Rheological Changes in Wheat Sourdough During Controlled and Spontaneous Fermentation

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ABSTRACT

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The changing rheological characteristics of wheat doughs during fermentation at 30°C for 72 hr were measured using a controlled stress rheometer. Dynamic oscillation tests were performed at frequencies ranging from 0.01 to 10 Hz. Wheat sourdoughs (dough yield 200) were prepared with a mixed starter culture containing typical hetero- and homofermentative sourdough lactic acid bacteria. Results from the controlled fermentation process were compared to results from spontaneous fermentation. Maximum phase angle values, especially at low frequencies, were closely related to total gas production in the doughs. Complex viscosity decreased during fermentation and reached lower final values for doughs without starter culture. Heating characteristics of doughs after various fermentation times were measured at temperatures ranging from 30 to 80°C. The highest values for complex viscosity were found at ≈65°C. When heated, fermented doughs produced weaker gels than fresh doughs. The temperatures at which these maxima occurred increased significantly with fermentation time for spontaneously fermented dough.

In recent years, the traditional sourdough bread production process has enjoyed renewed success due to increasing consumer demands for more natural, tasty, and healthy foods (Brümmer and Lorenz 1991). In wheat breads, sourdough is mainly used to improve flavor (Hansen and Hansen 1996). The fermentation process of wheat doughs containing lactic acid bacteria causes major changes in the dough and related products. Variation in process parameters (temperature, dough yield) and selection of specific starter cultures determine the quality and handling properties of sourdough (Salovaara and Valjakka 1987, Barber et al 1991, Martínez-Anaya et al 1994). Lactic acid is the main metabolic product of the microorganisms present in sourdough. The concentration of lactic acid and associated drop in pH level are often used as a control parameter in industrial sourdough production. Under defined conditions, such as dough yield, temperature, and flour extraction rate, measuring pH levels is regarded as a satisfactory method for controlling the ripening stage of sourdough. The production of preflavor substances, such as free amino acids or sugars, is most important for aroma development, and bacteria strains with a high capacity for producing metabolites are specifically selected for sourdough production (Collar et al 1991, Gobbetti et al 1994). Another advantage of sourdough is the improved shelf life of products (Armero and Collar 1996). The development of acetic acid, in addition to the lower pH level, is the most important factor and can be affected by adding electron acceptors (e.g., fructose) or using higher dough yields (Röcken and Voysey 1995). Production of CO_2 from heterofermentative lactic acid bacteria influences the leavening process of the final bread dough.

In addition to the positive aspects connected with sourdough, there are also some disadvantages, such as increased labor input and supposed higher production uncertainty. The invention of dried sourdough, which is easy to handle, is one attempt to overcome these problems. A major disadvantage of dried sourdough is lack of aroma (Röcken and Voysey 1995).

Successful development of equipment for mechanized sourdough production is a positive step toward safe, competitive application of sourdough in wheat bread production. Initially, most commercial sourdough preparation systems were based on liquid sourdoughs, with dough yields of 225 or more that could be pumped (Brümmer 1991). Recent developments have led to systems that also work with more solid doughs. These systems work either in batch processes or supply ripe sourdough in a continuous flow (Meuser 1995). The fermentation process changes not only the chemical composition and microbial status of sourdough, but also flow behavior, viscosity, and density of dough (Meuser and Zense 1993). Every system used in the ripening process of sourdough, therefore, has to be able to handle different dough characteristics at the beginning and end of the fermentation process.

The rheological characteristics of fermenting dough are determined by many factors. At the beginning of the mixing process, physical actions such as hydration take place, the gluten network is formed by proteins, and starch granules absorb water. Enzyme activity of amylases, proteases, and hemicellulases causes the breakdown of several flour components. Microbial growth and metabolic activity begin after a lag phase, depending on the activity of starter cultures. Changes in pH level caused by the production of lactic acid also alter the rheological behavior of dough (Wehrle et al 1997). Even small chemical and physical changes in the gluten network can lead to significant changes in rheological characteristics. The increasing amount of CO_2 in the dough leads to the formation of bubbles. In bread dough, the gas-holding capacity is one of the most important factors affecting the volume of the final product. Dough additives, such as emulsifiers and fat, are used to improve gas-holding capacity. In sourdough, the formation of gas bubbles leads to an increased volume and decreased density.

The objectives of this study were to characterize the changing rheological properties of a fermenting dough and to evaluate the effects of fermentation on the heating characteristics of fermented doughs.

MATERIALS AND METHODS

Wheat flour, with 12% (db) protein, was used in all tests (Odlum Group, Dublin, Ireland). Flour was not treated or fortified with additives. A commercial mixed starter (Böcker, Minden, Germany) specifically designed for use in wheat sourdough was used in the preparation of sourdough (SD). The starter is based on a coarse-grain material that contains a high number of living bacteria cells. The predominant microorganisms are different strains from heterofermentative *Lactobacillus sanfrancisco.*

Dough Preparation

A ripe SD, made from 10% (flour basis) commercial starter mixed with equivalent amounts of flour and water, was used to inoculate SD used in tests, producing consistent initial activity of microorganisms. SD was prepared with 10% (flour basis) seed dough and water and wheat flour in equal amounts. Seed dough was dispersed in water, and flour was added. Dough was mixed thoroughly for 1 min. After

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mixing, dough was divided into smaller portions, poured into single beakers, covered, and placed in an incubator at 30°C. The fermentation process began at time zero, when dough was placed in the incubator. After specified fermentation times, one portion of dough was poured (without stirring) into the coaxial cylinder of the rheometer.

Spontaneously fermented dough (SFD) was prepared by mixing equal amounts of flour and water thoroughly for 1 min; no additional microorganisms were added. The fermentation process was initiated by the native flora present in the flour. In a process similar to SD preparation, SFD was divided into smaller portions before placement in an incubator. Time zero in the ripening process began immediately after placement of SFD in the incubator.

pH and Gas Measurement

pH levels were measured potentiometrically in a suspension of 10 g of dough and 100 ml of deionized water (Arbeitsgemeinschaft Getreideforschung 1994). Gas production was measured in a rheofermentometer (Chopin S.A., Villeneuve-La-Garenne Cedex, France). Total gas production was calculated based on the increasing pressure in the testing bowl, with 100 g of either SD or SFD. Fermentation temperature was constant at 30°C.

Rheological Measurement

Dynamic oscillation tests were performed on a controlled stress rheometer (Bohlin Rheology AB, Lund, Sweden). A coaxial cylinder with a 25-mm-diameter bob measuring system was used. Two different tests were performed. A frequency sweep test, ranging from 0.01 to 10 Hz, was used to study the rheological properties of doughs at a constant temperature of 30°C. Frequencies decreased during measurements, from highest to lowest values, and an auto stress function was used to achieve the required strain of 1×10^{-3} at every frequency. Doughs showed a linear rheological response at the required strain. Fermentation tests were recorded for three fermentation batches of each dough type.

The second rheological test was a temperature sweep test at 1 Hz. SD and SFD were measured fresh and after 24, 48, and 72 hr of fermentation. Dough samples were taken from the incubator after specified times and poured into the pretempered measuring cylinder. The temperature of the sample was increased by 1.5°C/min, from an initial temperature of 30°C to a final temperature of 80°C. Measurements were taken every 20 sec.

TABLE I
pH Levels of Sourdough (SD) and Spontaneously Fermented Dough (SFD) After Various Fermentation Times at 30°C

Time (hr)	SD pH	SFD pH
0	6.2	6.4
5	6.1	6.2
10	4.6	6.0
15	4.2	5.5
20	3.8	5.2
25	3.9	4.2
30	3.8	4.0
35	3.8	3.9
40	3.9	3.7

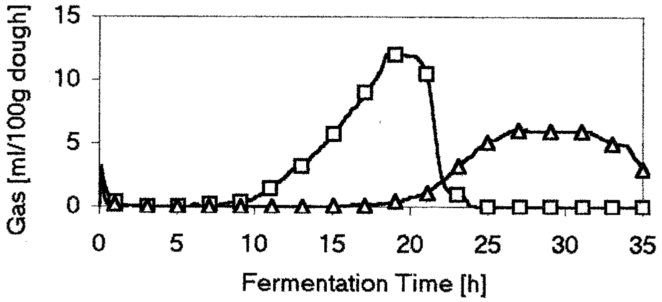

Fig. 1. Gas production in sourdough (□) and spontaneously fermented dough (△) at 30°C fermentation temperature.

RESULTS

pH Level Development

Initial pH levels for SD and SFD were 6.2 and 6.4, respectively (Table I). Addition of 10% ripe SD, which already contained a certain amount of acids, as seed dough led to initial lower pH levels in SD than in SFD. After 10 hr of fermentation, pH levels in SD dropped to 4.6, whereas pH levels in SFD remained above 6. pH levels in SD reached the lowest levels after 20 hr. In SFD, pH levels dropped until 40 hr of fermentation. At pH levels lower than 4, metabolic activity stopped, and no further decrease in pH level occurred. The lactic acid bacteria added to the SD with the 10% seed dough was metabolically active and continued producing acid and multiplied immediately when incubation started. In SFD, the indigenous flora of the flour was inactive and was activated by addition of water; initially pH levels dropped very slowly. Selection of lactic acid-producing bacteria caused a faster drop in pH levels at later stages of the fermentation process.

Gas Development

Production of gas in doughs was related to development of acids (Fig. 1), confirming the differences in microbial activity between SD and SFD. The gas produced was mainly CO_2 from heterofermentative bacteria. Gas development in SD began 5 hr after incubation and continued until 22 hr. Gas development in SFD was observed 15 hr after fermentation. Metabolic activity in SD began much earlier than in SFD due to inoculation with active starter culture.

Rheological Changes During Fermentation

At the beginning of the fermentation process, phase angles in SD and SFD were at the same level, between 25 and 35°, at a frequency range of 0.01 to 10 Hz (Fig. 2). Freshly mixed dough containing equal quantities of flour and water, equivalent to a dough yield of 200, had an elastic response. During the first hours of fermentation, phase angles did not change significantly. After 5 hr of fermentation, phase angles of SD increased sharply. Maximum phase angles in SD were achieved after fermentation times of 20 hr. The highest values, in the range of 70 to 80°, were at frequencies lower than 0.03 Hz. At frequencies higher than 1 Hz, phase angle ranged between 45 and 50°. With continuing fermentation, phase angles again decreased. Final values after 72 hr of fermentation were between 40 and 55°, with the highest values at lower frequencies.

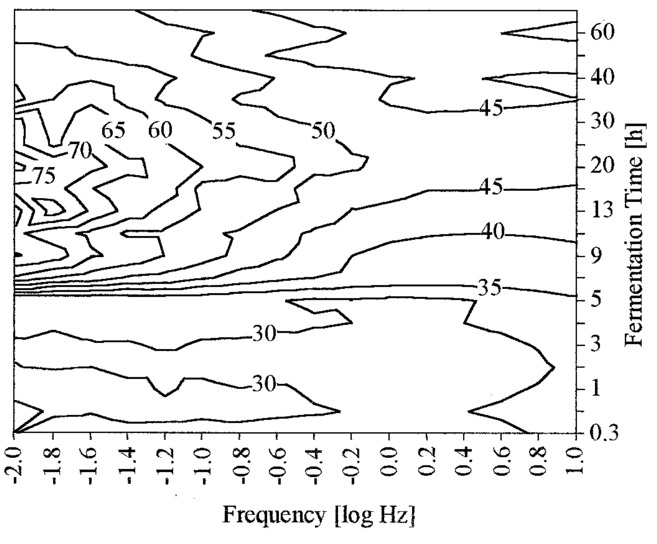

Fig. 2. Contour plot of sourdough phase angle at various frequencies over a fermentation time of 70 hr.

Phase angles in SFD changed significantly later than in SD (Fig. 3). A slow increase in phase angle was detected after 10 hr, followed by further increases until 50 hr of fermentation. Again, the highest values were at frequencies lower than 0.03 Hz, ranging from 60 to 70°. After a total fermentation time of 72 hr, phase angles ranged from 40 to 50°.

A high phase angle value indicates viscous behavior of material. Fermented SD after 20 hr of incubation responded in an entirely viscous manner, especially at low frequencies, with phase angles close to 90°, which indicates an ideal fluid. Fermented SD was easy to pour and did not show any elastic recovery. Rheological characteristics of ripe SD during short time changes (related to higher frequencies) showed more elastic response compared with long time changes (related to lower frequencies). However, even at higher frequencies, fermented dough behaved more viscously than nonfermented doughs. SD and SFD showed the same trend in phase angle, reaching maximum viscous behavior after a certain fermentation time, but followed different time scales.

Phase angle development was closely related to CO_2 production by heterofermentative microorganisms in the dough. The beginning of gas production in SD after 5 hr of fermentation (Fig. 1) marked the initial changes in phase angle. Decreasing gas production after 22 hr of fermentation corresponded to the decrease in phase angle that occurred at the same time. Major changes in phase angles in SFD began after 15 hr of fermentation. Differences in phase angle development in SD and SFD were due to differences in CO_2 development between the doughs.

Viscosity of nonfermented dough ranged from 2,500 Pa•sec at 0.01 Hz to 70 Pa•sec at 1 Hz (Fig. 4). Fresh dough with starter culture and fresh dough without starter culture showed similar viscosities at all frequencies. During the first and second hours of fermentation, viscosity increased slightly due to hydration of the macromolecules of flour. After 2 hr of fermentation, viscosity decreased with ongoing fermentation. The complex viscosity of SD dropped between 4 and 15 hr of fermentation at 1 Hz and remained stable throughout the remaining fermentation time, 72 hr total (Fig. 4). At 0.01 Hz, a sharp decrease in viscosity occurred after 5 hr of fermentation (Fig. 4). After 20 hr of fermentation, viscosity again increased slightly. SFD showed a slow decrease in viscosity, beginning after 3 hr of fermentation, followed by a sharp decline between 13 and 30 hr of fermentation. Decreasing viscosity continued during the remaining fermentation time. Final viscosities in SFD were significantly lower than final viscosities in SD. After 72 hr of fermentation, SD appeared less viscous than SFD. In SFD, separation of the liquid and solid phases occurred after 72 hr of fermentation.

Heating

Heating the flour-water mixture led to gelatinization of starch and denaturation of protein. These changes had a major impact on the rheological characteristics of dough, which changed from the viscoelastic behavior of dough to the elastic behavior of cooked starch gel. The complex modulus (η*) of dough did not change significantly between 30 and 55°C. Fresh SD showed an increase in viscosity at ≈57°C. Maximum values were reached between 65 and 66°C (Fig. 5). Within this temperature range, starch gelatinization took place. Maximum viscosity during heating of fresh SFD was the same as in fresh SD (Fig. 5). After more than 24 hr of

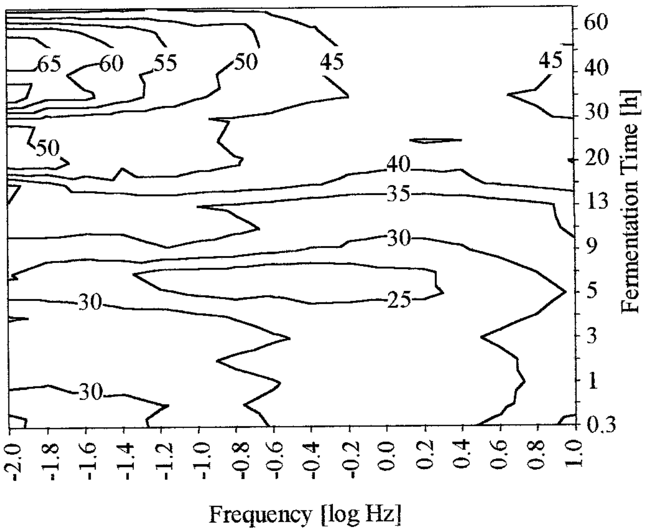

Fig. 3. Contour plot of the phase angle of spontaneously fermented dough at various frequencies over a fermentation time of 70 hr.

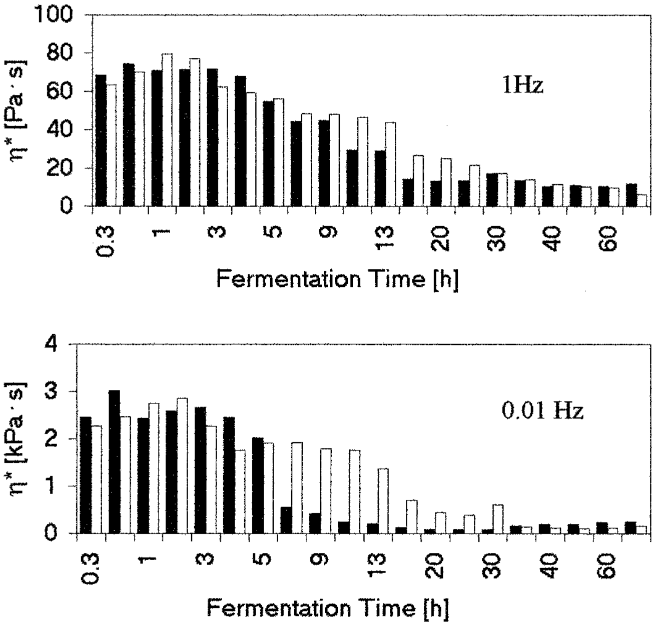

Fig. 4. Effects of fermentation on complex viscosity of sourdough (■) and spontaneously fermented dough (□) at oscillation frequencies of 1 and 0.01 Hz.

TABLE II
Properties of Heated Sourdough (SD) and Spontaneously Fermented Dough (SFD)

Dough	Fermentation Time (hr)	Peak η* (Pa•sec)	Temperature η* Peak (°C)	Peak G″ (Pa•sec)	Temperature G″ Peak (°C)
SFD	0	7,740ab[a]	65.2a	8,449a	61.3a
	24	4,542c–e	66.0ab	4,656bd	63.7b
	48	5,559cf–h	67.0b	5,826cd	64.5b
	72	6,262afi	68.7c	5,937cd	65.9b
SD	0	8,577b	65.4ab	9,456a	62.6ab
	24	2,602j	66.1ab	3,599b	63.9ab
	48	4,121dgi	65.5a	5,543cd	63.4ab
	72	5,008eh–k	66.4ab	6,169c	64.0b

[a] Each value represents the mean of three to six replicates; means followed by the same letter within the same column are not significantly different ($P > 0.01$).

fermentation, peak temperatures in SFD increased. Decreases in phase angle began at temperatures higher than 55°C (Fig. 6). Values for phase angle in the temperature range of 30 to 55°C were lowest for fresh SD and highest after 24 hr of fermentation. These results confirm the results from a previous test at 0.01–10 Hz (Fig. 2). Minimum phase angle values were similar for SD after different fermentation times.

Nonfermented doughs reached average peak viscosities of 8,000 Pa•sec (Table II). After fermentation times of more than 24 hr, SD showed a significant decrease in peak viscosity. The lowest peak values were recorded after 24 and 48 hr of fermentation, whereas peak values increased again after 72 hr of fermentation. The temperatures at which maxima were reached were not significantly different after various fermentation times.

When heated, SFD showed the same trend in peak viscosity development as found for SD. Maximum values for fresh SD were not significantly different than peak values of fresh SFD. Maximum viscosity in SFD did not drop to the same low levels as for SD after 24 hr but reached the same values as for SD after 48 and 72 hr of fermentation. The temperatures at which maximum values were reached increased significantly in SFD with longer fermentation times (Table II). After 72 hr of fermentation, SFD temperatures reached 68.7°C, whereas peak temperatures for SD were 66.4°C. Peak temperatures for complex viscosity were on average 2.6°C higher than peak temperatures for *G″*.

CONCLUSION

The rheological characteristics of doughs changed entirely with fermentation. Major developments included formation of a maximum viscous response and an overall decrease in viscosity. Development of a more viscous response during fermentation was mainly due to the amount of CO_2 in the dough. The CO_2 produced by microorganisms remained for only a limited time in the dough. The doughs had relatively low viscosity and less gas-holding capacity than did standard bread doughs, which is totally different from the behavior of bread doughs in which the CO_2 produced at the beginning of fermentation remains completely in the dough. Fermenting doughs showed the most viscous behavior when gas production was highest. Considering the measurement conditions, such as very low strain, we concluded that gas bubbles in the dough interrupted the elastic dough network and led to a highly viscous dough response. This is more significant at lower frequencies, related to long time changes, such as slow pouring or floating. During short time changes, related to higher frequencies, gas bubbles in the dough did not have the same liquefying effect.

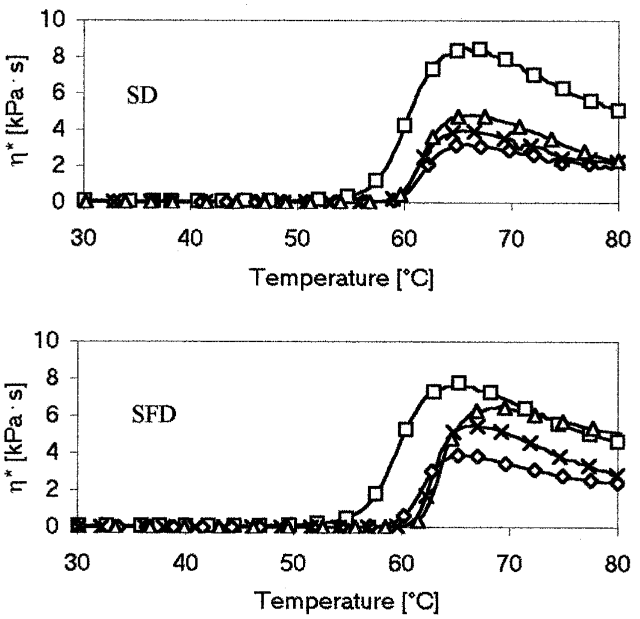

Fig. 5. Changes in complex viscosity of sourdough (SD) and spontaneously fermented dough (SFD) after various fermentation times during heating (□ = fresh, ◇ = 24 h, × = 48 h, △ = 72 h). Oscillation frequency was 1 Hz.

Decrease in viscosity was determined less by the amount of gas in the dough than by the development of pH level in the dough. Decreasing pH levels affect the solubility of certain protein fractions (Wrigley and Bietz 1988). Changes in pH level also influence enzymatic breakdown. The pH optima of carbohydrate-degrading enzymes, such as amylase, pentosanase, or cellulase, vary widely (between 3.6 and 5.6), depending on wheat variety and germination status (Fox and Mulvihill 1982). Acidification is used to inhibit α-amylase activity. Proteinases and peptidases in flour are active at pH levels ranging between 4 and 9, depending on substrate. The highest proteolytic activity in dough was reported at pH 4. Proteinase with an optimum at pH 7 and high activity at lower pH levels was isolated from *L. sanfrancisco* (Gobbetti et al 1996). The rapid drop in pH level in SD could cause reduced amylolytic activity, whereas the slower drop in pH level in SFD permitted further starch degradation. The proteolytic activity of flour and starter organisms in combination with the rapid drop in pH level in SD led to increased breakdown of proteins.

The characteristics of doughs during heating provided information about starch properties. Increases in dough viscosity when heated were mainly due to starch gelatinization. Absolute values for peak viscosity and temperature depended largely on water content, heating rate, and shear force applied during heating (Lineback and Rasper 1988). If measuring conditions are constant, results from doughs with various fermentation times could be compared. Variations in gelatinization behavior were related to genetic variations, mainly amylose content, or modifications during milling, such as granule damage (Zeng et al 1997). In our study, the same flour was used for SD and SFD. Modifications in starch during fermentation were responsible for changing gelatinization characteristics. pH levels dropped in SD and SFD, but only in SFD did peak temperature increase with fermentation, indicating higher starch degradation in SFD than in SD.

Rheological properties, as well as acidification and flavor development, were important parameters in controlling fermentation processes. Types of microorganisms, metabolic activity, and time-dependent development of pH levels had an effect on final rheological properties.

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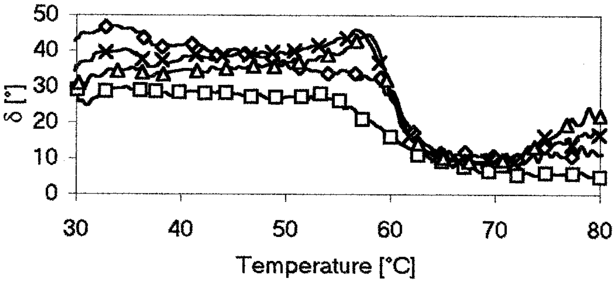

Fig. 6. Changes in sourdough phase angle after various fermentation times during heating (□ = fresh, ◇ = 24 h, × = 48 h, △ = 72 h). Oscillation frequency was 1 Hz.

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