

# Effects of Cultivar and Temperature During Grain Filling on Wheat Protein Content, Composition, and Dough Mixing Properties

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## ABSTRACT

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Three wheat cultivars, Bastian, Polkka, and Tjalve, were grown in growth chambers at 9, 12, 15, 18, and 21°C during grain filling in 1994, 1995, and 1996. The wheat samples were analyzed for protein content and sodium dodecyl sulfate (SDS) sedimentation volume. The mixing properties of sifted flours were determined by mixograph, and the flour protein composition was determined by size-exclusion fast protein liquid chromatography (SE-FPLC). The protein content, sedimentation volume, and mixogram parameters were affected by the temperature during grain filling. The protein content increased as the temperature increased. The sedimentation volumes and the mixograph data showed temperature

effects that could not be explained by variation in protein content. The proportion of the polymeric flour proteins increased with increasing temperature. Positive correlations were found between the proportion of polymeric proteins and SDS sedimentation volume and, within each year, between the proportion of polymeric proteins and mixograph peak time. Negative correlations were found between the proportion of low molecular weight flour proteins (proportion of fraction IV) and sedimentation volume. The differences in these quality parameters among cultivars exceeded the effect of temperature during grain filling.

Wheat quality is influenced by genotype, environmental factors, and the interaction between genotype and environment. The effects of genotype are of great importance for the quality of wheat. Cultivars are often classified according to their end-use properties (e.g., bread wheat, biscuit wheat, or feed wheat). The composition of glutenin subunits, particularly the high molecular weight subunits of glutenin, can partly explain the genotypic variance in quality (Payne et al 1984, 1987, 1988; Ng and Bushuk 1988; Sontag et al 1988; Rogers et al 1989; Pogna et al 1990; Uhlen et al 1990; Johansson 1995). The effects of environment are also important (Petersen et al 1992, Graybosch et al 1995). The interaction between genotype and environment is less predominant.

Positive correlations between the temperature during the early stages of grain filling and wheat protein content have been reported by Johnson et al (1972), Kolderup (1975), Spiertz (1977), and Rao et al (1993). Rao et al (1993) found the relationship between temperature and protein content varied among locations. The results of Kolderup (1975) indicated that the protein composition, as well as protein content, was affected by the temperature, because the ratio of alkali-soluble to salt-soluble proteins increased with increasing temperature. Schipper (1991) found that protein content increased as the temperature increased and as the application of nitrogen fertilizer increased, both in growth chambers and field experiments. Increases in grain protein content resulting from high temperatures during grain development were associated with greater dough resistance to extension, but lower extensibility than that of dough from grains of similar protein content produced at lower temperatures.

Blumenthal et al (1991, 1993) described a loss in dough strength in Australian wheats that was proportional to the number of hours at high temperatures (>35°C) during grain filling, and attributed this effect to a differential synthesis of gliadins, as opposed to glutenins, during periods of heat stress. High temperature stress (>35°C) decreased the glutenin-to-gliadin ratio and the proportion of very large glutenin polymers (Blumenthal et al 1995). Graybosch et al (1995) found a negative correlation between protein content and duration of the grain filling period. Also, they found a negative correlation between the proportion of glutenins,

measured by size-exclusion fast protein liquid chromatography (SE-FPLC), and the number of hours at high temperature (>32°C).

Effects of low temperature during grain filling on wheat quality have not been extensively studied. Low temperatures during the grain filling period are relatively common in Northern Europe. In wheat producing areas in Norway, the climatic conditions differ considerably from year to year, and the wheat will mature at rather cool conditions in some years. The aim of this study was to examine effects of different temperatures during maturation on protein content and gluten quality, and to study quantitative effects of the temperature on different protein fractions analyzed by SE-FPLC. The temperatures under investigation are typically low to moderate temperature levels encountered in the wheat producing areas in Norway.

## MATERIALS AND METHODS

### Plant Material

The plant material consisted of three hard spring wheat cultivars of very good (Bastian), good (Tjalve), and weak (Polkka) mixing properties. These cultivars were grown in growth chambers at 9, 12, 15, 18 and 21°C (relative humidities: 53.5, 62, 68.7, 74.2, and 78.6%, respectively) in 1994, 1995, and 1996. The seeds were sown in pots, 14 cm in diameter, and each pot contained 10 plants. Sixty pots of each cultivar were sown, and grown at the Department of Horticulture and Crop Sciences (Boks, Norway) until flowering. Extra fertilizer was added to each pot twice during this period, with 1 g and 1.5 g of NKP (16-7-19) fertilizer, respectively. After flowering, the pots were moved to growth chambers at the Department of Biology and Nature Conservation, Agricultural University of Norway, Ås. Twelve pots of each cultivar were then grown at five different temperatures until ripening. The ears were harvested and threshed.

In 1994, the plants were grown outdoors until flowering. In 1995, the plants were grown outdoors the first three weeks after sowing. Due to frequent rain during this period, the plants were moved into a greenhouse for an additional two weeks until flowering. Because of nitrogen leaking and some stress symptoms on the plants during this rainy period, 1 g of extra N-fertilizer was added to each pot. In 1996, the plants were grown in greenhouses until flowering, and then transferred to growth chambers as in 1994 and 1995.

### Protein Content

The protein content of the wheat samples was analyzed by near-infrared reflectance (NIR) using Infrateck 1255 FFA and the cali-

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bration WH3 AN 110-01/90 (Tecator AB, S-26 321 Höganäs, Sweden) and is given in percent of dry matter.

### Milling

Whole meal flour was obtained by milling the wheat samples on a Falling Number 3100 hammer mill (Perten Instruments, AB, Sweden).

### SDS-Sedimentation Test

SDS-sedimentation volume was determined according to Approved Method 56-70 (AACC 1995).

### SE-FPLC

Sifted flour samples (11 mg) were added to 1.0 mL of 0.05M phosphate buffer, pH 6.9, with 2% SDS (w/v), and sonicated for 30 sec at 11W output with an ultrasonic cell disrupter (Microson Heat Systems, Labcaire Systems, Ltd., Avon, UK). The sonication conditions were optimized as described by Singh et al (1990a). The samples were centrifuged and filtered (Millex-HA filter 0.45-µm, Millipore S.A., 67 Molsheim, Germany), and immediately separated by gel-filtration on a Superose-12 column (Pasaribu et al 1990) using a Pharmacia FLPC system (Pharmacia, Sweden). The chromatographic separation procedure was similar to that described by Singh et al (1990a). The proteins were separated into four peaks, and the chromatograms were integrated by using a Hewlett Packard Chemstation. The areas of the different fractions are presented as percent of total area of the chromatogram.

### Gel Electrophoresis

During gel filtration of flour from a sample of Bastian grown at 21°C, fractions were collected, desalted, and concentrated using a Centricon concentrator 3 (MW cut-off: 3,000 Da). The fractions obtained from gel filtration and one sample of sonicated total protein were reduced and alkylated and subjected to SDS-PAGE according to Payne et al (1981).

### Flour Mixing Properties

Mixograms were obtained from whole meal flour sifted through a 250-µm screen (Finney and Shogren 1972, Bruinsma et al 1978). For the samples grown in 1995 and 1996, which had very high protein contents, the mixograph slot location of the spring was changed from setting position 9 to 12. Because of this adjustment, the mixograms are compared only within years.

### Statistical Analyses

Data were analyzed by ANOVA and correlation analysis using an NM software package developed by the Agricultural Univer-

sity of Norway (Ås, Norway). Least significant differences at 5% level were calculated.

## RESULTS AND DISCUSSION

The recorded yield, protein content, and sedimentation volumes of the wheat samples grown at different temperatures during ripening in 1994, 1995, and 1996 are given in Table I. The sources of variation and their magnitude for yield, protein content, and SDS sedimentation volume are shown in Table II. Grain yields were much higher in 1994 than in 1995 and 1996. This affected the protein contents, which were very high in 1995 and 1996, and the sedimentation volumes, which were higher in 1995 and 1996 than in 1994. The main reason for these differences is the variable growth conditions of the plants in the period before anthesis in the three years. Despite the differences in protein content among crop years, the results from the different crop years showed similar quality effects of the different temperature treatments and of the cultivars.

The protein content increased significantly when the temperature during grain filling increased (Table I), and confirm the findings of Johnson et al (1972), Rao et al (1993), Schipper (1991), and Blumenthal et al (1995). There was a significant negative correlation between yield and protein content in 1994 ( $r = -0.85$ ,  $P < 0.01$ ) and 1995 ( $r = -0.49$ ,  $P < 0.05$ ). The yield decrease is most likely caused by the different duration of the grain filling periods at the different temperatures. These results are in agreement with the results of Graybosch et al (1995), who found negative correlation between the protein content and the duration of the grain filling period in material of wheat cultivars grown at different locations.

In 1994, the average protein contents of the three cultivars grown at 9, 12, and 15°C were 10.5, 10.1, and 10.8%, respectively. When

**TABLE II**  
Mean Squares from Analysis of Variance of Yield, Protein Content, and SDS-Sedimentation (SDSS) Volume for Three Wheat Cultivars Grown at Five Temperatures in Three Years

Source	DF	Mean Squares		
		Yield	Protein Content	SDSS Volume
Cultivar	2	30.93	2.28	1,342.82
Year	2	170.13	368.35	1,567.22
Temperature	4	19.39	17.26	51.52
Cultivar × year	4	1.58	0.65	55.72
Cultivar × temperature	8	0.38	0.24	20.82
Year × temperature	8	6.10	0.71	25.97
Cultivar × year × temperature	16	1.22	0.36	14.10

**TABLE I**  
Yield, Protein Content, and SDS-Sedimentation (SDSS) Volumes of Three Wheat Cultivars Grown at Five Temperatures in Three Years

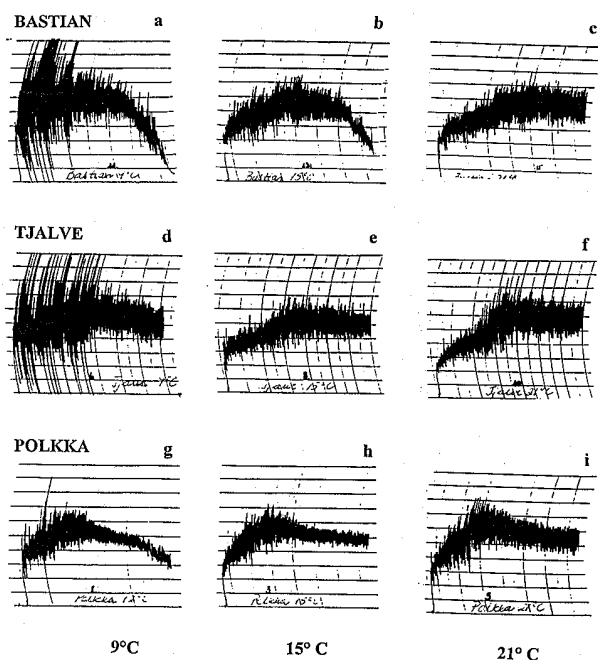
Year	Temperature (°C)	Bastian			Tjalve			Polkka		
		Yield <sup>a</sup> (g/pot)	Protein <sup>b</sup> (%)	SDSS Vol. (mL)	Yield (g/pot)	Protein (%)	SDSS Vol. (mL)	Yield (g/pot)	Protein (%)	SDSS Vol. (mL)
1994	9	11.8	10.8	74	16.4	10.1	53	17.1	10.6	49
	12	12.7	10.0	65	15.8	9.9	57	15.9	10.4	47
	15	11.0	10.7	69	15.2	10.7	66	13.9	10.9	47
	18	11.3	11.4	70	10.9	12.6	68	12.2	12.8	54
	21	7.4	13.7	74	6.6	14.8	72	9.2	13.9	58
1995	9	6.3	18.6	81	7.0	19.2	72	9.3	18.6	63
	12	6.9	19.0	88	6.2	19.9	77	8.8	18.8	67
	15	4.8	20.4	88	5.1	21.1	79	7.8	19.5	69
	18	3.0	21.2	90	6.3	22.1	78	7.3	22.0	66
	21	4.7	22.2	80	5.8	21.8	76	7.4	22.0	69
1996	9	6.0	18.3	94	6.6	18.8	69	9.3	17.7	70
	12	6.6	17.8	93	6.1	20.7	82	9.6	19.1	68
	15	7.0	18.4	94	5.9	20.8	81	9.3	20.1	77
	18	5.7	20.1	93	6.4	21.5	76	8.0	19.9	80
	21	4.3	21.0	92	5.6	21.2	70	7.1	21.8	79

<sup>a</sup> Average of 12 pots.

<sup>b</sup> Dry matter basis.

grown at 18°C, the average protein content of the three cultivars increased to 12.3%. When grown at 21°C, the average protein content increased further to 14.1%. In 1995 and 1996, there was an increase in protein content when the temperature was raised from 9 to 21°C. For samples grown in 1994, the sedimentation volumes increased as the protein content increased. For samples grown in 1995 and 1996, there was an increase in sedimentation volume as the protein content increased at the lower temperatures (9–15°C), but not at the higher temperatures. However, the protein contents were very high in 1995 and 1996, especially at the higher temperatures (18 and 21°C), which gave very high sedimentation volumes. The SDS sedimentation test appears to be less efficient in discriminating between samples of high sedimentation volumes. This was particularly the case for samples of the cultivar Bastian with very high protein contents in 1995 and 1996.

Among the three cultivars tested, there were no differences in overall protein levels, but significant differences in overall yield and sedimentation volumes. Bastian had the highest sedimentation volume, and Polkka the lowest, revealing the genotypic differences in protein quality of these cultivars.

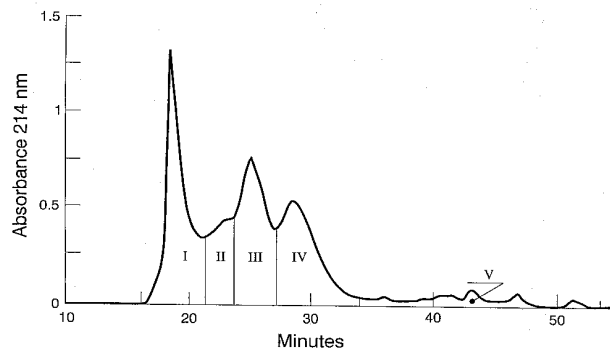


**Fig. 1.** Mixograms of three wheat cultivars, Bastian (a–c), Tjalve (d–f), and Polkka (g–i), grown in 1994 in growth chambers at 9, 15, and 21°C.

The mixograms for the three cultivars grown at 9, 15, and 21°C in 1994 are shown in Fig. 1, and the mixograph data for all treatments are shown in Table III. The sources of variation and their magnitude for the mixing properties are shown in Table IV. In 1994, the mixing properties changed with temperature for all three cultivars. When grown at lower temperatures, flour from Bastian gave mixogram curves that were very wide during hydration of the flour particles and in the early dough development phase (Fig. 1a). In the later phase of mixing, the dough was very weak and gave little resistance. Tjalve grown at 9°C (Fig. 1d) and, to a lesser extent Polkka (Fig. 1g), also showed wide mixograms in the early dough development phase. Polkka grown at 9°C produced dough with little resistance at the later phase of mixing, which was similar to

**TABLE IV**  
Mean Squares from Analysis of Variance of Mixograph Peak Time (PT), Maximum Resistance (MR), Resistance After 5 min of Mixing (R5), and Bandwidth After 5 min of Mixing (B5) for Three Wheat Cultivars Grown at Five Temperatures in Three Years

Source	DF	Mean Squares			
		PT (min)	MR (cm)	R5 (cm)	B5 (cm)
Cultivar	2	15.10	0.61	7.85	1.88
Year	2	5.26	28.22	9.45	6.09
Temperature	4	0.22	0.52	0.69	0.09
Cultivar × year	4	0.97	0.18	1.34	0.41
Cultivar × temperature	8	0.21	0.06	0.08	0.02
Year × temperature	8	0.21	0.66	0.54	0.05
Cultivar × year × temperature	16	0.23	0.18	0.12	0.03

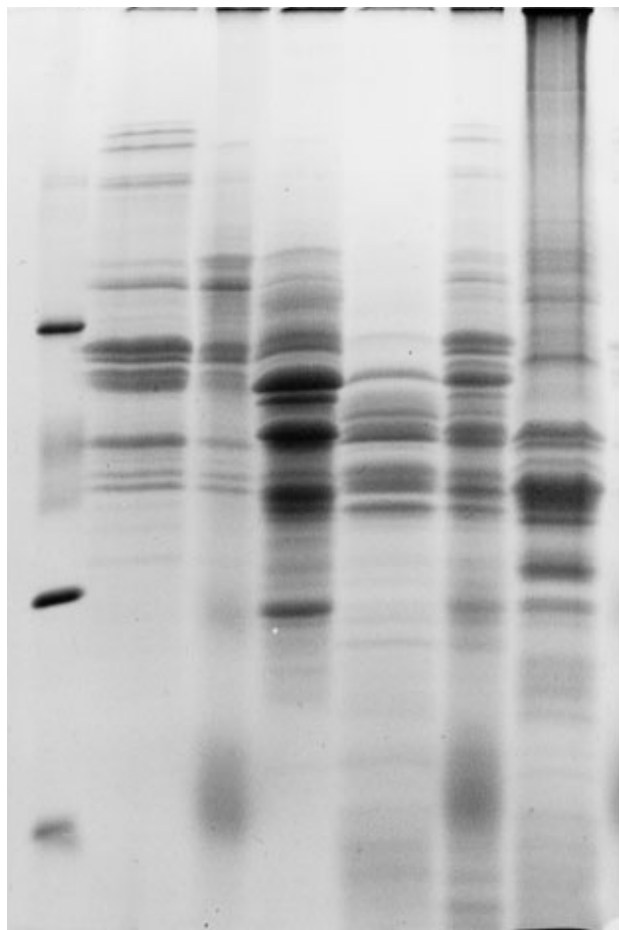


**Fig. 2.** Typical chromatogram obtained by size-exclusion fast protein liquid chromatography showing fractions I–V.

**TABLE III**  
Mixograph Peak Time (PT), Maximum Resistance (MR), Resistance After 5 min of Mixing (R5), and Bandwidth After 5 min of Mixing (B5) of Doughs from Three Wheat Cultivars Grown at Five Temperatures in Three Years

Year	Temperature (°C)	Bastian				Tjalve				Polkka			
		PT (min)	MR (cm)	R5 (cm)	B5 (cm)	PT (min)	MR (cm)	R5 (cm)	B5 (cm)	PT (min)	MR (cm)	R5 (cm)	B5 (cm)
1994	9	3.6	6.9	6.4	2.1	3.4	6.6	6.4	2.9	2.5	6.0	4.8	1.0
	12	3.0	6.5	6.0	2.1	4.0	6.1	5.7	2.4	2.3	6.4	5.4	1.0
	15	3.1	6.5	6.2	2.1	3.5	6.1	6.0	2.3	2.5	6.7	5.9	1.1
	18	3.7	6.1	6.0	2.1	3.2	6.6	6.4	2.0	2.2	6.8	6.0	1.1
	21	4.3	6.8	6.8	2.6	3.6	6.8	6.7	2.6	2.5	7.3	6.6	1.8
1995	9	3.1	8.1	7.2	1.2	2.5	7.7	6.5	0.8	1.3	8.7	5.3	0.5
	12	3.4	10.1	9.1	1.3	3.0	10.0	8.0	0.9	1.5	10.2	6.3	0.7
	15	3.4	10.1	8.9	1.2	3.3	9.0	7.7	1.0	1.4	9.2	5.8	0.7
	18	2.5	9.7	7.9	1.1	3.0	9.0	7.4	0.9	1.3	9.5	5.9	0.6
	21	3.0	9.6	7.9	1.2	3.1	8.3	7.1	1.0	1.5	9.2	5.8	0.7
1996	9	4.4	8.0	5.5	0.8	4.2	7.9	5.7	0.9	2.5	8.8	4.4	0.6
	12	4.2	7.9	5.5	0.8	3.4	7.9	5.4	0.7	1.7	8.7	4.5	0.6
	15	3.4	8.1	5.5	0.7	5.4	9.0	6.7	0.9	1.8	8.7	4.8	0.6
	18	3.8	8.8	6.0	1.0	5.8	8.5	6.7	1.0	2.1	8.7	4.9	0.5
	21	4.6	8.8	6.5	1.0	5.5	7.9	6.3	1.0	2.2	8.2	5.0	0.6

Bastian grown at low temperatures. As the temperatures during grain filling increased, the mixograms showed greater height at maximum resistance, and a greater width after 5 min of mixing (Fig. 1c,f,h,i). For samples grown at 18 and 21°C, the mixograms revealed the typical differences for these three cultivars as determined from other studies. Bastian and Tjalve had long dough development times, high resistances after 5 min of mixing, and broad bandwidths after 5 min of mixing. Polkka had a lower mixogram



**Fig. 3.** SDS-PAGE results at protein fractions obtained by size-exclusion fast protein liquid chromatography. Left to right: standard calibration kit; molecular weights 94,000, 67,000 and 43,000; fraction I, reduced; fraction II, reduced; fraction III, reduced; fraction IV, reduced; total protein extract, sonicated and reduced; total protein extract, sonicated and un-reduced.

value. In 1995 and 1996, the height at maximum resistance and the bandwidth after 5 min of mixing increased as the temperature during grain filling increased. There was a significant correlation between the protein content and the height at maximum resistance in 1994 ( $r = 0.62$ ,  $P < 0.05$ ), revealing a strong effect of the protein content on this mixograph parameter.

A typical size-exclusion chromatogram of total flour protein divided into four fractions (I, II, III, and IV) is shown in Fig. 2. The SDS electrophorograms of the different fractions are shown in Fig. 3. The results from gel electrophoresis of the four protein fractions indicated that fraction I mainly contained polymeric protein; fraction II contained mainly polymeric protein and more of the lower molecular weight subunits than fraction I; fraction III contained monomeric protein, mainly gliadins; and fraction IV contained lower molecular weight proteins, probably together with some gliadins. Batey et al (1991) and Pasaribu et al (1991) obtained three resolved peaks by SE-HPLC, of which peaks I, II, and III were characterized similarly to fraction I, III, and IV of this study.

The results from the SE-FPLC separations of the wheat samples of the three cultivars grown at different temperatures in 1994-96 are given in Table V. The sources of variation and the magnitude for the proportions of the various flour proteins are shown in Table VI. The averages of the five temperatures and the three cultivars are shown in Tables VII and VIII. The proportion of fraction I (polymeric protein) increased as the temperature increased ( $P < 0.05$ ). The proportion of fraction I also varied among cultivars ( $P < 0.01$ ). Bastian had the highest proportion, and Polkka the lowest. For fractions II and IV, there were significant effects of cultivar only ( $P < 0.05$  and  $P < 0.01$ , respectively). Polkka had the lowest proportion of fraction II and the highest proportion of fraction IV when compared to Bastian and Tjalve.

**TABLE VI**  
Mean Squares from Analysis of Variance for the Proportions of Flour Protein Fractions (I-IV) Obtained by Size-Exclusion Fast Protein Liquid Chromatography for Three Wheat Cultivars Grown at Five Temperatures in Three Years

Source	DF	Mean Squares			
		I	II	III	IV
Cultivar	2	24.03	3.41	5.06	53.51
Year	2	7.57	87.64	21.61	67.77
Temperature	4	2.48	2.18	0.22	2.04
Cultivar × year	4	0.43	3.20	15.10	11.65
Cultivar × temperature	8	0.64	0.51	1.10	1.60
Year × temperature	8	0.74	0.74	2.30	2.05
Cultivar × year × temperature	16	0.67	0.62	1.04	1.68

**TABLE V**  
Proportions (%) of Protein Fractions (I-IV) Obtained by Size-Exclusion Fast Protein Liquid Chromatography for Three Wheat Cultivars Grown at Five Temperatures in Three Years

Year	°C	Bastian				Tjalve				Polkka			
		I	II	III	IV	I	II	III	IV	I	II	III	IV
1994	9	30.78	10.80	22.39	25.69	30.15	11.22	22.38	25.77	28.37	10.41	22.23	27.05
	12	30.81	11.86	23.43	24.87	30.12	10.90	22.19	26.46	29.18	10.78	21.71	27.57
	15	31.60	10.49	24.53	24.21	30.63	9.64	23.02	25.75	29.85	9.77	21.76	27.97
	18	32.30	8.87	25.88	23.55	31.66	9.96	22.66	26.31	29.82	9.40	22.20	28.78
	21	32.23	9.17	25.71	23.95	32.49	9.85	22.69	25.78	30.88	7.96	22.89	29.15
1995	9	28.86	11.61	25.68	25.07	29.61	10.99	24.81	33.57	28.58	10.57	22.65	31.39
	12	31.37	8.96	25.77	27.78	30.47	11.03	23.26	29.15	27.96	11.79	23.48	30.23
	15	31.45	11.06	25.43	25.87	30.39	10.98	23.24	30.68	28.33	11.06	21.72	33.70
	18	31.97	10.06	23.83	30.41	30.76	10.05	20.31	35.42	27.38	11.64	21.35	32.22
	21	30.04	11.23	25.89	25.92	29.67	10.30	23.16	29.96	29.09	10.39	18.86	33.42
1996	9	29.79	15.99	19.67	25.98	29.85	16.53	20.39	25.44	27.29	13.88	22.27	28.90
	12	28.95	14.67	20.34	27.41	30.89	16.84	19.52	25.17	25.70	13.65	24.21	30.42
	15	31.77	14.30	19.74	26.87	29.87	15.86	20.69	26.01	27.88	12.51	22.50	29.69
	18	30.36	15.08	20.01	27.48	30.85	13.83	21.83	25.79	28.85	13.17	21.95	29.23
	21	30.83	15.19	18.98	27.27	29.08	14.89	22.13	25.88	28.27	13.13	22.31	29.13

**TABLE VII**  
Yield, Protein Content, SDS-Sedimentation (SDSS) Volume, Mixing Properties,<sup>a</sup> and Proportions (%) of Size-Exclusion Fast Protein Liquid Chromatography Protein Fractions (I–IV) for Wheat Grown at Five Temperatures Averaged for Cultivar and Year

°C	Yield <sup>b</sup> (g/pot)	Protein <sup>c</sup> (%)	SDSS Vol. (mL)	PT (min)	MR cm	R5 (cm)	B5 (cm)	I	II	III	IV
9	10.0	15.9	69	3.1	7.6	5.8	1.2	29.3	12.4	22.5	27.7
12	9.8	16.2	72	2.9	8.2	6.2	1.2	29.5	12.2	22.7	27.7
15	8.9	17.0	74	3.1	8.2	6.4	1.2	30.2	11.7	22.5	27.9
18	7.9	18.2	75	3.1	8.2	6.4	1.1	30.4	11.3	22.2	28.8
21	6.4	19.2	74	3.4	8.1	6.5	1.4	30.3	11.4	22.5	27.8
LSD <sup>d</sup>	1.8	0.8	6.7	ns <sup>e</sup>	ns	ns	ns	0.90	ns	ns	ns

<sup>a</sup> PT = mixograph peak time, MR = maximum resistance, R5 = resistance after 5 min of mixing, and B5 = bandwidth after 5 min of mixing.

<sup>b</sup> Average of 12 pots.

<sup>c</sup> Dry matter basis.

<sup>d</sup> Least significant difference ( $P < 0.05$ ).

<sup>e</sup> Not significant.

**TABLE VIII**  
Yield, Protein Content, SDS-Sedimentation (SDSS) Volume, Mixing Properties,<sup>a</sup> and Proportions (%) of Size-Exclusion Fast Protein Liquid Chromatography Protein Fractions (I–IV) for Three Wheat Cultivars Averaged for Temperature and Year

	Yield <sup>b</sup> (g/pot)	Protein <sup>c</sup> (%)	SDSS Vol. (mL)	PT (min)	MR (cm)	R5 (cm)	B5 (cm)	I	II	III	IV
Tjalve	8.4	17.7	72	3.8	7.8	6.6	1.4	30.4	12.2	22.2	27.8
Bastian	7.3	16.9	83	3.6	8.1	6.8	1.4	30.9	12.0	23.2	26.2
Polkka	10.1	17.2	64	2.0	8.2	5.4	0.8	28.5	11.3	22.1	29.9
LSD <sup>d</sup>	1.4	0.6	3.4	0.5	ns <sup>e</sup>	0.7	0.3	0.70	0.9	ns	1.6

<sup>a</sup> PT = mixograph peak time, MR = maximum resistance, R5 = resistance after 5 min of mixing, and B5 = bandwidth after 5 min of mixing.

<sup>b</sup> Average of 12 pots.

<sup>c</sup> Dry matter basis.

<sup>d</sup> Least significant difference ( $P < 0.05$ ).

<sup>e</sup> Not significant.

Within each year, positive correlations were found between the proportion of fraction I of the SE-FPLC separations and the wheat quality measured by SDS-sedimentation volume (1994:  $r = 0.87$   $P < 0.01$ ; 1995:  $r = 0.88$   $P < 0.01$ ; 1996:  $r = 0.59$   $P < 0.05$ ). Furthermore, strong negative correlations were found between the proportion of fraction IV and the sedimentation volume (1994:  $r = -0.71$   $P < 0.01$ ; 1995:  $r = -0.56$   $P < 0.05$ ). Within each year, mixograph peak time and resistance and bandwidth after 5 min of mixing were strongly positively correlated with the proportion of fraction I. Strong negative correlations were found between these mixogram parameters and the proportion of fraction IV. Bastian contained the highest proportion of polymeric proteins (fraction I). Polkka had a low SDS-sedimentation volume and gave weak mixing properties, and it contained the lowest proportions of polymeric proteins (fraction I) and the highest proportion of fraction IV. These results are in agreement with those of Singh et al (1990b), who found that the proportion of peak I was highly positively correlated to mixograph peak time. However, Gupta et al (1993) found that the percentage of fraction I protein showed variable relationships with flour properties, but the proportion of unextractable polymeric protein, defined by Gupta et al (1993) as proteins extracted with SDS-containing phosphate-buffer, pH 6.9, and sonication after removal of proteins extractable with SDS-containing phosphate-buffer, pH 6.9, and mixing, in total protein, had a strong positive effect on dough strength parameters for wheat flour. In our study, we did not include separation of unextractable polymeric proteins. The results from the present study showed that the proportion of polymeric protein (fraction I) increased as the temperature during grain filling increased, which can partly explain the large improvements in mixing properties from the lower to the higher temperatures in 1994, when the protein content was low (Fig. 1). In 1995 and 1996, when the protein content was high, the effect of temperature on the mixograph parameters was very small.

Our results show that the relationships between protein content, composition, and dough mixing properties were affected by the temperature during grain filling. Also, the results from the present study indicate that selection of cultivars with high SDS volumes and

strong mixing properties become even more important to ensure good and stable wheat quality in areas where the temperature during grain filling is low as compared to areas with higher temperatures.

## CONCLUSIONS

The protein content, sedimentation volume, and mixogram parameters of wheat samples were affected by the temperature during grain filling. Results from the SE-FPLC separations showed that the proportion of fraction I (polymeric protein) increased with increasing temperature. Furthermore, within each year, positive correlations were found between the proportion of fraction I and the SDS-sedimentation volume and the mixogram parameters peak time, resistance after 5 min, and bandwidth after 5 min. Negative correlations were found between these quality measurements and the proportion of fraction IV. The results of this study also showed that the effect of protein quality governed by the genotype exceeded that of the temperature during grain filling.

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