

8. Lindborg, K.M.; Trägårdh, C.; Eliasson, A.C.; Dejmek, P. Time-resolved shear viscosity of wheat flour doughs—Effect of mixing, shear rate, and resting on the viscosity of doughs of different flours. *Cereal Chem.* **1997**, *74*, 49–55. [CrossRef]

9. Mani, K.; Trägårdh, C.; Eliasson, A.C.; Lindahl, L. Water Content, Water Soluble Fraction, and Mixing Affect Fundamental Rheological Properties of Wheat Flour Doughs. *J. Food Sci.* **1992**, *57*, 1198–1209. [CrossRef]

10. Fanari, F.; Carboni, G.; Grosso, M.; Desogus, F. Thermogravimetric analysis of different semolina doughs: Effect of mixing time and gluten content. *Chem. Eng. Trans.* **2019**, *75*, 343–348.

11. Fanari, F.; Carboni, G.; Grosso, M.; Desogus, F. Effect of the relative amount of ingredients on the thermal properties of semolina doughs. *Chem. Eng. Trans.* **2019**, *76*, 1207–1212.

12. Delcour, J.A.; Hoseney, R.C. Chapter 12: Yeast-Leavened Products. In *Principles of Cereal Science and Technology*; AACC International, Inc.: St. Paul, MN, USA, 2010; pp. 177–206. ISBN 978-1-891127-63-2.

13. Levine, H.; Slade, L. Influences of the Glassy and Rubbery States on the Thermal, Mechanical, and Structural Properties of Doughs and Baked Products. In *Dough Rheology and Baked Product Texture*; Faridi, H., Faubion, J.M., Eds.; Van Nostrand Reinhold: New York, NY, USA, 1990; pp. 157–330.

14. Yovchev, A.G.; Stone, A.K.; Hucl, P.; Scanlon, M.G.; Nickerson, M.T. Effects of salt, polyethylene glycol, and water content on dough rheology for two red spring wheat varieties. *Cereal Chem.* **2017**, *94*, 513–518. [CrossRef]

15. Mastromatteo, M.; Guida, M.; Danza, A.; Laverse, J.; Frisullo, P.; Lampignano, V.; Del Nobile, M.A. Rheological, microstructural and sensorial properties of durum wheat bread as affected by dough water content. *Food Res. Int.* **2013**, *51*, 458–466. [CrossRef]

16. Chen, G.; Ehmke, L.; Sharma, C.; Miller, R.; Faa, P.; Smith, G.; Li, Y. Physicochemical properties and gluten structures of hard wheat flour doughs as affected by salt. *Food Chem.* **2019**, *275*, 569–576. [CrossRef] [PubMed]

17. Elz, M.C.E.; Ryan, L.A.M.; Arendt, E.K. The Impact of Salt Reduction in Bread: A Review. *Crit. Rev. Food Sci. Nutr.* **2012**, *52*, 514–524.

18. McCann, T.H.; Day, L. Effect of sodium chloride on gluten network formation, dough microstructure and rheology in relation to breadmaking. *J. Cereal Sci.* **2013**, *57*, 444–452. [CrossRef]

19. Tuhumury, H.C.D.; Small, D.M.; Day, L. The effect of sodium chloride on gluten network formation and rheology. *J. Cereal Sci.* **2014**, *60*, 229–237. [CrossRef]

20. Bernklau, I.; Neußer, C.; Moroni, A.V.; Gysler, C.; Spagnolello, A.; Chung, W.; Jekle, M.; Becker, T. Structural, textural and sensory impact of sodium reduction on long fermented pizza. *Food Chem.* **2017**, *234*, 398–407. [CrossRef]

21. Danno, G.; Hoseney, R.C. Effect of sodium chloride and sodium dodecyl sulfate on mixograph properties. *Cereal Chem.* **1982**, *59*, 202–204.

22. Angioloni, A.; Dalla Rosa, M. Dough thermo-mechanical properties: Influence of sodium chloride, mixing time and equipment. *J. Cereal Sci.* **2005**, *41*, 327–331. [CrossRef]

23. Belz, M.C.E.; Axel, C.; Arendt, E.K.; Lynch, K.M.; Brosnan, B.; Sheehan, E.M.; Coffey, A.; Zannini, E. Improvement of taste and shelf life of yeasted low-salt bread containing functional sourdoughs using Lactobacillus amylovorus DSM 19280 and Weisella cibaria MG1. *Int. J. Food Microbiol.* **2019**, *302*, 69–79. [CrossRef]

24. Beck, M.; Jekle, M.; Becker, T. Impact of sodium chloride on wheat flour dough for yeast-leavened products. I. Rheological attributes. *J. Sci. Food Agric.* **2012**, *92*, 585–592. [CrossRef]

25. Larsson, H. Effect of pH and sodium chloride on wheat flour dough properties: Ultracentrifugation and rheological measurements. *Cereal Chem.* **2002**, *79*, 544–545. [CrossRef]

26. Lynch, E.J.; Dal Bello, F.; Sheehan, E.M.; Cashman, K.D.; Arendt, E.K. Fundamental studies on the reduction of salt on dough and bread characteristics. *Food Res. Int.* **2009**, *42*, 885–891. [CrossRef]

27. Stone, A.K.; Hucl, P.J.; Scanlon, M.G.; Nickerson, M.T. Effect of damaged starch and NaCl level on the dough handling properties of a Canadian Western Red Spring Wheat. *Cereal Chem.* **2017**, *94*, 970–977. [CrossRef]

28. Aslankoohi, E.; Rezaei, M.N.; Vervoort, Y.; Courtin, C.M.; Verstrepen, K.J. Glycerol production by fermenting yeast cells is essential for optimal bread dough fermentation. *PLoS ONE* **2015**, *10*, e0119364. [CrossRef]

29. Meerts, M.; Ramirez Cervera, A.; Struyf, N.; Cardinaels, R.; Courtin, C.M.; Moldenaers, P. The effects of yeast metabolites on the rheological behaviour of the dough matrix in fermented wheat flour dough. *J. Cereal Sci.* **2018**, *82*, 183–189. [CrossRef]

30. Alvarez-Ramirez, J.; Carrera-Tarela, Y.; Carrillo-Navas, H.; Vernon-Carter, E.J.; Garcia-Diaz, S. Effect of leavening time on LAOS properties of yeasted wheat dough. *Food Hydrocoll.* **2019**, *90*, 421–432. [CrossRef]

31. Faridi, H.; Faubion, J.M. *Dough Rheology and Baked Product Texture*; Faridi, H., Faubion, J.M., Eds.; Springer: Boston, MA, USA, 1990; ISBN 978-1-4612-8207-5.

32. Dobraszczyk, B.J.; Morgenstern, M.P. Rheology and the breadmaking process. *J. Cereal Sci.* **2003**, *38*, 229–245. [CrossRef]

33. Morrison, F.A. *Understanding Rheology, Topics in Chemical Engineering*; Oxford University Press: Oxford, UK, 2001; ISBN 0-19-514166-0.

34. Amemiya, J.I.; Menjivar, J.A. Comparison of small and large deformation measurements to characterize the rheology of wheat flour doughs. *J. Food Eng.* **1992**, *16*, 91–108. [CrossRef]

35. Cox, W.P.; Merz, E.H. Correlation of dynamic and steady flow viscosities. *J. Polym. Sci.* **1958**, *28*, 619–622. [CrossRef]

36. Sun, M.; Sun, H.; Wang, Y.; Sánchez-Soto, M.; Schiraldi, D. The Relation between the Rheological Properties of Gels and the Mechanical Properties of Their Corresponding Aerogels. *Gels* **2018**, *4*, 33. [CrossRef] [PubMed]

37. Lee, H.C.; Brant, D.A. Rheology of concentrated isotropic and anisotropic xanthan solutions. 1. A rodlike low molecular weight sample. *Macromolecules* **2002**, *35*, 2212–2222. [CrossRef]

38. Vernon-Carter, E.J.; Avila-De La Rosa, G.; Carrillo-Navas, H.; Carrera, Y.; Alvarez-Ramirez, J. Cox-Merz rules from phenomenological Kelvin-Voigt and Maxwell models. *J. Food Eng.* **2016**, *169*, 18–26. [CrossRef]

39. Bistany, K.L.; Kokini, J.L. Comparison of Steady Shear Rheological Properties and Small Amplitude Dynamic Viscoelastic Properties of Fluid Food Materials. *J. Texture Stud.* **1983**, *14*, 113–124. [CrossRef]

40. Schofield, R.K.; Scott Blair, G.W. The relationship between viscosity, elasticity and plastic strength of a soft material as illustrated by some mechanical properties of flour dough IV—The separate contributions of gluten and starch. *Proc. R. Soc. Lond. Ser. A Math. Phys. Sci.* **1937**, *160*, 87–94.

41. Bloksma, A.H. Rheology and chemistry of dough. In *Wheat, Chemistry and Technology*; Khan, K., Shewry, P.R., Eds.; AACC International, Inc.: St. Paul, MN, USA, 1978; pp. 523–584.

42. Steffe, J.F. *Rheological Methods on Food Process Engineering*; Freeman Press: East Lansing, MI, USA, 1996.

43. Mainardi, F.; Spada, G. Creep, relaxation and viscosity properties for basic fractional models in rheology. *Eur. Phys. J. Spec. Top.* **2011**, *193*, 133–160. [CrossRef]

44. Sun, X.; Koksel, F.; Nickerson, M.T.; Scanlon, M.G. Modeling the viscoelastic behavior of wheat flour dough prepared from a wide range of formulations. *Food Hydrocoll.* **2020**, *98*, 105129. [CrossRef]

45. Mironeasa, S.; Codină, G.G. Dough rheological behavior and microstructure characterization of composite dough with wheat and tomato seed flours. *Foods* **2019**, *8*, 626. [CrossRef]

46. ICC. *Determination of the Total Nitrogen Content by Combustion According to the Dumas Principle and Calculation of the Crude Protein Content*; ICC: Dubai, United Arab Emirates, 2008.

47. ICC. *Gluten Index Method for Assessing Gluten Strength in Durum Wheat (Triticum Durum)*; ICC: Dubai, United Arab Emirates, 1995.

48. Phan-Thien, N.; Safari-Ardi, M. Linear viscoelastic properties of flour-water doughs at different water concentrations. *J. Nonnewton. Fluid Mech.* **1998**, *74*, 137–150. [CrossRef]

49. Malkin, A.Y. The state of the art in the rheology of polymers: Achievements and challenges. *Polym. Sci. Ser. A* **2009**, *51*, 80–102. [CrossRef]

50. Bourne, M.C.; Rao, M.A. Viscosity measurements of foods. In *Instrumental Methods for Quality Assurance in Foods*; CRC Press: Boca Raton, FL, USA, 2017; pp. 211–229. ISBN 9781351438148.

51. Tao, C.; Kutchko, B.G.; Rosenbaum, E.; Massoudi, M. A review of rheological modeling of cement slurry in oil well applications. *Energies* **2020**, *13*, 570. [CrossRef]

52. Fanari, F.; Frau, I.; Desogus, F.; Scano, E.A.; Carboni, G.; Grosso, M. Influence of wheat varieties, mixing time and water content on the rheological properties of semolina doughs. *Chem. Eng. Trans.* **2019**, *75*, 529–534.

53. Meerts, M.; Cardinaels, R.; Oosterlinck, F.; Courtin, C.M.; Moldenaers, P. The impact of water content and mixing time on the linear and non-linear rheology of wheat flour dough. *Food Biophys.* **2017**, *12*, 151–163. [CrossRef]

54. Fanari, F.; Carboni, G.; Grosso, M.; Desogus, F. Thermal properties of semolina doughs with different relative amount of ingredients. *Sustainability* **2020**, *12*, 2235. [CrossRef]