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Effect of Stem Elongation Waterlogging on Wheat Grain Yield, Grain Traits, and Quality of Chinese Southern-Type Steamed Bread

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Abstract: In this study, the effect of waterlogging stress at the stem elongation stage on the wheat grain yield, grain traits, and quality of Chinese southern-type steamed bread was investigated in a field experiment using three winter wheat varieties (Aikang 58, Yannong 19, and Huaimai 44). Waterlogging stress significantly ($p < 0.001$) decreased the grain yields of the three wheat varieties, and Aikang 58 was the most tolerant variety, achieving a 90.8% yield compared with that of the control (normal irrigation). A grain component analysis showed that waterlogging significantly ($p < 0.05$) decreased the ratios of glutenin to gliadin and amylopectin to amylose in wheat grain. A Mixolab analysis showed that waterlogging significantly ($p < 0.05$) decreased the dough development time; stability; and C2, C3, C4, and C5 values of the three wheat varieties. A steamed bread-making test showed that steamed bread made from Aikang 58 under waterlogging conditions showed a lighter color, a higher specific volume, and a lower hardness than that made from Yannong 19 and Huaimai 44 under waterlogging conditions. Overall, waterlogging showed different effects on the wheat grain and steamed bread qualities in the three wheat varieties, with Aikang 58 exerting the best performance under waterlogging conditions.

Keywords: wheat; stem elongation; waterlogging; grain quality; steamed bread quality

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1. Introduction

Wheat (*Triticum aestivum* L.) is one of the major crops in the world, and about 35% of the global population consumes wheat as a staple food [1]. In addition to being a major source of starch and energy, wheat also provides substantial amounts of components which are essential or beneficial for human health, such as protein, vitamins, dietary fiber, and phytochemicals. However, more than 25% of the wheat planting area around the world is affected by periodic waterlogging [2]. Waterlogging can accelerate the death of wheat roots, cause physiological metabolic disorders in wheat plants, inhibit its regular growth and development, and result in a lower grain yield of the wheat [3]. Besides a decrease in grain yield, waterlogging can also affect the grain traits of wheat, such as the protein content, protein composition, starch content, and starch composition [4,5]. Regarding climate change, waterlogging may have a greater effect on the wheat yield and quality due to the higher risk of floods and increased precipitation in parts of the world [6].

Chinese steamed bread is one of the most important staple foods in China, and about 40% of wheat is consumed in such products [7]. It is also consumed by many people in other Asian countries, like Korea, Japan, and the Philippines [8]. There are two major types of steamed bread made in China. Northern-type steamed bread has a very cohesive, elastic, and dense texture. Southern-type steamed bread is commonly known for a more open crumb structure, softer texture, and a white surface [9]. Although there is a well-established linear relationship between protein content and quality in Western bread, the same is not true for steamed bread, especially southern style steamed bread. Generally, southern-type steamed bread requires a flour protein content of about 9–11% with a weak to medium dough strength [7]. The quality characteristics of steamed bread usually include the volume, external characteristics, internal characteristics, eating quality, and flavor. Any significant deviation from the optimal characteristics can be considered as a reduction in the quality. Waterlogging stress can change the grain traits of wheat, which may further affect the quality of steamed bread.

Rice wheat rotation is the main cropping system in South China, especially in the Yangtze Plains and Huang-Huai Plains. Because of the long soaking time of rice fields, the viscosity of the soil is high, and its permeability is poor. Furthermore, the total rainfall can reach up to 500–800 mm during the growing stages from stem elongation to maturity (February to May), which often exceeds the normal water requirement of wheat and results in waterlogging. Ding et al. (2020) reported that wheat yield and yield components are more affected by waterlogging during the stem elongation stage when compared with the booting and anthesis stages in the Yangtze Plains [10]. According to the report of Arata et al. (2019), the effects of waterlogging on the yield and quality of wheat vary greatly in different studies depending on the wheat cultivars used, the duration of waterlogging, and the growing stage of the wheat [11]. Currently, information about the effect of waterlogging on Chinese steamed bread quality is still inadequate, particularly under field conditions. Therefore, the aim of this study was to investigate the effect of waterlogging stress at the stem elongation stage on the wheat grain yield, grain traits, and quality of Chinese southern-type steamed bread using three winter wheat varieties suitable for the production of Chinese steamed bread. The results of this study can provide scientific knowledge about the relationship between waterlogging and the steamed bread-making performance of wheat, as well as assistance in the choice of wheat varieties with good quality traits under waterlogging conditions.

2. Materials and Methods

2.1. Experimental Site and Design

The experiment was performed in soil pits (4.0 length, 3.0 m width, and 2.3 m depth) with a bottom at the Xinmaqiao Comprehensive Experimental Station of Irrigation and Drainage (Province of Anhui, China, 33°09′ N, 117°22′ E, 19.70 m above sea level). The soil in these pits is undisturbed soil that was collected from a local field. The soil type is fluvo-aquic soil, consisting of 26% clay, 70% loam, and 3.4% sand and containing 11.5 g/kg organic matter, 81.4 mg/kg available N, 75.7 mg/kg available K, and 29.6 mg/kg available *p*. The field trial was performed in randomized complete block designs with three replicates. Three winter wheat varieties (Table 1) suitable for the production of Chinese southern-type steamed bread were used in this study, which were selected in a preliminary steamed bread making test according to the method of Wang et al. [12]. The wheat was sown on 30 October 2022, with 8 rows of each plot, and harvested in the period of 28–30 May 2023. The irrigation water (conductivity of 772 μS/cm, ammonia nitrogen (0.08 mg/L), nitrate nitrogen (1.09 mg/L), total nitrogen (1.2 mg/L), soluble phosphoric acid (0.004 mg/L), total phosphorus (0.004 mg/L)) used in this study was shallow groundwater. The waterlogging treatment was imposed from the start of the stem elongation stage (2 March 2023) and lasted for 14 days with a 10 cm layer of free water above the soil surface. After the waterlogging treatment, the surface water was drained out in time, and the soil water was controlled at 70–80% of the field water capacity in the other growth stages. The control treatment was carried out by controlling the soil water at 70–80% of the field water capacity throughout the whole growth period of the wheat. The field water capacity was determined using the Wilcox method [13].

Table 1. The winter wheat varieties used in this study.

Cultivar	Year of Release	Pedigree	Origin	Main Planting Area
Aikang 58	2005	Zhoumai 11/Yumai 49/Zhengzhou 8960	Henan Institute of Science and Technology	Central Henan Province, North Anhui Province, North Jiangsu Province
Yannong 19	2001	Yang 1933 × Shan 82-29	Yantai Academy of Agricultural Sciences	Huang-Huai Plain
Huaimai 44	2017	Bainong 9711/Huaimai 95079 × Huaimai 9701	Huaiyin Institute Agricultural Science	Anhui Province along the Huai River

2.2. Determination of Wheat Yield and Grain Components

At maturity, a representative area of 1 m^2 from each plot was selected to investigate the number of spikes, and 30 wheat spikes were randomly selected to investigate the kernels per spike. After harvesting, the wheat samples were stored in paper bags for one month after ripening. Grain protein, gluten, and starch were determined using a near-infrared spectrometer (NIR Systems 6500, Foss Group, Hillerød, Denmark) and expressed on a 12.5% moisture basis. For further analysis, the wheat grains were milled into whole-wheat flour in a hammer mill (Labmill 3100, PerkinElmer Inc., Shelton, CT, USA). The contents of amylose and amylopectin in the whole wheat flour were determined using a coupled spectrophotometer assay according to the method described by Zhang et al. [14]. The gliadin and glutenin contents in the whole wheat flour were determined using the method described by Wollmer et al. [5].

2.3. Wheat Milling and Determination of Rheological Properties

Wheat samples were cleaned and tempered to 14.5 g/100 g of moisture. Then, the wheat samples were milled into straight-grade flour using a Brabender Quadrumat Senior mill (Brabender GmbH & Co. KG, Duisburg, Germany) according to the official method (26–50.01) of the American Association of Cereal Chemists (AACC). The dough mixing and pasting properties were determined using a Mixolab analyzer (Chopin Technologies, Paris, France) according to the AACC official method 54–60.01. The settings for the Mixolab testing were 8 min of initial mixing at 30 °C, a temperature increase at 4 °C /min until reaching 90 °C, holding for 7 min at 90 °C, a temperature decrease at 4 °C/min until reaching 50 °C, and holding for 5 min at 50 °C. A typical Mixolab curve (Figure 1) has five different stages (stage 1, initial kneading; stage 2, protein weakening; stage 3, starch gelatinization; stage 4, cooking stability; and stage 5, starch retrogradation) [15]. Parameters including water absorption (%), stability (min), and C2 [weakening of protein network, Newton meter (Nm)], C3 (peak viscosity, Nm), C4 (hot gel stability, Nm), and C5 values (starch retrogradation degree of cooling stage, Nm) were recorded from the Mixolab analysis.

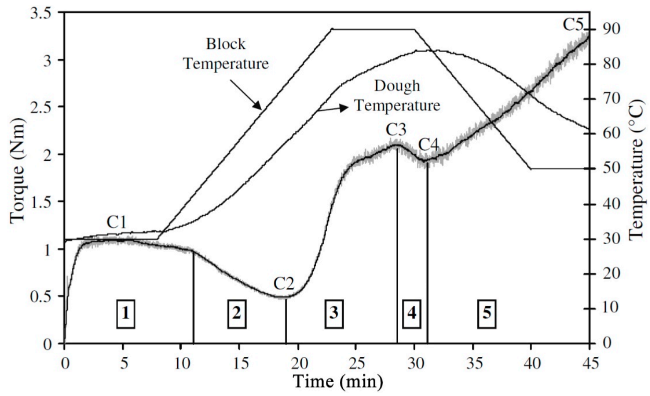

Figure 1. A typical Mixolab curve for wheat dough.

2.4. Preparation and Quality Evaluation of Chinese Steamed Bread

Chinese steamed bread was prepared using the method described by Wang et al. [12]. The formula for steamed bread consisted of 400 g of flour, 4 g of dry yeast, 20 g of sugar, 4 g of baking powder, and 16 g of shortening. The water added to each dough was 80% of the Mixolab water absorption. After steaming, bread samples were cooled at room temperature for 1 h and used for quality evaluation. The specific volume of steamed bread (volume to weight, cm^3/g) was determined using a laser volume analyzer (PV-X, Peikeng Technology Co., Ltd., Beijing, China). The crust and crumb color properties of steamed bread were determined using a colorimeter (CR-400, Konica Minolta Co., Ltd., Tokyo, Japan). Color values were recorded as L* (0, black; 100, white), a* (−100, green; +100, red), and b* (−100, blue; +100, yellow). The crumb structure of steamed bread was determined using the method described by Wang et al. [16]. Images of steamed bread slices were acquired using a flat-bed scanner (V19, Seiko Epson Corporation, Nagano-ken, Japan) and analyzed using Image J software (1.50i, National Institutes of Health, Bethesda, MD, USA). A 3×3 cm^2 area was intercepted from the center of each slice of steamed bread, and the porosity and density of the pores were calculated. A textural profile analysis (TPA) of steamed bread was performed according to the method described by Xu et al. [8] using a texture analyzer equipped with a 35 mm diameter acrylic cylindrical probe. Steamed bread was sliced horizontally, and a flat piece of 15 mm in thickness was compressed to 50% of its original height. The test conditions were as follows: pre-test speed, 2 mm/s; test speed, 1 mm/s; post-test speed, 1 mm/s; and trigger force, 5 g. The parameters of hardness, springiness, chewiness, and resilience were recorded.

2.5. Statistical Analysis

Statistical analyses were performed using one-way analyses of variance with the software SPSS 25.0. $p < 0.05$ (Duncan's test) was thought to be statistically significant.

3. Results and Discussion

3.1. Grain Yield and Yield Components

When waterlogging occurs, wheat roots switch from aerobic to anaerobic respiration due to the low oxygen concentration in soil. Long-term waterlogging stress can accelerate the senescence and death of winter wheat roots, reduce soil–plant analysis development and the net photosynthetic rate, inhibit its regular growth and development, and ultimately result in a lower yield of wheat [5,17]. The effects of waterlogging stress at the stem elongation stage on the wheat grain yield and yield components are shown in Table 2. Waterlogging caused significant grain yield losses ($p < 0.001$) in the three wheat varieties. Compared with their corresponding control groups (normal irrigation), the yield losses of Aikang 58, Yannong 19, and Huaimai 44 were 9.2%, 25.7%, and 35.4% under the waterlogging treatments, respectively. The yield loss of Aikang 58 was significantly lower than those of Yannong 19 and Huaimai 44, indicating that Aikang 58 is more tolerant to waterlogging stress than Yannong 19 and Huaimai 44. According to the study of Li et al. [17], waterlogging-tolerant wheat genotypes had a higher chlorophyll content than waterlogging-sensitive genotypes. They could maintain high photosynthetic rates under waterlogging stress and thus obtain high wheat grain yields. As shown in Table 2, for the three wheat varieties, especially for Yannong 19 and Huaimai 44, the decreases in kernels per spike and 1000-kernel weight were significantly ($p < 0.05$) higher than those in the spikes of their corresponding control treatments (normal irrigation). This meant that the decreases in kernels per spike and 1000-kernel weight were the main factors for the decrease in wheat yield under waterlogging conditions at the stem elongation stage. Similar trends were also reported by Alizadeh-Vaskasi et al. [18] and Araki et al. [19]. They found that waterlogging at the tillering and elongation stages reduced the kernels-per-spike and single-spike yields in wheat plants and thus resulted in reductions in grain yield.

Table 2. Effect of waterlogging on wheat grain yield and yield components.

Cultivars	Treatments	Spikes (10^4 hm^{-2})	RS (%)	Kernels Per Spike	RK (%)	1000-Kernel Weight (g)	RKW (%)	Yield (kg hm^{-2})	RY (%)
Aikang 58	CK	557 ^{a}		38 ^{aA}		34.1 ^{bABC}		7186 ^{A}	
	WL	543 ^{a}	2.5	35 ^{abAB}	7.9	33.5 ^{bcBC}	1.8	6528 ^{C}	9.2
Yannong 19	CK	520 ^{ab}		36 ^{abAB}		37.2 ^{aA}		6894 ^{B}	
	WL	499 ^{bc}	4.0	31 ^{cBC}	13.9	32.1 ^{cCD}	13.7	5121 ^{E}	25.7
Huaimai 44	CK	529 ^{ab}		34 ^{bAB}		35.6 ^{bAB}		6401 ^{D}	
	WL	483 ^{c}	8.7	28 ^{cC}	17.6	29.8 ^{dD}	16.3	4138 ^{F}	35.2

Values in the same column followed by different uppercase and lowercase letters represent significant differences at $p < 0.01$ and $p < 0.05$, respectively. CK, control (normal irrigation); WL, waterlogging; RS, reduction in spikes; RK, reduction in kernels per spike; RKW, reduction in 1000-kernel weight; RY, reduction in yield.

3.2. Components of Wheat Grain

The protein content of wheat grain is easily affected by environmental conditions [20]. Olgun et al. [21] reported that 20–50 days of waterlogging from the beginning of the flowering stage significantly decreased the grain protein content of wheat, while 5–15 days of waterlogging showed no significant effect ($p > 0.05$) on the grain protein content. In the present study, 14 days of waterlogging did not result in a significant change ($p > 0.05$) in the grain protein content in Aikang 58 and Yannong 19. However, a significant increase ($p < 0.05$) was found in the grain protein content of Huaimai 44 under waterlogging when compared with the control treatments. Wollmer et al. [5] also found that waterlogging significantly increased the grain protein concentration in two winter wheat cultivars. They thought the increase in the grain protein concentration of wheat under waterlogging could be due to a concentration effect (smaller and shriveled grains).

The gluten content is an important index for evaluating the wheat flour quality because it deeply affects the structure and texture of wheat foods [22]. Similarly to the grain content, waterlogging resulted in no significant effect ($p > 0.05$) on the gluten content of Aikang 58 and Yannong 19 but induced a significant increase ($p < 0.05$) in the gluten content of Huaimai 44. Besides the gluten content, waterlogging also exhibited a significant effect on the gluten composition in the wheat grain. As shown in Table 3, waterlogging significantly decreased the glutenin-to-gliadin ratio in the grain of the three wheat varieties, especially for Huaimai 44, the values of which decreased from 0.722 to 0.539. Similarly to our study, Lan et al. [23] also found that post-anthesis waterlogging significantly decreased the glutenin-to-gliadin ratio in wheat grain. The bread-specific volume has been suggested to be significantly correlated with the gliadin-to-glutenin ratio in wheat gluten [24]. Therefore, although waterlogging increased the gluten content of Huaimai 44 in this study, the quality of the final product that can be produced may not be higher when compared with wheat under normal irrigation conditions.

Table 3. Effect of waterlogging on wheat grain components.

Cultivars	Treatments	Protein (%)	RP (%)	Wet Gluten (%)	RWG (%)	Glu/Gli	RGG (%)	Total Starch (%)	RTS (%)	Ap/Am	RAA (%)
Aikang 58	CK	11.07 ^{aB}		24.92 ^{b}	1.89	0.759 ^{aB}		67.25 ^{bABC}		3.09 ^{A}	
	WL	10.82 ^{aB}	2.26	24.45 ^{B}		0.641 ^{cC}	15.55	67.94 ^{abAB}	−1.03	2.38 ^{aB}	22.98
Yannong 19	CK	11.20 ^{aB}		25.03 ^{b}		0.875 ^{A}		66.75 ^{cABC}		2.29 ^{aB}	
	WL	11.35 ^{aB}	−1.34	25.47 ^{b}	−2.37	0.612 ^{dC}	30.06	65.82 ^{dC}	1.41	2.06 ^{bB}	10.04
Huaimai 44	CK	11.29 ^{aB}		24.57 ^{B}		0.722 ^{bB}		68.13 ^{aA}		2.97 ^{A}	
	WL	13.52 ^{A}	−19.75	28.62 ^{aA}	−16.48	0.539 ^{D}	25.35	66.54 ^{cBC}	2.33	2.23 ^{B}	24.92

Values in the same column followed by different uppercase and lowercase letters represent significant differences at $p < 0.01$ and $p < 0.05$, respectively. CK, control (normal irrigation); WL, waterlogging; Glu/Gli, the ratio of glutenin to gliadin; Ap/Am, the ratio of amylopectin to amylose; RP, reduction in protein; RWG, reduction in wet gluten; RGG, reduction in the ratio of glutenin to gliadin; RAA, reduction in the ratio of amylopectin to amylose.

Starch is the major component in wheat endosperm and comprises 60–75% of the dry weight of wheat grain. The starch content and composition (amylopectin-to-amylose ratio) in wheat grain greatly affect the dough's rheological properties and, consequently, the end use of wheat flour [25]. Zhou et al. [4] found that waterlogging stress induced a slightly higher total starch content in mature grains in one winter wheat cultivar (Yumai 34), while the opposite trend was seen in another wheat winter cultivar (Yangmai 9). As shown in Table 3, waterlogging showed no significant effect ($p > 0.05$) on the grain starch content of Aikang 58 but significantly ($p < 0.05$) decreased the grain of Yannong 19 and Huaimai 44. Besides the starch content, waterlogging also significantly ($p < 0.05$) decreased the ratio of amylopectin to amylose in the wheat grains of the three wheat varieties. The soluble starch synthetase (SSS) in wheat grain is widely believed to mainly catalyze the synthesis of amylopectin, while the starch granule-bound starch synthetase mainly catalyzes the synthesis of amylose. Under waterlogging conditions, the activity of key starch-related enzymes decreased, especially the activity of SSS, which significantly reduced the content of amylopectin in wheat grain and led to a decrease in the ratio of amylopectin to amylose [26].

3.3. Thermo-Mechanical Properties of Wheat Flour

The first phase of a typical Mixolab curve determines the dough mixing properties and the water absorption, development time, stability, and C2 value (weakening of protein network) of dough, as shown in Table 4. Waterlogging stress showed no significant ($p > 0.05$) effect on the dough water absorption of Aikang 58 and Yannong 19 when compared with their corresponding control groups (normal irrigation), while the dough water absorption of Huaimai 44 was significantly ($p < 0.05$) increased by waterlogging. This might be attributed to the fact that waterlogging induced a higher grain protein content in Huaimai 44 but had no significant effect on the grain protein content of Aikang 58 and Yannong 19 (Table 3). For the three wheat varieties, waterlogging decreased the development time, stability, and C2 value of dough when compared with their corresponding control groups. The change in the values of the development time, stability, and C2 value indicated that waterlogging stress decreased the dough strength and might have detrimental effects on the final wheat products.

The second phase of the Mixolab curve determines the starch pasting and retrogradation properties in dough during the heating and cooling stages. As Table 4 shows, waterlogging significantly decreased the C3 (peak viscosity during the heating stage), C4 (hot gel stability), and C5 (the starch retrogradation degree in the cooling stage) values for the three wheat varieties when compared with their corresponding control wheat samples. Similar results were also reported by Zhou et al. [4], who found that grain-filling waterlogging stress decreased the peak viscosity, breakdown, final viscosity, and setback of wheat flour using an RVA analysis. Waterlogging changed the starch content and ratio of amylopectin to amylose in wheat grain (Table 3) and thus affected the pasting and retrogradation properties of wheat dough.

Table 4. Effect of waterlogging treatment on thermo-mechanical properties of wheat dough.

Cultivars	Treatments	WA (%)	DT (Min)	Stability (Min)	C2 (Nm)	C3 (Nm)	C4 (Nm)	C5 (Nm)
Aikang 58	CK	53.4 ^{ab}	1.60 ^{abAB}	4.99 ^{aB}	0.45 ^{aA}	3.09 ^{A}	2.22 ^{A}	3.52 ^{aA}
	WL	52.3 ^{bc}	1.26 ^{cBC}	4.23 ^{bC}	0.38 ^{bc}	2.38 ^{aB}	1.95 ^{bC}	3.05 ^{dC}
Yannong 19	CK	53.1 ^{bc}	1.75 ^{aA}	5.73 ^{A}	0.42 ^{ab}	2.29 ^{aB}	2.11 ^{aB}	3.31 ^{cB}
	WL	52.1 ^{cB}	1.05 ^{dC}	3.63 ^{cC}	0.34 ^{cd}	2.06 ^{bB}	1.96 ^{bC}	2.92 ^{eC}
Huaimai 44	CK	52.2 ^{cB}	1.48 ^{bAB}	4.35 ^{bBC}	0.41 ^{ab}	2.97 ^{A}	2.05 ^{aBC}	3.43 ^{bAB}
	WL	54.5 ^{aA}	0.94 ^{dC}	3.70 ^{cC}	0.30 ^{dB}	2.23 ^{B}	1.82 ^{D}	2.97 ^{eC}

Values in the same column followed by different uppercase and lowercase letters represent significant differences at $p < 0.01$ and $p < 0.05$, respectively. CK, control (normal irrigation); WL, waterlogging; WA, water absorption; DT, development time; C2, weakening of the protein network; C3, peak viscosity during the heating stage; C4, hot gel stability; C5, starch retrogradation degree in the cooling stage.

3.4. Specific Volume and Crumb Structure of Steamed Bread

The photographs of the steamed breads produced from the three wheat varieties under normal irrigation or waterlogging conditions are shown in Figure 2. Volume is a very important parameter for evaluating steamed bread quality because it strongly influences the consumer's choice. Generally, as shown in Table 5, for the three wheat varieties, waterlogging significantly ($p < 0.05$) decreased the specific volume of steamed bread when compared with the control groups (normal irrigation). Waterlogging stress resulted in lower stability and C2 values of dough (Table 4), which restricted the dough gas cell in its ability to expand and its capacity to retain gas and then reduced the steamed bread's specific volume. Among the three wheat varieties, waterlogging decreased the specific volume for steamed bread made from Aikang 58 by 5.5% when compared with the control group (normal irrigation), and the values were 15.2% and 14.7% for Yannong 19 and Huaimai 44, respectively. This result indicates that Aikang 58 was more resistant to waterlogging and could produce steamed bread with higher quality under waterlogging stress than the other two varieties (Yannong 19 and Huaimai 44).

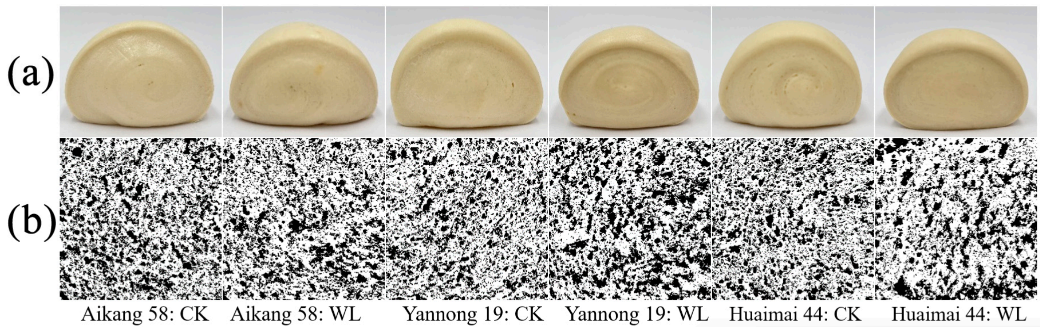

Figure 2. Photographs of steamed breads (**a**) and binary images of their crumb (**b**). CK, control (normal irrigation); WL, waterlogging.

Table 5. Effect of waterlogging on specific volume and crumb structure of steamed bread.

Cultivars	Treatments	Specific Volume (mL/g)	Porosity (%)	Cell Density (Cell/cm^2)	Average Cell Area (mm^2)
Aikang 58	CK	1.98 ^{bAB}	25.30 ^{aB}	77.27 ^{aB}	0.27 ^{bC}
	WL	1.87 ^{cBC}	23.83 ^{bB}	71.55 ^{bB}	0.29 ^{bBC}
Yannong 19	CK	2.11 ^{aA}	27.75 ^{A}	86.39 ^{A}	0.25 ^{bC}
	WL	1.79 ^{dC}	18.87 ^{cC}	62.90 ^{C}	0.34 ^{aAB}
Huaimai 44	CK	1.90 ^{cBC}	24.12 ^{bB}	73.58 ^{bB}	0.28 ^{bBC}
	WL	1.62 ^{D}	17.19 ^{dC}	55.68 ^{D}	0.35 ^{aA}

Values in the same column followed by different uppercase and lowercase letters represent significant differences at $p < 0.01$ and $p < 0.05$, respectively. CK, control (normal irrigation); WL, waterlogging.

The stomatal structure of the crumb of steamed bread is illustrated in Figure 2, and the structural information is given in Table 5. Porosity refers to the percentage of cell area in the total slice area, and a higher porosity value means the steamed bread has an open and soft texture [27]. As shown in Table 5, waterlogging stress decreased the values of porosity for steamed breads made from the three wheat varieties, which was similar to the trend for specific volume. According to the studies by Das et al. [28] and Scanlon and Zghal [29], a larger number of small cells can create a uniform crumb matrix of steamed bread and thus yield a softer and more elastic texture. For the three wheat cultivars, waterlogging stress resulted in fewer and bigger cells (lower cell density and higher average cell area) in the crumbs of steamed bread. Thus, the mouthfeel of steamed bread produced from wheat under waterlogging stress was reduced.

3.5. Color Characteristics of Steamed Bread

Different from baked bread, a bright and white color is preferred by consumers for steamed bread. Currently, few studies have investigated the effect of waterlogging on the color of wheat products. As shown in Figure 2, a darker color was found in steamed bread produced from wheat under waterlogging conditions. The crust and crumb color values (L*, a*, and b*) of the steamed bread samples are presented in Table 6. For the three wheat varieties, waterlogging significantly ($p < 0.05$) decreased the crust and crumb L* values of steamed breads compared with their corresponding control samples (normal irrigation). For Aikang 58, no significant difference ($p > 0.05$) was found in the a* and b* values of the control steamed breads (normal irrigation) and steamed breads made from wheat under waterlogging. However, for Huaimai 44 and Yannong 19, waterlogging increased the a* and b* values of steamed breads when compared with their corresponding control steamed breads (normal irrigation). These results indicate that waterlogging resulted in a darker, redder, and yellower color for steamed breads made from Huaimai 44 and Yannong 19 compared with the corresponding control samples (normal irrigation). Zhang et al. (2014) reported that the protein content and glutenin content in wheat grain were negatively correlated with the flour's L* value, while they were positively correlated with flour's a* and b* values [30]. In the present study, waterlogging changed the protein content and glutenin-to-gliadin ratio in wheat grain (Table 3) and thus affected the color characteristics of the resultant steamed bread.

Table 6. Effect of waterlogging on color properties (crumb and crust) of steamed bread.

Cultivars	Treatments	Crust			Crumb		
		L^*	a^*	b^*	L^*	a^*	b^*
Aikang 58	CK	87.02 ^{aA}	−1.66 ^{bAB}	20.78 ^{cB}	83.35 ^{aA}	−1.48 ^{aA}	14.31 ^{cB}
	WL	84.24 ^{bA}	−1.76 ^{bA}	21.72 ^{c}	79.10 ^{bA}	−1.56 ^{aA}	14.11 ^{cB}
Yannong 19	CK	86.85 ^{aA}	−2.05 ^{aA}	21.26 ^{c}	81.63 ^{abA}	−1.51 ^{aA}	14.74 ^{cB}
	WL	79.64 ^{B}	−1.18 ^{cB}	22.21 ^{bc}	70.43 ^{B}	−1.04 ^{bAB}	16.37 ^{bAB}
Huaimai 44	CK	85.23 ^{A}	−1.55 ^{bAB}	23.24 ^{ab}	82.80 ^{aA}	−1.43 ^{aA}	15.01 ^{cB}
	WL	78.49 ^{B}	−0.66 ^{C}	24.07 ^{aA}	68.67 ^{B}	−0.78 ^{cB}	17.76 ^{aA}

Values in the same column followed by different uppercase and lowercase letters represent significant differences at $p < 0.01$ and $p < 0.05$, respectively. CK, control (normal irrigation); WL, waterlogging.

3.6. TPA of Steamed Bread

Figure 3 shows the textural parameters of steamed bread based on a TPA. In the production of steamed bread, a soft texture is preferred by consumers. For the Yannong 19 and Huaimai 44 varieties, the hardness value of the steamed bread produced from wheat under waterlogging conditions was significantly ($p < 0.05$) higher than their corresponding control steamed bread. This might be because of its lower specific volume. Based on the study by De la Hera et al. [31], gas cells were more compact, and the crumb hardness increased when steamed bread showed a lower specific volume. For Aikang 58, although an increase was found in the hardness for steamed bread under waterlogging conditions when compared with the control steamed bread, the difference was not significant ($p > 0.05$). Sun et al. [32] found that the chewiness of steamed bread had a significant positive correlation with its hardness. As Figure 3 shows, the change in steamed bread chewiness showed a similar trend to hardness.

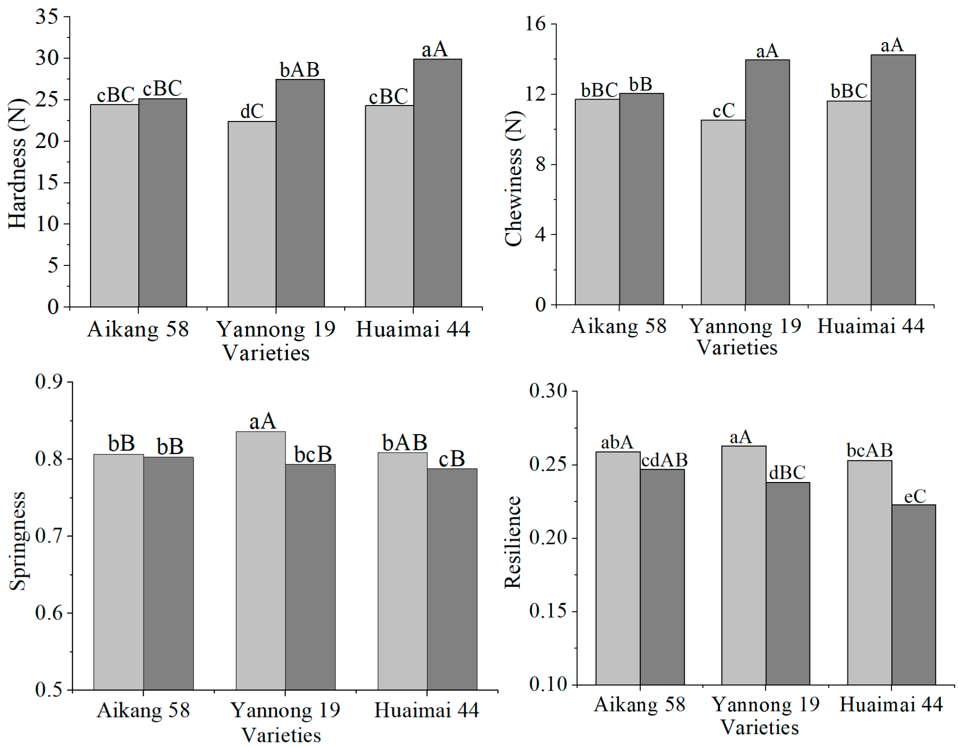

Figure 3. The effect of waterlogging treatment on the textural parameters of steamed bread. Different letters on the bars in the same chart indicate significant differences at $p < 0.01$ and $p < 0.05$, respectively. ▭ control, normal irrigation; ▬ waterlogging at the stem elongation stage.

In the production of bread, springiness determined by TPA reflects its freshness, and bread with a low value is brittle [33]. Resilience characterizes the beginning of a sample's elasticity, which is strongly correlated with the crumb cohesion of bread [34]. Decreases in the values of springiness and resilience reflect a deterioration in the bread crumb elasticity [35]. Therefore, having high springiness and resilience values is desired for the production of steamed bread. In contrast to hardness and chewiness, waterlogging stress induced significant ($p < 0.05$) decreases in the resilience and springiness of steamed bread, indicating that waterlogging stress had detrimental effects on the texture of steamed bread.

4. Conclusions

Waterlogging stress at the stem elongation stage resulted in significant decreases in the grain yields of the three wheat varieties, which was mainly attributed to the decreases in the kernels per spike and 1000-kernel weight. Waterlogging stress changed the wheat grain components and resulted in weaker doughs (decreases in the dough developing time, stability, and C2 value). At same time, the starch pasting and retrogradation properties were changed by decreasing the C3, C4, and C5 values of the dough. Regarding steamed bread performance, waterlogging resulted in detrimental effects on the quality of the steamed bread. Among the three wheat varieties, Aikang 58 showed better steamed bread performance than Yannong 19 and Huaimai 44.

Based on the above results, the development or selection of waterlogging-tolerant varieties is an effective and economical approach to improve grain yield under waterlogging conditions. The agronomic traits, including the plant height, tillers per meter, biological yield, thousand grain weight, and grain yield were often used to identify tolerant wheat varieties with high yield potential. However, direct selection only based on these agronomic traits under waterlogging might be misleading, and therefore, a successful selection will depend upon the combined information on the agronomic traits, grain component traits, and qualities of final products. Tolerance information obtained from this research suggests potential cultivars that could be incorporated as parents for future crosses in breeding programs, particularly for winter wheat cultivars targeted at the production of steamed bread.

The effect of waterlogging on the qualities of wheat and steamed bread was different depending on the wheat cultivars used and waterlogging severity. The present study only used a severe waterlogging treatment, which lasted for 14 days, and three winter wheat varieties. More wheat varieties and waterlogging treatment durations should be involved in order to systematically investigate the effects of waterlogging on the qualities of wheat and steamed bread. In addition, a long-term (several growing seasons) experiment should also be performed in the future.

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Abbreviations

The following abbreviations are used in this manuscript:

CK	control (normal irrigation)
WL	waterlogging
RS	reduction in spikes
RK	reduction in kernels per spike
RKW	reduction in 1000-kernel weight
RY	reduction in yield
RP	reduction in protein
RWG	reduction in wet gluten
RGG	reduction in ratio of glutenin to gliadin
RAA	reduction in ratio of amylopectin to amylose
Glu/Gli	ratio of glutenin to gliadin
Ap/Am	ratio of amylopectin to amylose
WA	water absorption
DT	development time
C2	weakening of protein network
C3	peak viscosity during heating stage
C4	hot gel stability
C5	starch retrogradation degree of cooling stage

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