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# Instantaneous wheat dough relaxation by alternating current electric fields

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ABSTRACT

Wheat dough exhibits poor processibility immediately after a mechanical strain, such as mixing or laminating. For proper dough processing, the relaxation of gluten network must occur during a process interrupting resting time of usually 10–25 min. The ability of electric fields to induce modifications in biological structures within seconds, makes an application of this technique reasonable for accelerating the structural relaxation during dough resting. Applying alternating current electric fields (AC-fields) to wheat dough, causes viscoelastic properties corresponding to those of rested dough: AC-fields (110–260 V, 1–5 s) increased extensibility and softness of dough corresponding to resting times up to 25 or rather 50 min. Based on this significant acceleration of structural relaxation, an almost continuously dough processing after a mechanical stress by a simple and short post-processing step without changing dough's gas release ($\Delta V_{total} \leq 3.0\%$) as well as holding capacity ($\Delta$gas retention $\leq 1.47\%$) and the textural properties of the product appears feasible.

## 1. Introduction

The input of mechanical energy to flour and water is a requirement for dough formation, but simultaneously hampers an immediate dough processing afterwards. The gluten-based polymeric matrix, which is formed during kneading, corresponds to a three-dimensional cohesive network with viscoelastic properties. The interactions of the network relevant gluten proteins, gliadin and glutenin, are based on non-covalent interactions, like hydrogen bonds, ionic or hydrophobic forces. In addition, covalent disulphide bridges, mediated via cysteine residues, affect network structure and functionality significantly (Wieser, 2007). According to Schiedt et al. the rheological behavior of dough results from a combination of microstructural and molecular properties of dough and can be assigned to the following three components (Schiedt et al., 2013): the influence of starch-gluten interactions (1), starch-starch interactions (2) and the state of the gluten network (3). In particular with regard to large mechanical deformations (e.g. kneading or laminating), gluten network is of significant importance (Amemiya and Menjivar, 1992). In consequence, gluten network properties are regarded as responsible for a limited processibility of wheat dough directly after a mechanical stress (Schiedt et al., 2013; Belton, 1999; Albrecht, 2003). The imposition of mechanical stress extends and aligns the gluten polymers (Belton, 2005). Compared to an entangled polymer system, an aligned system offers a higher resistance against deformation combined with a strong retraction force, thus, explaining the poor processibility of previously mechanical stressed gluten. Since the aligned conformation of gluten polymers does not correspond to the favorited state, a restructuring/re-polymerization takes place over time. According to Kim et al., who suppose a mechanism of gluten relaxation, the absence of mechanical stress promotes disulphide interchange reactions at the early state of relaxation process. Simultaneously, the polymers are prone to a random orientation. The faster disulphide interchange reactions increase the size of the aligned polymers and supports the formation of non-covalent interactions between the aligned polymers at the beginning of relaxation. However, polymer orientation becomes more and more random with increasing rest time. Therefore, non-covalent interactions decrease/become weaker (Kim et al., 2008). Regarding the rheological properties, this means a reduced resistance to deformation as well as restoring force and thus, a requirement for dough processibility. Since these structural rearrangements are time consuming and cause a compliance of rest periods between processing steps, more effective alternative are of great interest for a continuous wheat dough processing. In principle, techniques, which are able to modify biological structures, could be appropriate to accelerate the structural rearrangement during resting. Especially electric fields seem to be promising due to their ability to modify protein-based structures. Since peptides exhibit a dipole moment of approximately 3.46 Deby (Hol et al., 1978; Derr et al., 2020) their structure could be modified due to the resulting forces of an electric field. The modifications are assumed to occur at secondary and tertiary level (Zhao et al., 2012) and thus,

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maintain the molecular structure. In general, an electric field cause an orientation of an existing dipole as well as an induction of further dipoles due to a shifting of charge carriers within atoms/molecules, a movement of free electrons or charged particles and a change of the dielectric constant (Wada, 1976; Martin et al., 2018). This primarily affects non-covalent interactions. Since these interactions, especially hydrogen bonds, determine the elasticity of wheat dough (Belton, 1999), an electric field is assumed to affect dough structure comparable to the structural rearrangement during resting times and consequently, cause comparable viscoelastic properties. To limit the distorting impact of direct current electric fields on gluten networks, which was already demonstrated by Aibara et al. (1992), an alternating current electric field (AC-field) should be more appropriate. Therefore, this study assesses the impact of AC-fields on the rheological properties of wheat dough in comparison to resting times. In addition, the capability of AC-fields[1] to enable a more continuous dough processing by skipping intermediate resting times (between rounding/molding) of thin loaf production is assessed by baking tests.

## 2. Experimental

### 2.1. Wheat dough preparation

The optimum water absorption (in consideration of flour moisture) was determined in accordance to AACC method 54–21.02 using a doughLAB (Perten Instruments, Hamburg, Germany). For dough preparation 1000 g commercial wheat flour type 550 (Rosenmühle Landshut, Germany), and additionally demineralized water (54.92 parts), NaCl (1.8 parts), sucrose (2.0 parts) and fresh yeast (3.0 parts, only for rheofermentometer and baking tests) were mixed for 60 s at a speed of 100 rpm and kneaded for 360 s at a speed of 200 rpm in a spiral-kneader (Diosna, Osnabrück, Germany). To control final dough temperature, current flour temperature and temperature increase during kneading were considered by adjusting the temperature of the added water.

### 2.2. Dough preparation from flour of different gluten quantity

Six flours, three with a wet gluten quantity $<30\%$ (Keks, Primus I, Primus II) and three with a wet gluten quantity $> 30\%$ (Bun, Asano, Opal) were used. For each flour, optimum water adsorption (in consideration of flour moisture) and kneading time were determined in accordance to AACC method 54–21.02. Based on 50 g flour the appropriate amount of distilled water was added and the flour water mixture was kneaded for the corresponding optimum time at a speed of 63 rpm at 30 °C in a home-built z-kneading system.

### 2.3. Application of AC-fields to wheat dough

AC-fields with a frequency of 50 Hz and a voltage of 110–260 V were generated by the laboratory power supply BRS 2200 (BLOCK Verden, Germany). To apply AC-fields to wheat dough, two lateral limiting plates with a saw tooth profile at the top were mounted on a base plate. Both sides of the lateral limiting plates were equipped with an electrode (surface area $5 \times 10^{-3}$ m$^2$). One electrode was mounted at a fixed position, whereas the other electrode remains moveable to enable a treatment of different dough amounts. The moveable electrode is protected from slipping by mounting a fixation tap in a corresponding notch of the saw tooth profile (see Fig. 1). For safety reasons, the experimental setup is covered with a box, which is equipped with a magnet for closing the electrical circuit by a reed relay. Directly after kneading the dough was placed between the electrodes and the position of the moveable electrode was fixed to guarantee close contact to the dough (see Fig. 1, right side). To enable a reproducible treatment, complete coverage of the electrodes surface and an almost flush finish of the dough were ensured for every treatment. Electric circuit was closed by a reed relay after placing the upper part of the box (equipped with a magnet) on top of the experimental setup. Application time was limited to 5.0 s for 110–170 V, to 3.0 s for 170–230 V and to 2.0 s for 260 V.

### 2.4. Rheological characterization

To estimate the efficiency of AC-fields on dough relaxation, rheological tests were applied to wheat dough directly after kneading as well as after certain resting times, or rather to wheat dough, which was exposed to the AC-field directly after kneading. All analysis were performed in triplicate.

#### 2.4.1. Kieffer dough extensibility rig

Based on the method of Dunnewind et al. (2003), a texture profile analyzer (TPA) (Stable Micro Systems, Godalming, UK), equipped with a Kieffer dough extensibility rig (Stable Micro Systems) and a 10 kg load cell, was used for evaluating the extensibility of dough depending on resting time or the exposure to AC-fields by measuring the force, which is required for elongating a dough strand until rupture (force in elongation mode). The test was performed with a pre-test speed of 2 mm/s, a test speed of 3.3 mm/s, a post-test speed of 10 mm/s and a trigger force of 0.05 N. Directly after kneading, dough was pressed in an appropriate molder with indentations for dough strand formation. To prevent drying-out and facilitate the removal of dough strands the indentations were coated with paraffin oil. Before measurement dough was allowed to rest for 5, 10, 15, 25, 37 or 50 min at 30 °C, or was directly exposed to the AC-field within the molder. Extensibility is calculated using the distance covered by the hook until strand rupture ($y$), the length of the dough at the beginning of the experiment ($l_0$) as well as at the end ($l_1$) with equations (1) and (2) (Dunnewind et al., 2003).

$$l_1 = 2^* \sqrt{\left(\frac{l_0}{2}\right)^2 + y^2} \qquad \text{Eq 1}$$

$$Extensibility\ (\%) = \left(\frac{l_1 - l_0}{l_0}\right)^* 100 \qquad \text{Eq 2}$$

#### 2.4.2. Dough softness

For evaluating dough softness, the measurement of the appearing normal force during sample compression, according to the practical tips of TA instruments (TA instruments), is appropriate. After kneading, dough rested for 0 or 50 min in a small sealed container at 30 °C or was directly exposed to the AC-field. Dough samples of 11.5 g were weighted, carefully rounded and placed between the plate-plate geometry (crosshatched, 40 mm diameter) of a rheometer (ARG2, TA Instruments New Castle, USA). Before every measurement, normal force was zeroed. The upper plate moved down with a linear velocity of 200 μm/s until a final gap of 3 mm was reached. During this downward movement, the occurring normal force was measured until the final gap position was reached.

#### 2.4.3. Flow relaxation test

After kneading, dough rested for 5, 10, 15, 25, 37 or 50 min in a small sealed container at 30 °C or was directly exposed to the AC-field. Dough sample was placed in a MRC 502 rheometer (Anton Paar, Ostfildern-Scharnhausen, Germany) equipped with a crosshatched plate-plate-plate geometry of 25 mm diameter. Gap was set to 2000 μm, the sample edges were trimmed and covered with paraffin oil. A strain of 100% was applied to the dough sample with a shear rate of 0.0208 s$^{-1}$. Subsequently, flow relaxation behavior was monitored at the constant strain of 100% and evaluated by the time, which is necessary to reduce the initial stress at 100% strain to 50% (Don et al., 2005). Measurement was performed at 30 °C.

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[1] AC-fields, alternating current electric fields.

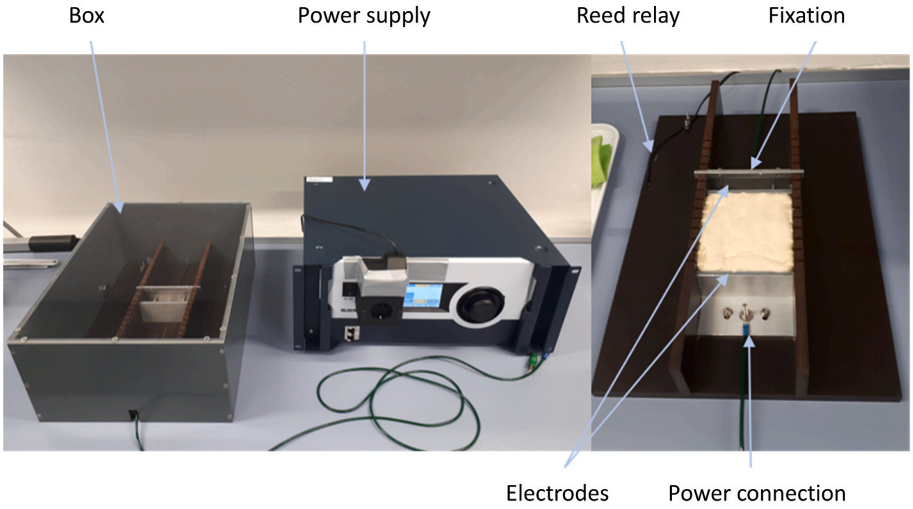


**Fig. 1.** Experimental setup for the application of AC-fields to wheat dough.

### 2.5. *Confocal laser scanning microscopy*

Directly after kneading the whole dough was exposed to the AC-field or rather just stained for the reference sample. For staining 15 μl of rhodamine b, which was dissolved in water (0.01 g/10 ml), were dropped at dough surface. For visualization of gluten structure, an eclipse Ti–U inverted microscope with an e-C1 plus confocal system (Nikon GmbH, Düsseldorf, Germany), a Plan Apo VC 60x/1.40 oil objective and 534 nm laser was used. Microscopic analysis was performed in triplicate based on three different doughs. Three images of each sample, which was exposed to the AC-field, were taken at different positions. In contrast, for the evaluation of time-based dough relaxation, images were taken after defined resting times at one position. Each image had resolution of 1024 × 1024 pixel (size 215 × 215 μm).

### 2.6. *Gas forming and holding properties*

Gas formation, based on the yeast activity, and gas holding properties of dough were monitored with a rheofermentometer (F3, Chopin, Villeneueve-La-Garenne Cedex, France). A dough sample of 315 g was exposed to the AC-field (260 V, 2 s), or rather directly (reference) placed into the fermentation basket and weighted with two 0.5 kg weights. Gas forming and holding were monitored over a period of 180 min at a temperature of 30 °C. Analysis was performed in triplicate.

### 2.7. *Baking tests and quality assessment*

After kneading, a 660 g dough piece was rounded and stored in the proofing chamber (30 °C, 80% relative humidity) for 0, 10 or 20 min of resting (reference samples) or directly exposed to the AC-field (260 V, 2 s). The subsequent proceeding dough, which was exposed to an AC-field, and rested dough was equal. The 660 g dough piece was divided into three pieces, each with a weight of 220 g, and placed into loaf pans. For final proofing, dough was stored in the proofing chamber at 30 °C, 80% relative humidity for 60 min. Baking was performed in a Matador 12.8 oven (Werner & Pfleiderer Lebensmitteltechnik GmbH, Dinkelsbühl, Germany) at 220 °C top and 230 °C bottom heat with 0.5 l initial steam for 25 min. Afterwards, breads were cooled down for 2 h at room temperature. For the evaluation of bread quality, the bread volume, crumb hardness and pore structure were analysed. The specific volume was determined with a laser-based volumeter (Volscan BVM-L 370, TexVol Instruments, Viken, Sweden). A texture profile analyzer (TA.XT2, Stable Micro System, Godalming, England), equipped with a 50 kg load cell, measured the crumb hardness according to AACC standard 74-09. Briefly, two slices, each of 12.5 mm thickness, were compressed (40%) after exceeding the trigger force (0.05 N) with a compression plunger (diameter 25 mm) and a compression speed of1 mm/s in two cycles with a rest of 5 s between the cycles. Crumb hardness is defined as the maximum force of the first compression. For pore structure analysis, a bread slice from the middle part of the bread was used. After taking a photo, a section of 401 × 401 pixels was analysed regarding the number and area of pores, using MATLAB 2020a based on MATLAB's app designer, which provides a set of interactive UI components, which can be used within a fully integrated version of MATLAB editor. The autonomous algorithm was designed following a morphological image processing and colour/size based segmentation approaches. Regarding the image acquisition, all images were obtained at the same camera and lens settings, as well as, at the same transversal position with respect to the camera location to ensure a stable focus, contrast, and brightness of the obtained images. To obtain the spatial resolution of the acquired images, an image of a reference object (with a previously known dimensions) was acquired where the spatial resolution was determined depending on the instantaneous field of view (Fahmy et al., 2020). First, the acquired crumb images were converted to grayscale by using a weighted average luminous model. An equation of perceived luminance was used for the RGB channels of each image pixel: $0.299R + 0.587G+0.114B$ (Anderson et al., 1996). Then, the contrast of the grayscale images was enhanced using morphological operations by a series of erosion and dilation techniques. Second, the crumb images were converted to black and white using Otsu's method for clustering-based image thresholding (Otsu, 1979). Third, the black and white images are complemented to prepare for successful labelling of the pores. Connected components within a single image (representing the pores) were labelled using different colors for segmenting and area-based sorting of the pores (Haralick and Shapiro, 1992). Finally, the spatial resolution was used to convert pores' pixel count into SI units where the pores were categorized depending on their size.

Baking trials were conducted as triplicates with 3 breads per replicate.

### 2.8. *Statistical analysis*

The statistical analysis was performed with GraphPad Prism 6 (Version 6.01, GraphPad Software Inc., La Jolla, USA). One-way ANOVA with Tukey's multiple comparisons tests were used to confirm corresponding properties of wheat dough after resting and wheat dough exposed to AC-fields.

## 3. Results and discussion

### 3.1. *Wheat dough rheology depending on resting time and AC-field exposure*

The structural rearrangement of gluten after a mechanical stress affects the rheological properties of dough. In general, dough becomes softer, more extensible and less elastic with increasing resting time (Létang et al., 1999; Weegels et al., 1996). To assess these properties, three different rheological tests are used. The Kieffer-rig test evaluates the extensibility, a compression test the softness and a flow relaxation test the elasticity (Lichtendonk et al., 2000). All previously described rheological modifications become visible for the rested wheat dough: During a resting time of 50 min extensibility increases linear (linear regression with $r^2$ 0.87) from 166.1 ± 17.7% to 475.74 ± 45.2% (Fig. 2 a). Furthermore, an increase of dough softness during resting becomes visible by the decrease of the desired force to elongate the dough strand (Fig. 2b), respectively to compress the dough (Fig. 2c). For elongation, force decreases from 0.50 ± 0.07 N to 0.29 ± 0.04 N and for compression from 29.98 ± 2.9 N to 18.03 ± 1.1 N over a resting time of 50 min. According to the loop and train model, the structural relaxation correlates with the formation of loop regions (Belton, 1999). Compared to train regions, loops are slightly deformable. Therefore, the increasing extensibility and softness indicate the loss of polymer alignment over resting time. The flow relaxation behavior in Fig. 2 d) shows a slight (not significant) decrease of flow relaxation halftime within the first 15 min of resting. A prolongation of resting time up to 50 min cause a significant increase of flow relaxation halftime to 26.3 ± 1.1 s. An increase of flow relaxation halftime over resting time is in accordance to literature (Don et al., 2005) and implies a higher elastic response of the material under the application of a constant stress due to the formation of more persistent interactions between the structural elements (Lichtendonk et al., 2000).

For evaluating the effect of AC-fields on dough rheology, an appropriate set of parameters has to be defined to avoid an excessive increase of dough temperature. The acceptable increase of dough temperature was limited to 2 °C. This enables treatments up to 5 s for 110–170 V, to 3 s for 170–230 V and to 2 s for 260 V. In general, the exposure of wheat dough to AC-field of 110–260 V for 1–5 s causes rheological properties corresponding to rested dough of different duration (compare Fig. 2 a-d). Therefore, the application of AC-fields can be regarded as a highly efficient method for accelerating the structural relaxation of wheat dough structure during resting. Depending on the analysed rheological property, the effectivity of AC-fields to modify the mechanical dough properties varies. This demonstrates Fig. 2 for selected AC-fields of varying combinations of voltage and application time. In terms of elasticity and softness in compression mode, the lowest AC-field (110 V, 3 s) induces an effect corresponding to 10–15 min resting time, whereas stronger AC-fields can increase this effect corresponding up to 25 min resting time for the elasticity, or rather 50 min resting time for the softness. Also, the force in elongation mode shows lower corresponding resting times for the lowest AC field of 110 V 3 s (10–37 min) and higher corresponding resting times (10–50 min) for higher AC-fields. Regarding the flow relaxation halftime, only the lowest AC-field (110 V 3 s) shows corresponding relaxation halftimes to rested dough of 25–37 min. Higher AC-fields exceed the effect of resting time and increase the relaxation halftime to values ≥ 31 s. In general, the rheological results indicate a structural modification of wheat dough due to the exposure to AC-fields. However, the varying effectivity of AC-fields regarding the corresponding resting times based on the different rheological tests, suggest a deviating structural rearrangement to that of rested dough. The supposed mechanism will be discussed later in chapter 3.3. The

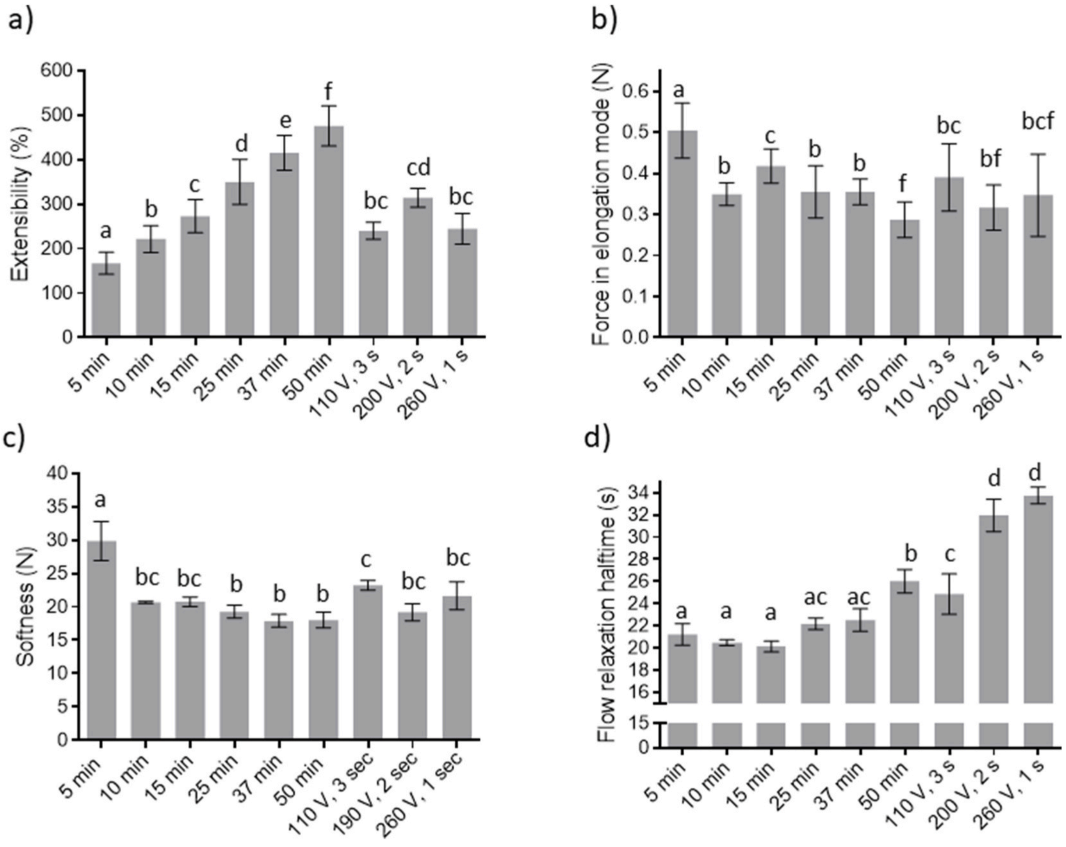


**Fig. 2.** Comparison of rheological dough properties depending on resting time or exposure to AC-fields. Measurement of maximum extensibility a) of a dough strand and force in elongation mode b) until rupture (Kieffer dough extensibility rig). Measurement of normal force in compression mode (softness) during a compression test in c) and measurement of flow relaxation halftime in d). Different letters indicate significant differences between means (ANOVA, $p < 0.05$).

consideration of strength (110–260 V) or application time (1–5 s) of the AC-fields and the resulting impact on dough rheology reveals no correlations. Therefore, an instantaneous effect of AC-fields on the structural relaxation of wheat dough is assumed.

### 3.2. *Impact of protein quantity on dough rheology depending on resting time and AC-field exposure*

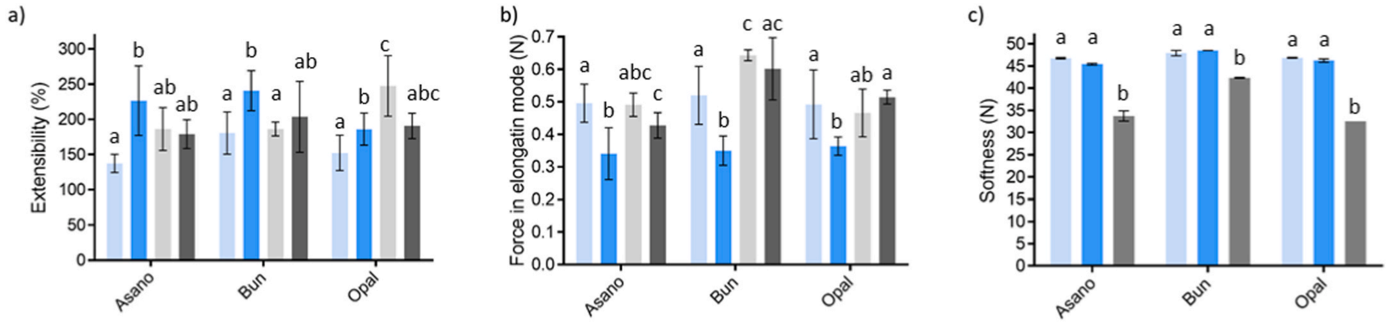
The quality and quantity of gluten protein significantly affect dough rheology. Therefore, six flours (single variety) of two different categories of gluten quantities ($<$ or $>$ 30% wet gluten) were analysed regarding their rheological modifications due to resting respectively the exposure to an AC-field. Due to the limited sample amount of the single variety flours, only a limited experimental setup was used, which gives the most processing relevant information based on defined AC-field settings of high effectivity. Flours high in protein (wet gluten $\geq$ 30%) show a significant increase of extensibility (Fig. 3 a), as well as decrease of force in elongation mode (Fig. 3 b), but a constant softness in compression mode (Fig. 3 c) over resting time. The impact of AC-fields on dough rheology shows Fig. 3 for two selected AC-fields (170 V 2 s; 260 V 2 s). Interestingly, after the exposure to AC-fields, dough behaves appropriate to rested dough regarding the extensibility, but contrary regarding the force in elongation mode and the softness in compression mode. Compared to non-rested dough, force in elongation mode remains constant or even increases, but softness in compression mode decreases after the exposure to an AC-field. This supports the previously assumed divergence in the structural rearrangement induced by time or AC-fields. Nonetheless, concerning the processibility of dough, an important increase of extensibility can be achieved by the exposure of high-protein dough (wet gluten $\geq$ 30%) to AC-fields.

Regarding the low-protein flours, resting time induce a significant decrease of force in elongation mode (Fig. 3 e), whereas softness in compression mode is only affected for Primus II (Fig. 3 f) and extensibility is not affected at all (Fig. 3 d). Due to the low amount of gluten protein, only weak network structures can be developed during kneading. Consequently, the occurring structural rearrangement after mechanical stress is expected to be lower. In contrast, the exposure to AC-fields causes a significant increase of extensibility or rather softness in compression mode for keks and Primus I, respectively all flours. However, force in elongation mode remains constant or even increases compared to non-rested samples. Consequently, the effect of AC-fields is comparable to that of high-protein flours. Based on the lower protein content, minor changes over resting time, as well as the exposure to AC-fields, appear reasonable, since the occurring gluten-based structural rearrangement is lower after a mechanical stress and could be dominated by of other dough components, like starch or the amount of water (hydration). In general, minor effects of resting time on dough rheology of low protein flours are in agreement to literature (Lindborg et al., 1997). Furthermore, stress relaxation occurs faster for low-protein dough, probably, based on the lower amount of entanglements (Rao et al., 2000). Therefore, the time consumption of sample preparation could lower the detectable amount of structural rearrangement of low-protein doughs.

### 3.3. *Discussion of structural rearrangement induced by resting time and AC-fields*

The above shown rheological results demonstrate a tremendous acceleration of structural rearrangement induced by the exposure to AC-field for 1–3 s. Depending on flour quality, the analysed rheological values are in full (commercial bread-wheat quality) or partial (low/high-protein flours) accordance with those of rested dough. The observed rheological properties after the exposure to AC-fields correspond to different resting times, depending on the applied analysis. In

**High-protein quantity (wet gluten > 30 %)**



**Low-protein quantity (wet gluten < 30 %)**

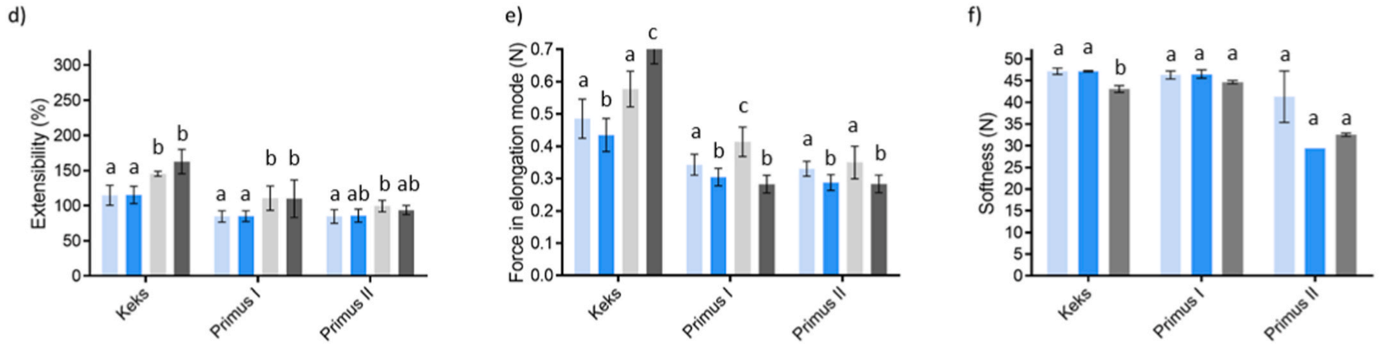


**Fig. 3.** Impact of protein quantity (high and low) on the rheological dough properties depending on resting time or exposure to AC-fields. Measurement of maximum extensibility (a & d) of a dough strand and force in elongation mode (b & e) until rupture (Kieffer dough extensibility rig) for dough after 5 min resting (▢), 25 min resting (🟦), exposure to AC-fields of 170 V for 2 s (⬜) and 260 V for 2 s (⬛). Measurement of normal force (softness) during a compression test in c) and f) after 5 min resting (▢), 25 min resting (🟦), exposure to AC-field of 200 V for 1 s (⬛). Different letters indicate significant differences between means (ANOVA, $p < 0.05$).

combination with the opposed effects for low/high protein flours in softness due to resting or AC-fields, a divergent mechanism of structural rearrangement induced by AC-fields is assumed. The time-based structural rearrangement after kneading corresponds to a reconfiguration of covalent disulphide bonds and non-covalent interactions and results in a transfer of aligned polymers into coiled and random configuration. These conformational changes are hardly visible at the microscopic scale (compare Fig. 4 a and b). However, the exposure to AC-fields leads to a notable modification. Fig. 4 c) shows an alignment of gluten polymer after the application of 260 V for 2 s. This effect is already known to occur in stronger electric fields (Aibara et al., 1992), but also seems to appear here. Interestingly, an alignment caused by mechanical stress, hampers dough processibility, whereas an AC-field-based alignment improves it. Stretching the gluten polymers by a mechanical force is accompanied by pulling apart constituents of interactions and causing structural break down. In contrast, an electric field could change the affinity of constituents in existing interactions among each other, due to an orientation of dipoles, an induction of further dipoles or a movement of free electrons/charged particles (Wada, 1976; Marklund et al., 2017). In consequence, structural modification induced by an electric field is rather based on a shift of the equilibrium state of the system. In particular, electrostatic-based interactions will be affected by an electric field. Regarding wheat dough, this would mainly affect hydrogen bonds, which are important for the elasticity of the dough system (Belton, 1999). If the exposure of wheat dough to an electric field lowers the affinity of hydrogen bond formation, due to a reorientation of the electronegative parts (oxygen of water and nitrogen of proteins) in the electric field, relaxation of mechanical stress could be accelerated. However, to achieve this shielding of existing electrostatic interactions in the dough system, a critical field strength seems to be reasonable. If the critical field strength is achieved, the existing electrostatic interactions would be shielded and structural relaxation could be accelerated. This could also explain the independency of the observed rheological effects from the strength or application time of the AC-field as described in chapter 3.1, since the critical field strength was exceeded for all settings. Furthermore, the impact of the electric field could be strengthened due the use of alternating fields (AC-field). The consistent reorientation of the electric field with a frequency of 50 Hz could hinder the formation of persistent interactions during the exposure of dough to the AC-field and therefore, maintain the process of stress relaxation as long as dough is exposed the AC-field.

Compared to rested dough, those structural rearrangement results in a random and coiled conformation, dough, which was exposed to the AC-field, is assumed to remain the aligned conformation. Overall, the rheological results indicate a tremendous ability of AC-fields to increase the processibility of dough within seconds. Independent of flour quality, processing relevant rheological parameter (elasticity, softness, flow relaxation-halftime) can achieved corresponding to resting times between 15 and 50 min.

### 3.4. Impact of resting time and AC-fields on gas-forming/-holding and bread texture

Exposing microorganisms to an electric field can induce lethal effects. Furthermore, the induced structural modification of wheat dough could affect gas-holding capacity. Therefore, the impact of the AC-field with the highest voltage used (260 V) and whose longest application time (2 s) is analysed, regarding the gas-forming and -holding capacity by rheofermentometer and baking tests. Within the 3 h fermentation cycle of the rheofermentometer a specific dough volume of 5.34 ± 0.00 $cm^3/g$ was achieved after a previous exposure of dough to the AC-field. Compared to the specific volume of the reference dough (5.17 cm ± 0.03 $^3/g$), the specific volume of the AC-field exposed dough is slightly (but statistical significantly) higher, whereas the retention capacity is negligible lower. Even the rheofermentometer is temperature controlled (30 °C), the slightly higher temperature ($< 2\ ^\circ C$) at the beginning of the fermentation cycle of the AC-field exposed dough, is probably responsible for the higher specific volume. Therefore, the results of the rheofermentometer tests are assessed as comparable for the reference and the dough, which was exposed to AC-fields. For analysing the effect of AC-fields on the baking performance, reference samples with different resting times (0, 10 or 20 min) between kneading and further processing were compared with dough, which was exposed to AC-fields (instead of resting times) after kneading. The analysis of the reference breads demonstrate the importance of an appropriate resting time between kneading and further processing on the bread quality (compare Table 1). Without resting, the specific loaf volume is significantly lower, which consequently results in a higher crumb hardness. In contrast, with dough resting times, the specific loaf volume increases, whereas crumb hardness decreases and in consequence a less dense crumb structure results, which becomes visible by the analysis of crumb structure. The number of pores per slices significantly decreases whereas the pore area per slice increases as longer the resting time. This corresponds to destabilization mechanisms, like coalescence or disproportionation, of small gas bubbles and results in a lower number of larger gas bubbles. Regarding the analysed quality parameters, the exposure of dough to AC-fields shows corresponding properties to 10–20 min rested dough, except a higher pore area (compare Table 1). In conclusion, any reduction of gas-forming or -holding properties due to the exposure of dough to AC-fields can be excluded. Thus, a huge increase of process efficiency will be possible, since a time difference of 10–20 min (resting time) in the processing of dough to bread can be compensated by the exposure of dough to an AC-field for a few seconds (1–5 s). The comparable loaf volume of rested dough and AC-field exposed dough is, at least in parts, attributed to the initial higher dough temperature ($< 2\ ^\circ C$). However, an accelerated consumption of different sugars by wine yeast, which were

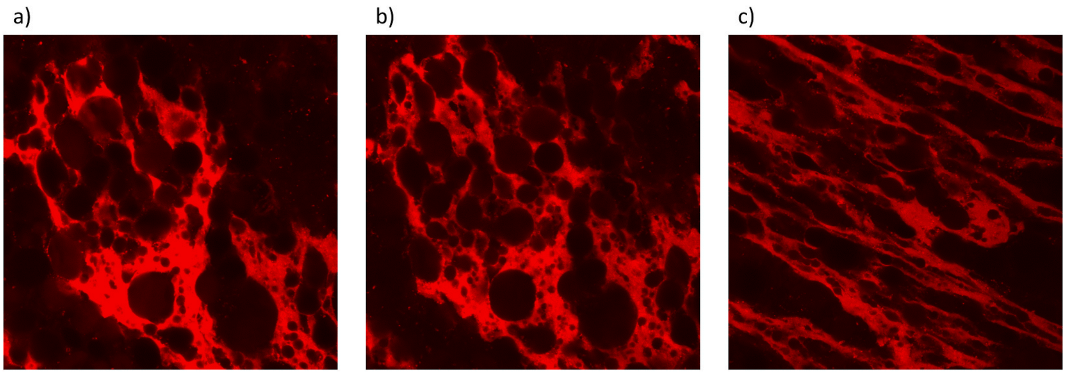
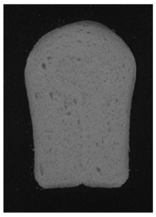
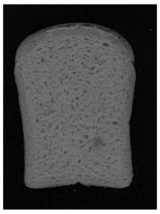
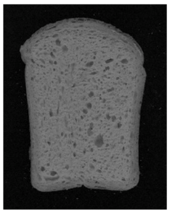


**Fig. 4.** Visualization of gluten structure via confocal laser scanning microscopy. Gluten structure after 5 min resting in a), after 50 min resting in b) and after the exposure to an AC-fields of 260 V for 2 s in c).

**Table 1**
Impact of AC-fields on gas-forming/-holding properties of dough and texture properties of breads in comparison to rested dough. Based on the flour amount, 3% of fresh yeast were added. Different letters indicate significant differences between means (ANOVA, $p < 0.05$).

| Gas-forming/-holding capacity of | | | | |
|---|---|---|---|---|
| **Dough** | *Reference* | | | *260 V, 2 s* |
| Specific volume ($cm^3/g$) | $5.17 \pm 0.03^{a}$ | | | $5.34 \pm 0.00^{b}$ |
| Gas retention (%) | $86.07 \pm 0.94^{a}$ | | | $84.60 \pm 0.61^{a}$ |
| **Crumb** | 0 min *resting* | 10 min *resting* | 20 min *resting* | *260 V, 2 s* |
| Specific loaf-volume ($cm^3/g$) | $2.73 \pm 0.06^{a}$ | $2.87 \pm 0.09^{b}$ | $2.93 \pm 0.02^{b}$ | $3.03 \pm 0.10^{b}$ |
| **Texture-related properties** | | | | |
| | 0 min *resting* | 10 min *resting* | 20 min *resting* | *260 V, 2 s* |
| Hardness (N) | $4.22 \pm 0.39^{a}$ | $2.45 \pm 0.41^{b}$ | $2.37 \pm 0.35^{b}$ | $2.63 \pm 0.23^{b}$ |
| Number of pores/slice (–) | $603 \pm 55^{a}$ | $354 \pm 56^{b}$ | $244 \pm 42^{b}$ | $288 \pm 28^{b}$ |
| Pore area/slice (%) | $25.95 \pm 3.09^{a}$ | $29.38 \pm 4.69^{a}$ | $34.54 \pm 4.89^{a}$ | $36.13 \pm 2.00^{b}$ |
| Pore structure |  |  |  |  |

previously exposed to an electric field, could already be demonstrated (Mattar et al., 2013). In consequence, an enhanced activity of yeast in wheat dough due to the impact of AC-fields cannot be excluded and could contribute to a higher loaf volume.

## 4. Conclusion

The presented approach of exposing wheat dough to AC-fields of 110–260 V for 1–5 s demonstrates a structural rearrangement of wheat dough structure within seconds. Even the structural rearrangement differs from that of a time-based relaxation (rested wheat dough), the resulting rheological properties are comparable. The supposed mechanism of AC-field induced structural rearrangement mainly bases on the shielding of weaker electrostatic interactions, in particular hydrogen-bonds, and facilitated network relaxation by the alternating orientation in the electric field. Consequently, an immediately processing of dough after a mechanical stress becomes possible. Depending on gluten quantity, the efficiency of AC-fields to affect the mechanical properties varies. In addition, changes of electric conductivity, based on ion content, sample mass, or aeration stage, influence the efficiency of AC-fields. Therefore, a consideration of these factors is necessary for a successful adaptation and implementation in an industrial application. According to the current state-of-the-art, no other technology enables an almost continuously dough processing after a mechanical stress by a simple and short post-processing (exposure to AC-field). Although, there are some possibilities for continuous dough processing, like extrusion-based processes or the chorleywood bread process, these techniques are just applicable in huge dimensions or are accompanied by modified textural properties. Due to this simple technology, which is necessary for exposing dough to AC-fields, the application is not limited to defined processing steps or machines. An implementation in existing process workflows seems feasible. Beside the presented application after kneading, an application in the process of dough laminating appears also reasonable. In summary, the exposure of wheat dough to an AC-field offers a process, which enables extensibility, softness and elasticity corresponding to rested wheat dough in a few seconds without a significant change of gas formation/holding capacity and texture properties of bread.

## Author statement

**Silvia Brandner**: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft **Thomas Becker**.: Supervision **Mario Jekle**: Writing – review & editing

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## References

Aibara, S., Hisaki, K., Watanabe, K., 1992. Effects of high-voltage electric field treatment on wheat dough and bread-making properties. Cereal Chem. 69 (4), 465–467.

Albrecht, T., 2003. In: Fachkunde Bäcker/Bäckerin: Praxis und Theorie, first ed. Fachbuchverl. Pfanneberg, Haan-Gruiten.

Amemiya, J.I., Menjivar, J.A., 1992. Comparison of small and large deformation measurements to characterize the rheology of wheat flour doughs. In: BORWANKAR, R., SHOEMAKER, C.F. (Eds.), Rheology of Foods. Elsevier, Amsterdam, pp. 91–108.

Anderson, M., Motta, R., Chandrasekar, S., Stokes, M., 1996. Proposal for a standard default color space for the internet—sRGB. In: Proc. IS&T/SID 4th Color Imaging Conf.: Color Science, Systems Applications. Proc. IS&T/SID 4th Color Imaging Conf.: Color Science, Systems Applications, pp. 238–246.

Belton, P.S., 1999. Mini review: on the elasticity of wheat gluten. J. Cereal. Sci. 29 (2), 103–107. https://doi.org/10.1006/jcrs.1998.0227.

Belton, P.S., 2005. New approaches to study the molecular basis of the mechanical properties of gluten. J. Cereal. Sci. 41 (2), 203–211. https://doi.org/10.1016/j.jcs.2004.06.003.

Derr, J.B., Tamayo, J., Clark, J.A., Morales, M., Mayther, M.F., Espinoza, E.M., Rybicka-Jasińska, K., Vullev, V.I., 2020. Multifaceted aspects of charge transfer. Phys. In: Physical Chemistry Chemical Physics : PCCP, vol. 22, pp. 21583–21629. https://doi.org/10.1039/D0CP01556C, 38.

Don, C., Lichtendonk, W.J., Plijter, J.J., van Vliet, T., Hamer, R.J., 2005. The effect of mixing on glutenin particle properties: aggregation factors that affect gluten function in dough. J. Cereal. Sci. 41 (1), 69–83. https://doi.org/10.1016/j.jcs.2004.09.009.

Dunnewind, B., Sliwinski, E.L., Grolle, K., Vliet, T., 2003. The kieffer dough and gluten extensibility rig - an experimental evaluation. J. Texture Stud. 34 (5–6), 537–560. https://doi.org/10.1111/j.1745-4603.2003.tb01080.x.

Fahmy, A.R., Becker, T., Jekle, M., 2020. 3D printing and additive manufacturing of cereal-based materials: quality analysis of starch-based systems using a camera-based morphological approach. Innovat. Food Sci. Emerg. Technol. 63, 102384. https://doi.org/10.1016/j.ifset.2020.102384.

Haralick, R.M., Shapiro, L.G., 1992. Computer and Robot Vision, ume 1. Addison-Wesley.

Hol, W.G., van Duijnen, P.T., Berendsen, H.J., 1978. The alpha-helix dipole and the properties of proteins. Nature 273 (5662), 443–446. https://doi.org/10.1038/273443a0.

Kim, Y.-R., Cornillon, P., Campanella, O.H., Stroshine, R.L., Lee, S., Shim, J.-Y., 2008. Small and large deformation rheology for hard wheat flour dough as influenced by mixing and resting. J. Food Sci. 73 (1), E1–E8. https://doi.org/10.1111/j.1750-3841.2007.00599.x.

Létang, C., Piau, M., Verdier, C., 1999. Characterization of wheat flour–water doughs. Part I: rheometry and microstructure. J. Food Eng. 41 (2), 121–132. https://doi.org/10.1016/S0260-8774(99)00082-5.

Lichtendonk, W.J., Kelfkens, M., Orsel, R., Bekkers, C.A., Plijter, J.J., 2000. The impact of water-soluble pentosans on dough properties. In: Shewry, P.R., Tatham, A.S. (Eds.), Wheat Gluten. The Royal Society of Chemistry, pp. 512–518.

Lindborg, K.M., Trägårdh, C., Eliasson, A.-C., Dejmek, P., 1997. Time-resolved shear viscosity of wheat flour doughs—effect of mixing, shear rate, and resting on the viscosity of doughs of different flours. Cereal Chemistry Journal 74 (1), 49–55. https://doi.org/10.1094/CCHEM.1997.74.1.49.

Marklund, E.G., Ekeberg, T., Moog, M., Benesch, J.L.P., Caleman, C., 2017. Controlling protein orientation in vacuum using electric fields. J. Phys. Chem. Lett. 8 (18), 4540–4544. https://doi.org/10.1021/acs.jpclett.7b02005.

Martin, Lewis, M., Behnam, A., Marcela, B., 2018. Electric fields control the orientation of peptides irreversibly immobilized on radical-functionalized surfaces. Nat. Commun. 9 (1), 357. https://doi.org/10.1038/s41467-017-02545-6.

Mattar, J., Turk, M., Nonus, M., Lebovka, N.I., El Zakhem, H., Vorobiev, E., 2013. Electro-stimulation of Saccharomyces cerevisiae wine yeasts by Pulsed Electric Field and its effect on fermentation performance. arXiv, 1304.5681 [physics, q-bio.

Otsu, N., 1979. A threshold selection method from gray-level histograms. IEEE Trans. Syst. Man. Cybern. 9, 62–66. https://doi.org/10.1109/TSMC.1979.4310076.

Rao, V.K., Mulvaney, S.J., Dexter, J.E., 2000. Rheological characterisation of long- and short- mixing flours based on stress–relaxation. J. Cereal. Sci. 31 (2), 159–171. https://doi.org/10.1006/jcrs.1999.0295.

Schiedt, B., Baumannm, A., Conde-Petit, B., Vilgis, T.A., 2013. Short- and long-range interactions governing the viscoelastic properties during wheat dough and model dough development. J. Texture Stud. 44 (4), 317–332. https://doi.org/10.1111/jtxs.12027.

TA instruments. http://www.tainstruments.com/pdf/literature/RH063.pdf. (Accessed 28 July 2021).

Wada, A., 1976. The alpha-helix as an electric macro-dipole. Adv. Biophys. 1–63.

Weegels, P.L., van de Pijpekamp, A.M., Graveland, A., Hamer, R.J., Schofield, J.D., 1996. Depolymerisation and Re-polymerisation of wheat glutenin during dough processing. I. Relationships between glutenin macropolymer content and quality parameters. J. Cereal. Sci. 23 (2), 103–111. https://doi.org/10.1006/jcrs.1996.0010.

Wieser, H., 2007. Chemistry of gluten proteins. Food Microbiol. 24 (2), 115–119. https://doi.org/10.1016/j.fm.2006.07.004.

Zhao, W., Yang, R., Zhang, H.Q., 2012. Recent advances in the action of pulsed electric fields on enzymes and food component proteins. Trends Food Sci. Technol. 27 (2), 83–96. https://doi.org/10.1016/j.tifs.2012.05.007.