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Article

Strategy for Enhancing Wheat Drying Efficiency and Flour Quality: Hybridization of Tempering and Hot Air Drying

Peijie Zhang, Linlin Li,* Wenchao Liu, Weiwei Cao, Junliang Chen, Tongxiang Yang, Xu Duan, Huiping Fan, Debang Zhang, and Guangyue Ren*

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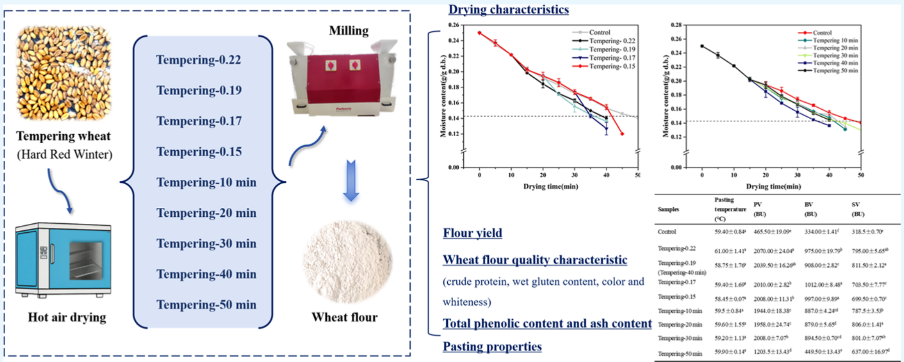

ABSTRACT: The moderate processing of wheat is increasingly valued. One of the technological means to achieve moderate processing is the hybridization of tempering and hot air drying for postharvest wheat. The initial moisture content at onset of tempering (IMCOT) of wheat significantly influences the efficiency of hot air drying as well as the yield and quality of wheat flour. This study investigates the effects of varying IMCOT and tempering durations on the drying characteristics of wheat, the flour yield, the flour properties, and the properties of flour slurries. The findings revealed that tempering treatments reduced the drying time and altered the pasting characteristics of the flour slurries. This phenomenon could be attributed to the alteration of the kernel structure and starch destruction caused by tempering treatment. Tempering significantly ($P < 0.05$) affected the protein content and wet gluten content of wheat flour (WF). For the effect of IMCOT, the shortest drying time (35 min) was observed at an IMCOT of 0.17 g/g d.b., while the highest wet gluten content of WF was achieved when it was 0.19 g/g d.b. The lowest breakdown value (908.00 Brabender Units, BU) and highest setback value (811.50 BU) of WF were observed at an IMCOT of 0.19 g/g d.b. For the effect of tempering duration, the shortest drying time (35 min) was achieved at a tempering duration of 40 min. Tempering duration improved the whiteness and brightness of the flour, as well as increased its protein content. Considering the drying efficiency and the quality attribute, the optimal tempering condition was the IMCOT of 0.19 g/g d.b. and a tempering duration of 40 min.

1. INTRODUCTION

Wheat, a primary staple food crop globally, is widely used in various food products. Its bran is rich in essential nutrients, such as dietary fiber, minerals, and phytochemicals, which are vital for human nutrition and health.[1,2] However, modern refined wheat flour often suffers significant nutrient loss despite being labeled as “high-quality.” As a public concern for food nutrition, it is crucial to optimize wheat processing techniques to preserve its nutritional value and enhance production efficiency. Specifically, applying tempering techniques in the drying process can improve both the efficiency and nutritional integrity of wheat flour.[3]

Drying is essential for processing high-moisture wheat to prevent mold and insect infestation.[4,5] During drying, high-moisture wheat kernels experience uneven heating, resulting in a moisture gradient and internal cracking. This results in kernel browning, increased damaged starch content, and reduced milling efficiency and flour quality.[6−8] Tempering is an essential step in wheat kernel processing that reduces energy consumption and improves product quality by mitigating internal moisture gradients and thermal stress, thereby minimizing the degradation in flour quality.[9,10] Recent studies[11−13] have employed mathematical and physical models, as well as numerical simulations, to examine the fluctuations in

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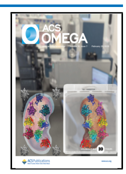

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internal temperature and humidity gradients and their effects on stress levels during kernel tempering. The objective of these studies was to forecast the impact of tempering on alterations in kernel quality.[14,15] Zhao et al.[16] demonstrated that tempering during microwave vacuum drying (MVD) of lotus seeds could decrease the moisture gradient, enhance moisture diffusion, and reduce drying time. Additionally, the tempered samples exhibited minimal overall color alteration along with elevated concentrations of flavor-active amino acids. Wei et al.[17] reported that the optimized multistage tempering drying with variable time parameters (OTD), continuous drying (CD), and multistage tempering drying process could effectively shorten the drying time of corn. Moreover, this process resulted in a reduced moisture and temperature gradient in the corn endosperm during drying, which helped to minimize the occurrence of cracking caused by hygrothermal stress. Application of tempering in high-temperature fluidized-bed drying of rice resulted in partial gelatinization, which enhanced the gel network.[18] In summary, by controlling the heat and mass transfer that occurs between the material and its surrounding environment, tempering improves the quality of the dried product by affecting the drying kinetics of the material.

Several studies have investigated the impact of drying on the drying characteristics and physicochemical properties of kernels.[16,19−21] Notably, previous research on wheat kernel quality has emphasized that drying methods can profoundly affect quality attributes, including protein, gluten, and starch properties. These studies have also warned of the risks associated with varying drying temperatures and methods, such as protein denaturation and a decline in kernel quality.[22,23] This highlights the critical need for precise control over the drying process to enhance the quality and nutritional value of wheat kernels.

While the influence of tempering on wheat processing aspects—like milling performance, energy use in grinding, and the particle size distribution of middlings and flour—has been examined at various moisture levels during milling (12, 14, 16, or 18%),[24] there is a clear gap in the literature regarding the nutritional implications of wheat kernels, especially concerning the effects of tempering moisture levels and duration. This knowledge gap underscores the importance of understanding the role of tempering in maintaining and potentially improving the nutritional profile of wheat kernels. Therefore, comprehensive research into the impact of tempering on wheat kernel nutrition is both timely and essential, as it can inform best practices for optimizing the drying process to preserve kernel quality and nutritional benefits.

Therefore, in order to understand the effect of the tempering process on flour quality, the changes in flour milling quality indicators (flour yield, wet gluten content, whiteness, and ash content), nutritional quality indicators (protein and total phenolic content), and flour slurry properties (pasting properties), as affected by the tempering process, were studied. The outcomes of this research are poised to furnish pivotal data that will enhance the optimization of wheat drying processes, thereby catalyzing the evolution of drying strategies that are not only more efficient but also more aligned with environmental sustainability principles. Furthermore, these discoveries are anticipated to bolster the scientific underpinnings necessary for the enhancement of flour quality and the subsequent improvement of products derived from therefrom. Consequently, this optimization and enhancement of drying processes will exert a beneficial influence on both the food industry and consumer health.

2. MATERIALS AND METHODS

2.1. Materials. Wheat (Hard Red Winter) was sourced from the Dengzhou Branch of the Central Grain Reserve (Inspection Center of Henan Branch of China Grain Reserves, China) and was produced in Nanyang City, Henan Province, China. The wheat underwent a rigorous screening process to ensure uniformity and consistency, thereby guaranteeing the quality and reliability of the wheat grains for further processing. The size ranged from 2.0 to 3.5 mm, which met the conventional processing requirements. The moisture content of the wheat was approximately 0.10 ± 0.01 g/g on a dry basis (d.b.), as determined by the AACC Method 44-15.02. All chemical reagents used were of analytical quality. The chemicals obtained from Omerson Chemical Products Co. (Luoyang, China) included copper sulfate, potassium sulfate, boric acid, sodium carbonate, and standards of gallic acid. (Figure 1).

Figure 1. Image of Hard Red Winter wheat.

2.2. Design Scheme for the Tempering Process. To simulate the drying process of freshly harvested wheat, the wheat was wetted to achieve a moisture content of 0.25 g/g d.b. Subsequently, the wheat was subjected to drying tests. In each trial, a uniform layer of 200 g of wheat, approximately 2–3 cm deep, was carefully spread out in trays. The relative humidity in the laboratory was maintained between 45 and 55%.

2.2.1. Drying of Wheat: Selection of Temperature and IMCOT for Tempering. Pre-experiments were conducted at various drying temperatures (40, 50, 60, 70, 80, and 90 °C) until the drying end point was reached, which was a moisture content of 0.14 g/g on a dry basis (d.b.). The moisture level was considered safe for grain storage according to Chinese National Standard GB/T 43994-2024. The optimum drying temperature was determined to be 70 °C based on drying characteristics, wheat flour yield, and wet gluten content. Based on these findings, a tempering program was designed.

This study examined the effects of different initial moisture contents at the onset of tempering (IMCOT) and different tempering durations on wheat flour quality. All tests were conducted at a fixed drying temperature of 70 °C and air tempering at room temperature.[20,25]

For the drying process of IMCOT of wheat, first, 200 g of wheat was dried to achieve specific moisture content levels, X_i

Table 1. Experimental Program for Assessing Various Initial Moisture Contents at the Onset of Tempering (IMCOT) Tests[a]

		first tempering			second tempering		third tempering
samples	initial moisture (g/g d.b.)	drying time (min)	moisture after drying (g/g d.b.)	tempering duration (min)	drying time (min)	tempering duration (min)	drying time (min)
tempering-0.22	0.25	10	0.22	40	10	20	···
tempering-0.19 (tempering-40 min)	0.25	20	0.19	40	20	20	
tempering-0.17	0.25	30	0.17	40	30	20	
tempering-0.15	0.25	40	0.15	40	40	20	

[a]Tempering-0.22, 0.19, 0.17, and 0.15 are the IMCOT of 0.22, 0.19, 0.17, and 0.15 g/g, d.b., respectively.

Table 2. Experimental Program for Assessing Various Tempering Durations[a]

		first tempering		second tempering		third tempering	
samples	initial moisture (g/g d.b.)	tempering duration (min)	drying time (min)	tempering duration (min)	drying time (min)	tempering duration (min)	drying time (min)
tempering-10 min	0.25	10	20	10	20	10	···
tempering-20 min	0.25	20	20	20	20	20	
tempering-30 min	0.25	30	20	30	20	30	
tempering-40 min	0.25	40	20	40	20	40	
tempering-50 min	0.25	50	20	50	20	50	

[a]Tempering-10, 20, 30, 40, and 50 min correspond to the tempering duration of 10, 20, 30, 40, and 50 min, respectively.

(0.22, 0.19, 0.17, 0.15 g/g d.b.) over a corresponding drying time, T_i (the duration required to reduce the wheat's moisture content to 0.22, 0.19, 0.17, 0.15 g/g, respectively). After each X_i was reached, the wheat was tempered for 40 min. Following the tempering period, the wheat was subjected to further drying for time T_i. This tempering and drying cycle was repeated until the drying was fully completed, with the final moisture content of wheat reaching 0.14 g/g d.b. The experimental parameters for different IMCOTs are shown in Table 1.

2.2.2. Drying of Wheat: Tempering Duration. In the study of wheat with varying tempering durations, first, the process commenced with drying 200 g of wheat to achieve a moisture content of 0.19 g/g d.b. This was accomplished by drying at 70 °C for 20 min. After drying, the wheat was subjected to tempering for different durations, X_t (10, 20, 30, 40, and 50 min). After each tempering period, the wheat was returned to the dryer for an additional 20 min. This sequence of drying and tempering was repeated until the moisture content of the wheat was reduced to the desired level of 0.14 g/g db, marking the end of the drying process. The experimental parameters for different tempering durations are shown in Table 2. Each experimental group was conducted in triplicate, and statistical analysis was performed with its mean. The test with an IMCOT of 0.19 g/g d.b. and the test with a tempering duration of 40 min were identical.

2.3. Wheat Milling. The raw wheat was manually cleaned of impurities and then conditioned according to the AACC method 26-10A.[26] Prior to milling, the moisture content of the wheat was uniformly conditioned to 0.16 g/g d.b. Subsequently, the milling process was conducted using a laboratory mill (model PLM-T, Perkone Scientific, China) in accordance with the AACC method 26-21.02. The break roller spacings were 0.5 and 0.05 mm, and the reduction roller spacings were 0.05 and 0.03 mm, respectively. The coarse flour from the mill was subjected to sieving using a flour sieve (Model PPS-308, Perkone Scientific, China) with screen sizes of CQ10 and CB36. Each sieving process was fixed at 300 s.

2.4. Measurement and Analysis Methods. *2.4.1. Analysis of Wheat Flour Quality Characteristics.* The AACC methods 44-15.02, 46-11.01, and 08-01.01 were used to determine the moisture, crude protein, and ash content of the wheat flours, respectively.[26] The flour yield was expressed as a percentage of the total amount of wheat fed into the mill. The wet gluten content was determined in accordance with the ISO 21415-2:2015 method.[27] The color of WF was measured using a colorimeter (Color I5-, X-rite Incorporated, United States). The formula for calculating Hunter Whiteness is as follows:

$$\text{Hunter whiteness} = 100 - [(100 - L^*)^2 + a^{*2} + b^{*2}]^{1/2}$$

where L^* represents the lightness or brightness of a color, with a^* indicating its position on the red-green axis, where positive values suggest a redder hue and negative values indicate a greener tint. The b^* value represents the color's position on the yellow-blue axis, with positive values denoting a yellowish cast and negative values signifying a bluish tone.

2.4.2. Determination of Total Phenolic Content (TPC). The Folin−Ciocalteu method was used to determine the total phenolic content. The total phenolic content (TPC) was determined using the Folin−Ciocalteu method, with slight modifications to the procedure described by Akman.[28] The sample extract (100 μL) was mixed with 900 μL of distilled water, followed by 125 μL of a solution of Folin & Ciocalteu's Phenol reagent and 375 μL of 20% Na_2CO_3 solution. Absorbance was recorded at 765 nm by using a microplate reader (Spark, Tecan, Switzerland) after incubation for 30 min in the absence of light. Standard curves were plotted with different concentrations of gallic acid standards (25, 50, 75, 100, 150, and 200 μg/mL). From the standard curve, the total phenolic content of wheat was calculated. The results were expressed as gallic acid equivalent (GAE) with the unit of mg GAE/g on a dry basis.

2.4.3. Analysis of Pasting Properties. Brabender visco analyzer (Model 803302, Brabender GmbH & Co. KG, Germany) was used to measure the pasting properties of WF following the AACC method.[26] The sample concentration

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(WF/water) was 1:5 (w:w). After the determination, peak viscosity (PV), breakdown viscosity (BV), setback viscosity (SV), and pasting temperature were recorded.

2.5. Statistical Analysis. The data were analyzed statistically using Origin 2022 and SPSS 19.0 software. All experiments were conducted with at least three replicates. One-way analysis of variance (ANOVA) with Duncan's test was employed for statistical analysis, with significance set at $P < 0.05$.

3. RESULTS AND DISCUSSION

3.1. Drying Characteristics of Wheat. Figure 2 shows the drying curves of wheat with different IMCOT. It should be

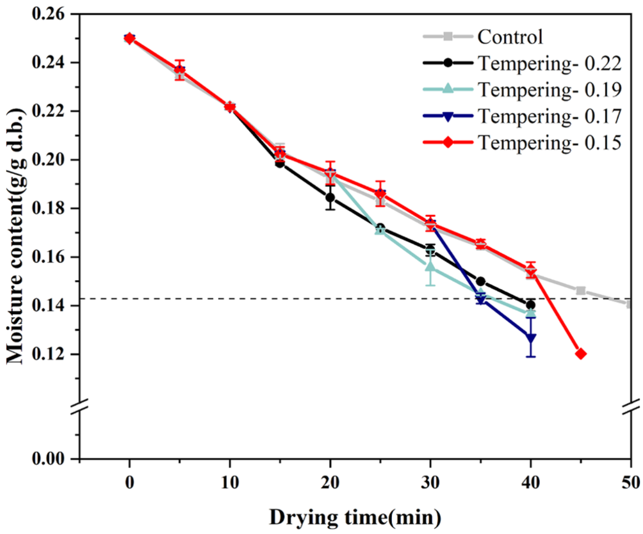

Figure 2. Drying curves of wheat with different initial moisture contents at the onset of tempering (IMCOT) during hot air drying.

noted that the drying time in the drying curve is only the time of the effective drying phase, with the tempering duration being excluded. This exclusion allowed for a direct comparison with the continuous drying curve. It was evident from Figure 2 that the drying curves for wheat samples that underwent tempering showed a marked divergence from the continuous drying curve (control). This distinction underscored the significant impact of the tempering on the overall drying process. The moisture content of wheat was observed to decrease gradually over time during the drying process. The effective drying time decreased as the IMCOT decreased. The shortest drying time required to reach the end point was 35 min at 0.17 g/g d.b., which was significantly lower than that of the control (48 min). In summary, our findings suggested that tempering played a pivotal role in substantially reducing the working time of the dryer, thereby contributing to electrical energy conservation. The reduction in drying time was attributed to the fact that tempering facilitated the movement of moisture from the kernel's interior to its exterior surface. This, in turn, led to a reduction of the moisture gradient and consequently brought about an accelerated drying rate.[29] Notably, similar findings were reported in a previous study[30] in their investigation of rice tempering.

The control is hot air drying of wheat without tempering. Tempering-0.22, 0.19, 0.17, and 0.15 are the hot air drying of wheat with IMCOT at 0.22, 0.19, 0.17, and 0.15 g/g d.b., respectively.

As depicted in Figure 3, tempering led to a shorter drying time for wheat compared to the control. Drying time decreased

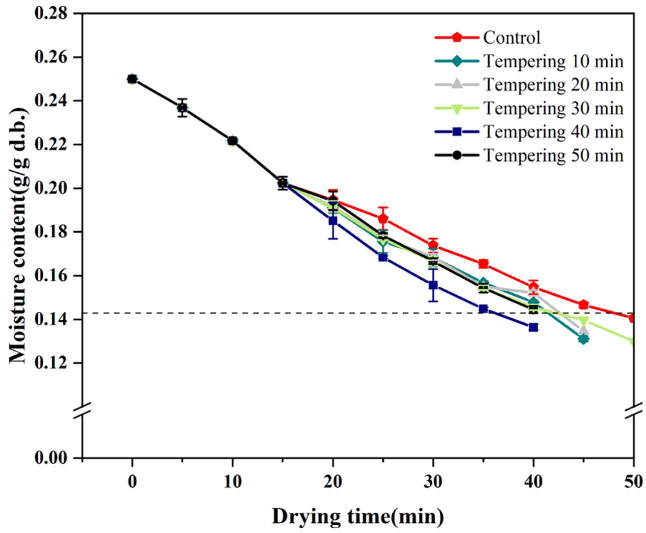

Figure 3. Drying curves of wheat with different tempering durations during hot air drying. The control is hot air drying without tempering. Tempering-10, 20, 30, 40, and 50 min are the hot air drying with a tempering duration of 10, 20, 30, 40, and 50 min, respectively.

as the tempering duration increased. The shortest drying time (35 min) was observed at a tempering duration of 40 min, whereas the control group required 47 min. The most pronounced change in moisture content of wheat was observed after 40 min tempering as compared to the control. This could be due to the optimal uniformity of moisture diffusion within the wheat kernel at 40 min tempering. Tempering during drying did have the potential to enhance the drying rate to a certain extent, however, its capacity to improve the drying rate was limited. Excessive tempering time might result in an increase in total drying time and therefore reduce the average drying rate.[12] In the current study, the effective drying time for wheat in the test group with a tempering duration of 50 min exceeded that in the group with a tempering duration of 40 min. Previous studies have shown that under conditions of 0.95 g/g d.b. (IMC) and 25 °C, high-temperature tempering treatment could reduce the drying time of lotus seeds by 31.25%.[16] Our results were consistent with these findings, indicating that tempering treatment had certain advantages in improving drying efficiency. However, variations in tempering conditions could lead to different outcomes in terms of the treatment's effectiveness.

3.2. Protein Content, Wet Gluten Content, and Flour Yield of Wheat. Differences in the composition of WF result in variations in its morphology and surface properties.[31] Protein content and wet gluten content are key indicators for assessing the quality characteristics of WF. Table 3 shows the protein content, wet gluten content, and flour yield of WF obtained through drying combined with tempering at different IMCOT and different tempering durations. The protein content of the tempering-0.22, tempering-0.17, tempering-10 min, tempering-30 min, and tempering-50 min tempered samples were significantly different from the non-tempered control. Compared with the control group, the protein content of wheat flour with IMCOT values of 0.22 and 0.17 g/g d.b. decreased significantly. However, the protein content increased

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Table 3. Protein Content, Wet Gluten Content, and Flour Yield of Wheat Flour at Different Initial Moisture Contents at the Onset of Tempering (IMCOT) and Different Tempering Durations[a]

samples	protein content (g/100 g)	wet gluten content (g/100 g)	flour yield (g/100 g)
control	12.56 ± 0.05[b]	25.51 ± 0.86[c]	66.12 ± 7.82[a]
tempering-0.22	11.47 ± 0.02[d]	28.46 ± 0.29[a]	63.39 ± 0.51[ab]
tempering-0.19 (tempering-40 min)	12.54 ± 0.05[b]	28.79 ± 0.51[a]	61.40 ± 0.46[ab]
tempering-0.17	12.38 ± 0.01[c]	25.84 ± 0.26[c]	56.77 ± 0.18[b]
tempering-0.15	12.61 ± 0.01[b]	25.96 ± 0.81[c]	60.52 ± 3.41[ab]
tempering-10 min	12.40 ± 0.15[c]	26.15 ± 0.64[c]	59.42 ± 0.61[ab]
tempering-20 min	12.54 ± 0.06[b]	26.50 ± 1.73[bc]	60.78 ± 0.60[ab]
tempering-30 min	12.33 ± 0.04[c]	27.95 ± 0.07[ab]	59.42 ± 1.07[ab]
tempering-50 min	12.98 ± 0.11[a]	25.06 ± 0.49[c]	58.26 ± 1.21[b]

[a]The control group was dried at 70 °C at a constant temperature without tempering. Tempering-0.22, 0.19, 0.17, and 0.15 are the IMCOT of 0.22, 0.19, 0.17, and 0.15 g/g, d.b., respectively. Tempering-10, 20, 30, 40, and 50 min correspond to the tempering duration of 10, 20, 30, 40, and 50 min, respectively. Different letters in the same column represent a significant difference ($P < 0.05$). The values presented in the table pertain to the wet mass.

Table 4. Color and Whiteness of Wheat Flour at Different Initial Moisture Contents at the Onset of Tempering (IMCOT) and Different Tempering Durations[a]

samples	L^*	a^*	b^*	Hunter whiteness
control	92.73 ± 0.15[d]	0.55 ± 0.03[a]	9.90 ± 0.09[a]	87.70 ± 0.03[d]
tempering-0.22	93.23 ± 0.10[c]	0.38 ± 0.02[cd]	8.15 ± 0.21[b]	89.40 ± 0.18[bc]
tempering-0.19 (tempering-40 min)	93.36 ± 0.13[bc]	0.30 ± 0.03[d]	8.26 ± 0.07[b]	89.39 ± 0.12[bc]
tempering-0.17	93.20 ± 0.06[c]	0.32 ± 0.06[d]	8.33 ± 0.15[b]	89.24 ± 0.13[c]
tempering-0.15	92.83 ± 0.16[d]	0.42 ± 0.06[bcd]	8.06 ± 0.37[b]	89.19 ± ± 0.19[c]
tempering-10 min	94.00 ± 0.44[a]	0.50 ± 0.02[ab]	8.08 ± 0.20[b]	89.91 ± 0.28[a]
tempering-20 min	93.64 ± 0.16[ab]	0.55 ± 0.10[a]	8.39 ± 0.31[b]	89.45 ± 0.31[bc]
tempering-30 min	93.64 ± 0.09[ab]	0.44 ± 0.04[abc]	8.35 ± 0.04[b]	89.49 ± 0.09[bc]
tempering-50 min	93.75 ± 0.23[a]	0.45 ± 0.11[abc]	8.08 ± 0.14[b]	89.76 ± 0.12[ab]

[a]The control group was dried at 70 °C at constant temperature without tempering. Tempering-0.22, 0.19, 0.17, and 0.15 are the IMCOT of 0.22, 0.19, 0.17, and 0.15 g/g, d.b., respectively. Tempering-10, 20, 30, 40, and 50 min correspond to the tempering duration of 10, 20, 30, 40, and 50 min, respectively. Different letters in the same column represent a significant difference ($P < 0.05$).

significantly when the tempering duration was 50 min. This was because the protein content of wheat flour was influenced by both moisture content and tempering duration.[32] The study by Bharathi et al.[33] confirmed that the protein content of the sample powders varied with different moisture levels, and there were differences in protein content for different tempering durations. The lowest protein content of 11.47/100 g was found in WF at an IMCOT of 0.22 g/g d.b. From the inner to the outer layers, the nutritional content of wheat kernels varies, and tempering-induced changes in the degree of milling result in different protein content in the flour.[34] The maximum protein content in the wheat flour was 12.98/100 g at a tempering duration of 50 min, which was significantly higher than that in the control. Similar results were reported by Tyl et al.,[20] who found that tempering could reduce bran contamination in flour with minimal loss of protein. This suggested that tempering could improve the purity of flour without exerting a significant effect on its protein content. Flours with different protein contents could be utilized to produce food products with varying elasticity and hardness requirements. For instance, a higher protein content is positively correlated with pasta hardness,[35] which can lead to poorly cooked noodles if the hardness is excessive.[36] Conversely, Australian Noodle Wheat, with a protein content of 12−13%, has been shown to be suitable for making biscuits.[37] Thus, changes in the protein content of wheat flour due to tempering can significantly affect the processing characteristics of food products. Therefore, appropriate processing techniques should be chosen based on the specific requirements of the intended use.

As the IMCOT decreased, the wet gluten content showed a tendency to increase and then decrease. The highest wet gluten content (28.79/100 g) was observed when IMCOT was 0.19 g/g d.b. Comparatively, the wet gluten content of WF was significantly lower ($P < 0.05$) in comparison to the control group when the IMCOT was 0.17 or 0.15 g/g d.b. A possible reason for this was that tempering was carried out at a later stage of the drying process, the accumulated heat caused by the previous drying period might have caused thermal damage to the wheat kernels, leading to the weakening of the wheat gluten.[38] This resulted in the formation of a limited amount of gluten. In contrast, IMCOT of 0.19 and 0.22 g/g d.b. had a shorter heat treatment time before tempering. The timely tempering allowed for the redistribution of kernel moisture, preventing the weakening of the gluten network due to excessive heat damage during drying. Compared to the control, the wet gluten content was significantly higher at tempering-40 min and tempering-30 min, which indicated that tempering duration affected wet gluten content.

Flour yield exhibited a pattern of initial decline followed by an increase with decreasing IMCOT. At an IMCOT of 0.22 g/g d.b., the flour yield had a maximum value of 63.39/100 g among the tested groups. Conversely, the lowest flour yield was observed in samples subjected to tempering at an IMCOT of 0.17 g/g d.b. The decrease in the flour observed in the tempering test group in comparison with that in the control group suggested that the tempering treatment had a negative

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impact on wheat flour production. This was likely due to the decrease in the IMCOT process, which prolonged the duration of dry heat treatment. The prolonged heat treatment induced severe surface hardening of the kernel.[39] During the water conditioning process prior to milling, the water was unable to penetrate the interior of the kernel. Instead, it became concentrated in the outer husk of the wheat kernel.[40,41] This resulted in an increase in the toughness of the wheat epidermis, which in turn caused it to adhere to the endosperm during the milling process. This ultimately resulted in a decrease in the yield of flour. As a result, more endosperm adhered to the bran and was removed during milling. Furthermore, the softened endosperm was more prone to adhering to the milling rollers, leading to a higher loss of milling yield.

3.3. Color and Whiteness of WF. The whiteness and color of the WF were measured, and the corresponding data are shown in Table 4. A significant increase ($P < 0.05$) was observed in the whiteness of WF obtained from different wheat drying processes compared to the control. A higher L^* value indicates a brighter appearance of the sample. Significant increases were also observed in the lightness values (L^*) of the flours at the IMCOT of 0.22, 0.19, and 0.17 g/g d.b. between the different IMCOT test groups. The lowest lightness of WF was noted at the IMCOT of 0.15 g/g d.b. The possible reason was that the application of tempering in the wheat drying interrupted the continuous drying process, which reduced the continuous heat accumulation on the wheat kernel epidermis. This change reduced the degree of browning of the epidermis, which in turn led to an increase in the brightness and whiteness of the flour.[42] On the other hand, the application of a tempering process resulted in a more uniform distribution of moisture within the wheat kernel. It might cause the flour particles obtained during the milling process to be more uniform in size. This uniformity enabled the flour to reflect light more evenly, which in turn improved the brightness of the flour.[43]

The highest whiteness value of the flour was 89.91 when tempered for 10 min. It was found that tempering contributed to the enhancement of the flour whiteness. The tempering treatment likely facilitated the movement of more water from the interior to the surface, alleviating capillary shrinkage of the epidermis caused by heat treatment. Moreover, the increased toughness of the epidermal layer after water absorption resulted in more intact bran removed during milling, reducing the bran particle content of the flour. As a result, the whiteness values of the tempered wheat flour were elevated.

3.4. Total Phenol Content and Ash Content of WF. Phenolic compounds in wheat kernel are predominantly found in the bound state, linked to cell wall material in the bran, and are particularly abundant in the aleurone layer.[1,44] Research has shown that the aleurone layer of wheat kernels contains a high concentration of phenols. Wheat flour with a high total phenol content usually has a stronger antioxidant capacity, which contributes to the quality and health benefits of the final product. However, as shown in Table 5, there was no significant trend ($P > 0.05$) in the total phenolic content of wheat flour between different IMCOT. A significant difference ($P < 0.05$) was observed in the total phenolic content between samples subjected to different tempering durations. As the tempering duration increased, the total phenol content of wheat flour initially increased and then decreased, while the ash content exhibited a pattern of initial decrease followed by an increase. The maximum total phenol content of WF was 0.885 mg GAE/g d.b. at the tempering duration of 20 min, which also corresponded to the lowest ash content. The polyphenol content was affected by a combination of temperature and exposure time.[45] Therefore, a tempering duration of 20 min was determined to be the optimal condition for extracting phenolic compounds. The degradation of some heat-sensitive phenolic compounds led to a decrease in free phenols as the tempering duration increased,[46] resulting in no significant difference between tempering-30 min and tempering-50 min when the tempering duration exceeded 20 min. The low ash content indicated a limited presence of bran in WF. This suggested that the wheat epidermis was softer, allowing the mill rollers to more effectively remove the intact bran.[47]

Table 5. Total Phenol Content and Ash Content of Wheat Flour at Different Initial Moisture Contents at the Onset of Tempering (IMCOT) and Different Tempering Durations[a]

samples	total phenol content (mg GAE/g d.b.)	ash content (g/100 g)
control	0.680 ± 0.446^{bc}	0.608 ± 0.003^{abc}
tempering-0.22	0.668 ± 0.014^{bc}	0.688 ± 0.002^{a}
tempering-0.19 (tempering-40 min)	0.583 ± 0.075^{bc}	0.582 ± 0.030^{bc}
tempering-0.17	0.730 ± 0.116^{b}	0.559 ± 0.001^{c}
tempering-0.15	0.630 ± 0.013^{bc}	0.642 ± 0.002^{abc}
tempering-10 min	0.549 ± 0.015^{c}	0.662 ± 0.021^{ab}
tempering-20 min	0.885 ± 0.083^{a}	0.566 ± 0.027^{bc}
tempering-30 min	0.730 ± 0.011^{b}	0.683 ± 0.128^{a}
tempering-50 min	0.724 ± 0.094^{b}	0.613 ± 0.015^{abc}

[a]The control group was dried at 70 °C at constant temperature without tempering. Tempering-0.22, 0.19, 0.17, and 0.15 are the IMCOT of 0.22, 0.19, 0.17, and 0.15 g/g, d.b., respectively. Tempering-10, 20, 30, 40, and 50 min correspond to the tempering duration of 10, 20, 30, 40, and 50 min, respectively. All values are expressed as mean ± standard deviations. Different letters in the same column represent a significant difference ($P < 0.05$).

The ash content is frequently employed as an important indicator for assessing the wheat flour quality. It reflects the degree of separation between the bran and endosperm. A lower ash content indicates a reduced presence of bran in the flour and higher processing accuracy.[48] The ash content of WF reached its lowest value of 0.559/100 g at an IMCOT of 0.17 g/g d.b. The reduction in ash content might be attributed to the alteration in wheat kernel structure induced by prolonged heat treatment before tempering, which resulted in the reduction of the paste layer in the flour after milling.[49] This finding aligned with the results of the wheat flour yield presented in Section 3.2. At a tempering duration of 30 min, the prolonged tempering duration led to the slow evaporation of water from the kernel surface, resulting in the formation of a relatively hard kernel skin. This caused a finer bran fraction in the flour, which in turn, led to a higher total ash content in the flour.

3.5. Pasting Properties of Flour Slurry. The pasting properties of wheat flour, which reflect viscosity changes during heating and subsequent cooling, are crucial in determining the sensory attributes that define the overall edible quality of the final product. As shown in Table 6, these properties were influenced by the hot air drying process combined with varying initial moisture content at the onset of tempering (IMCOT) and tempering durations. The BV values of the tempered samples varied significantly, consistent with

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Table 6. Pasting Properties of Wheat Flour at Different Initial Moisture Contents at the Onset of Tempering (IMCOT) and Different Tempering Durations[a]

samples	pasting temperature (°C)	PV (BU)	BV (BU)	SV (BU)
control	59.40 ± 0.84[a]	465.50 ± 19.09[e]	334.00 ± 1.41[f]	318.5 ± 0.70[e]
tempering-0.22	61.00 ± 1.41[a]	2070.00 ± 24.04[a]	975.00 ± 19.79[b]	795.00 ± 5.65[ab]
tempering-0.19 (tempering-40 min)	58.75 ± 1.76[a]	2039.50 ± 16.26[ab]	908.00 ± 2.82[c]	811.50 ± 2.12[a]
tempering-0.17	59.40 ± 1.69[a]	2010.00 ± 2.82[b]	1012.00 ± 8.48[a]	703.50 ± 7.77[c]
tempering-0.15	58.45 ± 0.07[a]	2008.00 ± 11.31[b]	997.00 ± 9.89[a]	699.50 ± 0.70[c]
tempering-10 min	59.5 ± 0.84[a]	1944.0 ± 18.38[c]	887.0 ± 4.24[cd]	787.5 ± 3.53[b]
tempering-20 min	59.60 ± 1.55[a]	1958.0 ± 24.74[c]	879.0 ± 5.65[d]	806.0 ± 1.41[a]
tempering-30 min	59.20 ± 1.13[a]	2008.0 ± 7.07[b]	894.50 ± 0.70[cd]	801.0 ± 7.07[ab]
tempering-50 min	59.90 ± 0.14[a]	1203.5 ± 13.43[d]	449.50 ± 13.43[e]	637.00 ± 16.97[d]

[a]The control group was dried at 70 °C at a constant temperature without tempering. Tempering-0.22, 0.19, 0.17, and 0.15 are the IMCOT of 0.22, 0.19, 0.17, and 0.15 g/g, d.b., respectively. Tempering-10, 20, 30, 40, and 50 min correspond to the tempering duration of 10, 20, 30, 40, and 50 min, respectively. PV: peak viscosity, BV: breakdown value, and SV: setback value. BU: Brabender Units.

the findings of Irondi et al.[50] The pasting temperature of WF exhibited a gradual decline as IMCOT decreased. The minimum pasting temperature of 58.45 °C was observed when the IMCOT was 0.15 g/g d.b. The peak viscosity of tempered wheat flour decreased as the IMCOT decreased. The maximum peak viscosity of 2070.00 BU was observed in the WF at an IMCOT of 0.22 g/g d.b., indicating that the starch granules in this flour were extensively swollen and exhibited strong swelling and water absorption capabilities. However, a longer duration of drying under low IMCOT conditions before tempering treatment led to greater heat accumulation in the kernels and severe thermal deterioration of both branched and straight-chain starches during hot air drying, resulting in lower peak viscosity. The reduction in peak viscosity may be the result of thermal deterioration of amylopectin and amylose during drying with heated air.[51] Similar to the results of Anderson and Guraya,[52] rice amylopectin and amylose thermally degraded with increasing heating time, leading to a decrease in peak viscosity. When the IMCOT was 0.19 g/g d.b., the WF slurry exhibited the smallest BV value and the highest SV value among the tempered samples. This indicated that the WF slurry was the most stable and most difficult to age under these conditions. Conversely, the WF slurry with an IMCOT of 0.17 g/g d.b. exhibited the highest instability and susceptibility to aging. This phenomenon might be attributed to the dominance of the drying process over the tempering process. The heat involved in drying had a detrimental effect on the physicochemical properties of the WF, particularly due to the disruption of the starch structure, resulting in poor pasting properties of the WF.

As the tempering duration increased, the PV, BV, and SV values of the flour slurry exhibited a tendency to increase and then decrease. The PV value of the flour slurry was the highest at 40 min, which was 2039.50 BU. The extension of the tempering duration was favorable to starch pasting. Changes in BV and SV values indicated that the increase in tempering duration was beneficial to the stability and retrogradation resistance of wheat flour slurry.[53] The lower SV observed after tempering of SAEW might be attributed to the weaker interaction between the straight-chain starch and other starch molecules during the cooling process. This weaker interaction is somewhat favorable for improving retrogradation resistance.[54] However, an excessively long tempering duration (50 min) led to the formation of higher molecular weight proteins, which restricted the expansion of starch granules.[55] This led to a reduction in PV, making the slurry unstable and more susceptible to aging, ultimately affecting product quality.[56]

It has been established that the swelling capacity and extent of swelling of starch granules largely determine the viscosity of starch paste. Highly swollen starch granules occupy a larger volume and are closely packed. During the pasting process, these granules press against each other, generating high internal friction, which leads to an increased PV value of the flour.[57] Appropriate tempering time (10−40 min) could enhance swelling and water absorption of starch granules, resulting in increased viscosity of starch. However, an excessively long tempering time (50 min) caused excessive swelling and dissolution of starch as well as disruption of molecular ordering during the heating of wheat flour. This resulted in reduced PV of the flour and easy pasting. Therefore, tempering at an optimal duration was beneficial for improving the quality of the flour.

4. CONCLUSIONS

Moderate IMCOT (0.19 g/g d.b.) and extended tempering durations enhanced the quality and nutritional value of WF flours. The results indicated that tempering reduced the drying time of the wheat. The shortest drying time was achieved when the IMCOT was 0.17 g/g d.b. and the tempering duration was 40 min. In addition, the pasting temperature and PV of WF showed a gradual decrease as the IMCOT was reduced. The IMCOT had a significant effect ($P < 0.05$) on the protein and wet gluten content of WF. Under conditions of IMCOT levels at 0.17 and 0.15 g/g d.b., or with excessive tempering durations, there was a detrimental effect on the color and pasting properties of wheat flour. Specifically, at an IMCOT of 0.19 g/g d.b., the BV of WF was minimized, and the SV was maximized. Tempering duration significantly affected ($P < 0.05$) the protein, wet gluten, and total phenol content of WF. The tempered flour exhibited greater whiteness compared to the control. Considering the drying characteristics, nutrient content, and flour slurry characteristics, the optimal tempering conditions were IMCOT of 0.19 g/g d.b. and a tempering duration of 40 min.

■ ASSOCIATED CONTENT

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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AUTHOR INFORMATION

Corresponding Authors

Linlin Li − *College of Food and Bioengineering, Henan University of Science and Technology, 471000 Luoyang, Henan, China; Henan Province Engineering Research Center of Agricultural Products Processing Equipment, 471000 Luoyang, Henan, China; Henan Province Engineering Technology Research Center of Agricultural Product Drying Equipment, 471000 Luoyang, Henan, China;* Email: linlinli2020@126.com

Guangyue Ren − *College of Food and Bioengineering, Henan University of Science and Technology, 471000 Luoyang, Henan, China; Henan Province Engineering Research Center of Agricultural Products Processing Equipment, 471000 Luoyang, Henan, China; Henan Province Engineering Technology Research Center of Agricultural Product Drying Equipment, 471000 Luoyang, Henan, China;* orcid.org/0000-0002-5504-3599; Email: guangyueyao@163.com

Authors

Peijie Zhang − *College of Food and Bioengineering, Henan University of Science and Technology, 471000 Luoyang, Henan, China;* orcid.org/0009-0007-9152-0317

Wenchao Liu − *College of Food and Bioengineering, Henan University of Science and Technology, 471000 Luoyang, Henan, China; Henan Province Engineering Research Center of Agricultural Products Processing Equipment, 471000 Luoyang, Henan, China; Henan Province Engineering Technology Research Center of Agricultural Product Drying Equipment, 471000 Luoyang, Henan, China*

Weiwei Cao − *College of Food and Bioengineering, Henan University of Science and Technology, 471000 Luoyang, Henan, China; Henan Province Engineering Research Center of Agricultural Products Processing Equipment, 471000 Luoyang, Henan, China; Henan Province Engineering Technology Research Center of Agricultural Product Drying Equipment, 471000 Luoyang, Henan, China;* orcid.org/0000-0001-8383-9933

Junliang Chen − *College of Food and Bioengineering, Henan University of Science and Technology, 471000 Luoyang, Henan, China; Henan Province Engineering Research Center of Agricultural Products Processing Equipment, 471000 Luoyang, Henan, China; Henan Province Engineering Technology Research Center of Agricultural Product Drying Equipment, 471000 Luoyang, Henan, China*

Tongxiang Yang − *College of Food and Bioengineering, Henan University of Science and Technology, 471000 Luoyang, Henan, China; Henan Province Engineering Research Center of Agricultural Products Processing Equipment, 471000 Luoyang, Henan, China; Henan Province Engineering Technology Research Center of Agricultural Product Drying Equipment, 471000 Luoyang, Henan, China*

Xu Duan − *College of Food and Bioengineering, Henan University of Science and Technology, 471000 Luoyang, Henan, China; Henan Province Engineering Research Center of Agricultural Products Processing Equipment, 471000 Luoyang, Henan, China; Henan Province Engineering Technology Research Center of Agricultural Product Drying Equipment, 471000 Luoyang, Henan, China*

Huiping Fan − *College of Food Science and Technology, Henan Agricultural University, 450002 Zhengzhou, Henan, China*

Debang Zhang − *Zhengzhou Wangu Machinery Co., Ltd., 450000 Zhengzhou, Henan, China*

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.4c10657

Author Contributions

P.Z.: Methodology; investigation; formal analysis; visualization; data curation; writing—original draft; and writing—review and editing. L.L.: Conceptualization; methodology; investigation; formal analysis; visualization; data curation; supervision; writing—original draft; writing—review and editing; and funding acquisition. W.L.: Methodology; formal analysis; supervision; and funding acquisition. W.C.: Methodology; supervision; and funding acquisition. J.C.: Methodology and funding acquisition. T.Y.: Methodology and funding acquisition. X.D.: Supervision and funding acquisition. H.F.: Methodology and supervision. D.Z.: Methodology and supervision. G.R.: Conceptualization; supervision; resources; writing—review and editing; and funding acquisition.

Notes

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