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Enhanced and Integrated Crop Management Improved Hard Red Winter Wheat Grain Yield and End-Use Characteristics

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ABSTRACT

Background and Objectives: Crop management, variety selection, and environment can affect wheat milling and baking quality attributes. To optimize hard red winter wheat (HRWW) production, selecting appropriate varieties and implementing effective agronomic management strategies are essential. In this study, two wheat varieties (WB4458 and WB-Grainfield) were evaluated under five management strategies (i.e., a "farmer practice" plus four treatments with consecutively increasing management intensity) across six site-years, including three locations (Hutchinson, Belleville, and Leoti, Kansas, USA) over two growing seasons (2018 and 2019 harvest years). Our objective was to investigate whether management intensification could simultaneously improve yield and milling and baking attributes of HRWW.

Findings: Yield was impacted by the interaction among year (Y), location (L), management (M), and genotype (G). The $Y \times L \times G \times M$ interaction impacted grain kernel quality. The $Y \times G \times M$ interaction impacted dough mixing properties, and the $L \times G \times M$ was significant for flour pasting parameters. Certain crop management strategies, particularly those with enhanced fertility, significantly improved end-use quality traits (e.g., bread specific volume) as compared to conventional farmer's practice. Additionally, management practices with fungicide applications increased wet gluten content and flour water absorption.

Conclusion: Our results demonstrated that end-use quality traits including kernel and flour properties, and bread-making quality are strongly influenced by genotype, field management, environment, and interactions. Implementing genotype-specific, enhanced crop management strategies can improve both HRWW's grain yield and selected end-use characteristics.

Significance and Novelty: Our findings suggest that wheat end-use quality can be greatly improved by optimizing management strategies for specific, well-characterized production environments. The research provides breeders and food scientists with valuable insights into future studies aimed at optimizing HRWW to achieve high quality in both yield and end-use.

Yijie Gui and Gengjun Chen contributed equally to this paper.

1 | Introduction

Wheat (*Triticum aestivum* L.) is a globally consumed staple food, providing essential nutrients such as proteins, carbohydrates, dietary fibers, minerals, and bioactive phytochemicals. The Southern Great Plains (SGP) of the United States is the primary region for cultivating hard red winter wheat (HRWW), accounting for over 90% of the total HRWW production in the country. Kansas is the largest HRWW producing state in the United States, with an annual cultivation area ranging from 3.2 to 4.8 million hectares (Lollato et al. 2017). HRWW is primarily used to produce all-purpose flours for bread-making and other food products. The selection of an appropriate genotype is crucial for optimizing crop profitability (Lollato et al. 2020), yield (Munaro et al. 2020), and quality (Lollato et al. 2021); and proper crop management practices, such as crop fertilization (Lollato, Figueiredo, et al. 2019), foliar protection (Cruppe et al. 2021), and seeding rates (Lollato, Ruiz Diaz, et al. 2019), are necessary to maximize yield while aligning with environmental conditions.

End-use characteristics for HRWW may refer to kernel quality traits (e.g., test weight, hardness, and diameter), flour characteristics (e.g., protein content, water absorption, and dough mixing properties), and bread-making quality (e.g., bread volume, and texture). These characteristics are influenced by multiple factors (Rozbicki et al. 2015). For instance, nitrogen is an essential nutrient for wheat growth and yield; and nitrogen availability also determines wheat protein concentration; thus, an appropriate level of N fertilization is required for the enhancement of end-use quality (Cruppe et al. 2017; Giordano et al. 2023). Beyond fertilization, field management strategies such as integration of several in-season and location-specific decisions have been related to the end-use characteristics (Al-Zubade et al. 2021). Kong et al. (2013) indicated that grain test weight was mostly affected by the environment, whereas Brennan et al. (2012) observed that flour pasting properties were mainly associated with genotype rather than environment factors. Rozbicki et al. (2015) found that both genotype and genotype by environment interactions considerably influenced end-use quality properties, for example, wet gluten. Raj et al. (2023) suggested that foliar-protection-based practices improved milling attributes, while fertilizer-based practices improved baking attributes of wheat flour. However, it is still unclear which factors are more important for the quality traits (Rozbicki et al. 2015). Additionally, some studies have recognized that wheat genotype, environment, and their interactions considerably affect HRWW productivity such as the grain yield (Lollato, Ruiz Diaz, et al. 2019; Jaenisch et al. 2019). For example, Jaenisch et al. (2019) reported that foliar fungicides could significantly improve wheat grain yield in disease-conducive environments. However, some of the studies were conducted under standard management conditions, with few efforts on investigating the enhancement of intensifying management on flour and/or bread-related end-use quality.

In this study, we evaluated a range of agronomic managements, reflecting a stepwise increase in input intensity from a baseline control representing typical farmer practice. These stepwise increases included first an increase in fertility level, then two levels of improved foliar protection, and finally the addition of micronutrients. Within this set of designs, we investigated the effect of genotype (G), management (M), location (L), year (Y), and their interactions on grain yield and quality characteristics of selected HRWW cultivars, including a set of traits for the kernel, flour, and bread quality. Our findings provide valuable contribution to the understanding of how various factors and their interactions can impact the end-use quality of HRWW. By examining the combined impact of genotypes and management strategies, this study highlights opportunities for breeders and growers to simultaneously enhance yield and end-use quality. Furthermore, it provides a direction for future research into optimizing HRWW for desired end-use characteristics.

2 | Materials and Methods

2.1 | Wheat Cultivation Experiments

The field experiment was partially described in our previous study (Jaenisch et al. 2022). The soil conditions are summarized in Supporting Information S1:Table S1. Winter wheat was grown across six site-years, representing combinations of three locations (Belleville, Hutchinson, and Leoti) and two seasons (2017–2018 and 2018–2019), capturing the environmental variability typical of central and western Kansas. The field study was carried out in a split-plot design in a complete factorial structure with management level assigned to whole plots (arranged as randomized complete block design), and varieties assigned to sub-plots (completely randomized within whole plot). The different levels of agronomic management intensity included a farmer practice (FP), enhanced fertility (EF), economical intensification (EI), increased foliar protection (IFP), and water-limited yield potential (YW). These practices reflect a stepwise increase in input intensity, from a baseline reflecting the level of technology adoption of an average producer in the region (Supporting Information S1: Table S2). Two HRWW cultivars (WB4458 and WB-Grainfield) were selected due to their good standability in the main wheat-producing regions, widely adapted in central and western Kansas. Weather data, including available water for the entire season (AW, precipitation plus available water at sowing) and photothermal quotient for the critical period (PQ) for yield determination, were measured following our previous report (Jaenisch et al. 2022), which provides more details about agronomic management and experimental conditions.

2.2 | Wheat Grain Yield and End-Use Quality Traits

Grain yield (YD) was measured using a combination of harvesting equipment from a harvested plot area of 1.5×9.0 m (Jaenisch et al. 2022). End-use quality traits, including wheat kernel, flour, and bread characteristics, were utilized to assess the effects of genotype, environment, and management practices. Grain kernel quality was analyzed via a Single Kernel Characteristic System (SKCS 4100, Perten Instruments Huddinge, Sweden), and kernel hardness index (HI), kernel diameter (KD), and kernel weight (KW) were recorded. TW was conducted according to AACC Method 55-10.01 (AACC 2000). Wheat grains were cleaned and tempered to a constant moisture content (15%)

according to the AACC Approved Method 26-10.02 (AACC 2000). The samples were milled with a Quadrumat Senior laboratory mill (Brabender, Duisbury, Germany). The refined flour samples were stored at 4°C until analysis.

Flour protein content (PC) was determined using Perten 7250 diode-array NIR (Perten Instruments, Hagersten, Sweden). Wet gluten content (WG) was determined using a Glutomatic 2200 (AACC Method 38-12, 2000). Dough rheology traits (e.g., water absorption [WA], development time [DT], and dough stability [DS]) were analyzed via a DoughLAB instrument (Perten Instruments, Hagersten, Sweden). Pasting characteristics (e.g., peak viscosity [PV], breakdown viscosity [BD], final viscosity [FV], and setback viscosity [SB]) of the flour were characterized using a Rapid Visco Analyzer (RVA4500, Perten Instruments, Hagersten, Sweden). Flour falling number (FN) was determined using a Falling Number Test Apparatus, type 1700 (Perten Instruments, Hagersten, Sweden) according to AACC Method 56-81B (AACC 2000). All the chemical reagents were of analytical grade and purchased from ThermoFisher Scientific (Fairlawn, NJ, USA).

Bread-baking was performed following AACC Approved Method 10-10.03, which is a straight dough method (Kong et al. 2013). The formula consisted of flour (100 g), shortening (3 g), salt (1.5 g), sucrose (6 g), active dry yeast (2 g), and water (optimized from mixograph). Dough fermentation and proofing were conducted at 30 ± 1°C and 95% relative humidity. Each dough was baked at 205°C for 24 min in a reel oven (National Manufacturing Co, Lincoln, NE, USA). Loaf volume was measured using a rapeseed displacement method recorded as the specific volume (SV). C-Cell image analysis system (CCFRA Technology Ltd., UK) combined with C-Cell software 2.0 was utilized to quantify characteristics and features of crumb cells (number of cells [NC] and cell volume [CV]). The crumb hardness (CH) was assessed on a TA-XTPlus Texture Analyzer (Stable Micro System, Godalming, Surrey, UK) according to the previous method (Chen et al. 2018).

2.3 | Statistical Analysis

SAS statistical software University Edition (SAS Institute, Cary, NC, USA) was used for the analysis of variance (ANOVA) via PROC GLIMMIX, where the effects of year (Y), location (L), genotype (G), management (M), and their interactions were treated as fixed effects. Replicate (rep), rep (Y), rep (L), M*rep (Y), and M*rep (L) were considered random effects. Tukey test was applied for post hoc mean comparisons. Pearson's correlations were performed between the parameters of the end-use traits.

3 | Results and Discussion

3.1 | Weather Conditions During Field Experiments and Their Impact on Measured Variables

The 2017–2018 growing season featured an extremely dry winter and early spring. Belleville and Hutchinson received only 60% and 55% of their average annual rainfall, respectively, and Leoti received only 41% (Jaenisch et al. 2022). The drought, together with the cool temperatures, delayed the growth of the wheat crop until late April, leading to decreased spring tillering and grain yield. Consequently, grain yield ranged from 5.3 to 5.9 Mg ha^{-1} in Belleville and from 3.4 to 4.5 Mg ha^{-1} in Hutchinson (conventional till, central Kansas), while it ranged from 4.7 to 5.6 Mg ha^{-1} in Leoti (no-till, western Kansas) (Jaenisch et al. 2022). In contrast, the 2018–2019 growing season was marked by very different weather conditions, receiving about 150% of normal precipitation. As a result, the difference between the cropping season and the average precipitation caused a remarkable increase in grain yield in 2019 as well as in yield response to management, with yields ranging from 2.8 to 5.1 Mg ha^{-1} in Belleville, from 3.3 to 6.7 Mg ha^{-1} in Hutchinson, and from 7.6 to 9.5 Mg ha^{-1} on Leoti.

3.2 | Agronomic and Genotypic Effects on Grain Yield and Grain Quality

Across all sources of variation, mean yield for the different management intensities was 4.6, 5.3, 6.1, 5.8, and 6.2 Mg ha^{-1} for FP, EF, EI, IFP, and YW, respectively (Table 1), indicating that all the tested management strategies improved the wheat grain yield effectively compared to the baseline FP, however, with null yield gain resulting from management intensifications beyond EI. There was a significant interaction of year × location × management for wheat grain yield (Supporting Information S1: Table S3). This three-way interaction resulted from some site-years showing no response to management (e.g., Belleville 2018 treatments) while other site-years showed as much as 82%–102% yield gain from the FP (e.g., Belleville 2019 treatments, Hutchinson 2019 treatments, Supporting Information S1: Table S4). There was also a significant two-way interaction of genotype × year on grain yield (Supporting Information S1: Table S5), suggesting the wheat grain yield of Grainfield 2018 (5.9 Mg ha^{-1}) performed better than WB4458, with yields ranging from 5.1 Mg ha^{-1} (2018) to 5.6 Mg ha^{-1} (2019). The mean value of WB4458 (5.1 Mg ha^{-1}) was the smallest in a dry environment (2018).

The wide range in weather and yielding conditions also contributed to varied quality traits. A significant fourth-order interaction among year × location × genotype × management was observed for key kernel qualities such as kernel diameter and kernel weight (Supporting Information S1: Table S3 and Figure S1). Details of the significance of differences are presented in Supporting Information S1: Table S6 and S7. The largest average kernel diameter was found in 2019 for the genotype WB4458 under IFP treatment in Hutchinson (2.96 mm)—a treatment that received two fungicide applications in a fairly moist (e.g., disease prone) season. In contrast, the smallest kernel diameter was 2.23 mm observed in the drier 2018 season for the genotype WB-Grainfield with YW (i.e., the most input-intensive treatment) in Hutchinson. A similar trend was found in terms of the effect on kernel weight (Supporting Information S1: Figure S1), where the largest weight was 38.2 g for 2019 WB4458 under IFP treatment in Hutchinson, and the smallest weight was 22.4 g in 2018 for WB-Grainfield with YW treatment in Hutchinson. Wheat kernels from 2019 Hutchinson had higher average diameter and weight than the other samples. The interaction (Y × L × G × M) had significant effects on the hardness index and TW (Supporting Information S1:

TABLE 1 | Effects of management strategies consisted of a farmer practice (FP), enhanced fertility (EF), economical intensification (EI), increased foliar protection (IFP), and water-limited yield potential (YW), on end-use qualities.

	YD	HI	KD	KW	TW	PC	WG	WA	DS	PV	FV	FN	SV
Management													
FP	4.6a	57.88c	2.61a	30.31a	66.23b	10.07c	27.35b	58.45c	10.51ab	2920.8a	3446.8a	553.9b	5.34b
EF	5.3b	64.22b	2.53c	28.34c	65.62d	11.29a	30.70a	60.60b	9.96b	2861.1b	3409.5ab	591.1a	5.78a
EI	6.1c	63.48b	2.59b	29.49b	66.46a	11.06b	30.28a	60.62b	9.10b	2837.3b	3366.1b	576.8ab	5.52ab
IFP	5.8c	65.77a	2.55c	28.80bc	66.12b	11.32a	30.89a	60.85a	10.49ab	2881.2ab	3415.5a	568.9ab	5.63ab
YW	6.2c	64.31b	2.53c	28.35c	65.91c	11.26a	31.12a	60.46b	11.51a	2862.6b	3407.9ab	585.7a	5.58ab
Genotype													
WB4458	5.5a	61.28a	2.63a	30.36a	66.46a	11.06a	30.70a	60.36a	10.99a	2885.7a	3410.7a	585.6a	5.80a
WB-Grainfield	5.7b	64.98b	2.49b	27.76b	65.67b	10.94b	29.44b	60.04b	9.65b	2859.6b	3407.6a	564.9b	5.34b

Abbreviations: DS, dough stability; FN, falling number; FV, final viscosity; HI, hardness index; KD, kernel diameter; KW, kernel weight; PC: flour protein content; PV, peak viscosity; SV, specific volume; TW, test weight; WA, water absorption; WG: wet gluten content; YD, wheat grain yield.
[a–d]Values with different letters in the same column are significantly different ($p < 0.05$).

Table S3). In Belleville, the trend was clear as the wheat in 2018 had higher average TW than corresponding samples in 2019 (Supporting Information S1: Figure S2).

The management strategies consisting of different treatment intensities influenced the kernel quality of HRWW. As shown in Table 1, all the enhanced treatments, that is, EF, EI, IFP, and YW, significantly increased the HI compared to FP (average value of 57.88). Furthermore, management intensities receiving foliar fungicide applications (i.e., EI, IFP, and YW) led to a significant decrease in kernel diameter and kernel weight. In agreement with a previous finding (Liu et al. 2021), high nitrogen markedly decreased the kernel weight. The inhibitory effect of high nitrogen may be caused by the reduction in the filling rate of inferior grain. Treatments EI significantly increased the TW of HRWW varieties. Rozbicki et al. (2015) also observed that high-input crop management, such as increased foliar fertilizer up to a dose of 40 kg ha^{-1}, can greatly change the wheat quality (e.g., TW). In addition, the Y × L × G × M was significant for HRWW grain qualities in our study, and factors such as the starting N fertilizer in the soil or fungicide application could also contribute to wheat quality. Previous studies have indicated that genotype strongly influenced spring wheat grain quality such as hardness (Yong et al. 2004; Studnicki et al. 2016), as seen in our results for kernel quality traits (Supporting Information S1: Table S3). However, another study on wheat cultivars found that the genotype may have less influence on grain quality under certain conditions, implying that breeders' effort should be tailored to the target environment for optimal results (Kaya and Akcura 2016).

3.3 | Agronomic and Genotype Effects on Flour Characteristics

The flour protein quality of HRWW was greatly affected by the interaction (Y × L × G × M), such as protein content (9.0%–13.3%), and WG (22.6%–37.4%), as shown in Supporting Information S1: Table S3 and Figure S3. The statistical significance of these differences is further detailed in Supporting Information S1: Tables S8 and S9. The highest protein content was observed in Hutchinson during 2018 for the WB4458 genotype under YW treatment (13.3%), while the lowest value also occurred in Hutchinson but during 2019 for the genotype WB-Grainfield under YW treatment (9.0%). Significant two-way interactions (Supporting Information S1: Table S3) were also found for protein contents. For example, the mean protein content (across treatments and genotypes) ranged from 10.0% in WB-Grainfield under FP to 11.4% in WB4458 under YW, with overall greater values in 2019 (11.6%) as compared to 2018 (10.3%) within a dry environment, respectively. The Y × L × G × M interaction showed similar effects on the WG, with the highest average value of 37.4% recorded for the 2018 WB-Grainfield under YW treatment in Hutchinson. All the enhanced treatments (EF, EI, IFP, and YW) significantly increased the protein and WGs, in comparison with the corresponding samples under FP treatment (Table 1).

These results suggest that the application of fungicide and/or fertilizer positively affected the end-use protein quality, as also reported by Ottman et al. (2000) who found that the wet gluten content was significantly increased with increasing nitrogen fertilizer. However, in another study on spring and winter wheat cultivars in China, Kong et al. (2013) indicated that the environmental factors, such as sufficient solar radiation, played a key role in accumulating the protein when fertilization is not a limiting factor. Given that protein quality is known as a genotype-dependent trait, a previous study emphasized the importance of selecting suitable genotypes to enhance protein quality for various end-uses (Gil et al. 2011). Indeed, recent research suggests that the proportion of variability in baking attributes explained by genotype factor is fairly high when compared to other agronomic and rheological traits where environment and management play larger roles (Raj et al. 2023). These varying results may be attributed to differences in regional environments and wheat cultivars.

Results showed that the flour mixing traits, such as water absorption, dough development time, and dough stability, were significantly influenced by the year × genotype × management (Y × G × M) interaction (Figure 1). The least-square mean values of water absorption ranged from 57.3% (2018 WB-Grainfield under FP) to 61.9% (2019 WB4458 under EF). The FP samples without fungicide or added fertilizer had the lowest average

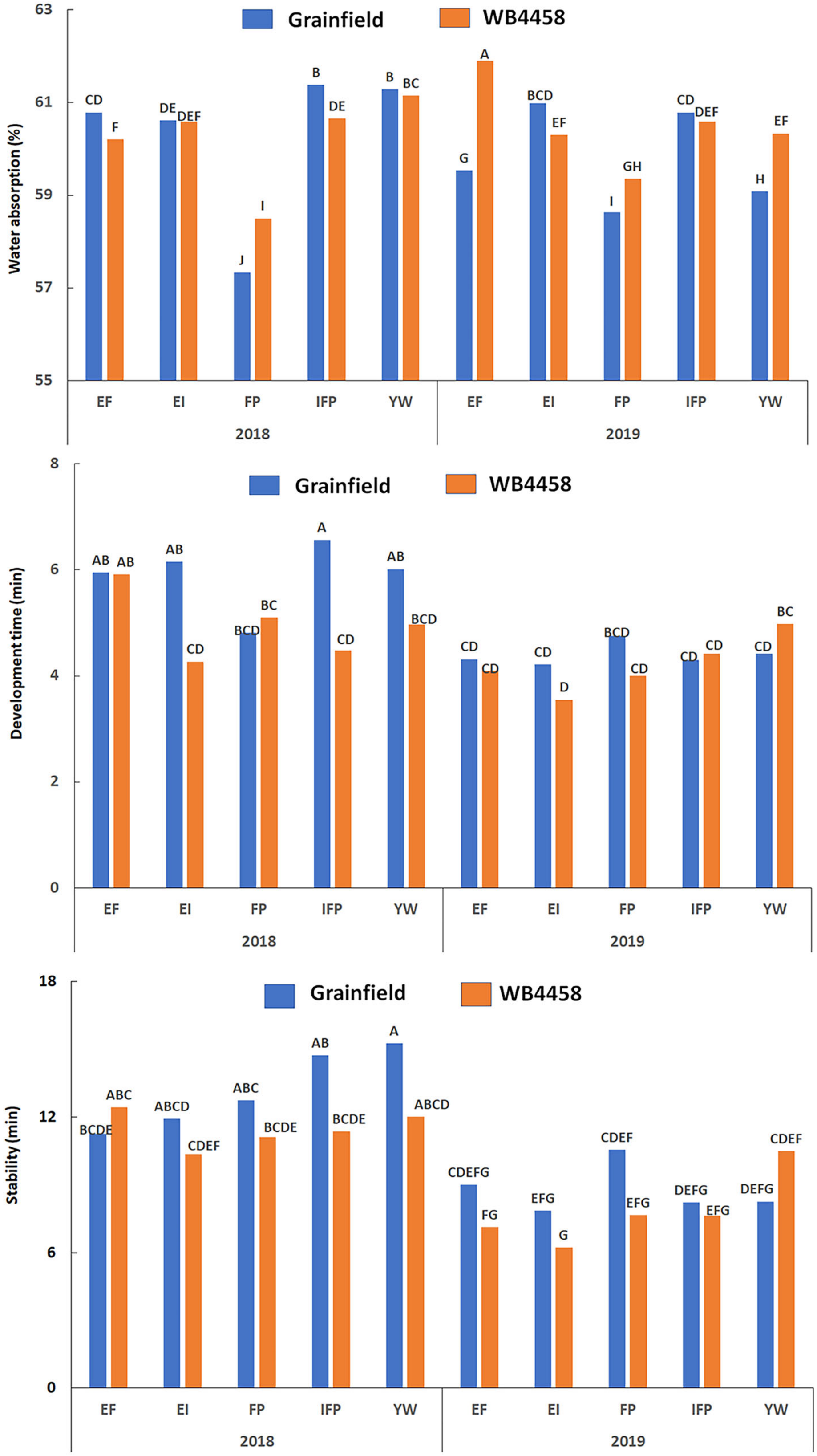

FIGURE 1 | Year × genotype × management interaction on dough mixing quality for water absorption (WA, %), development time (DT, min), and dough stability (DS, min). $^{A–J}$Bars with different letters differ significantly ($p < 0.05$). Note: Farmer practice (FP), enhanced fertility (EF), economical intensification (EI), increased foliar protection (IFP), and water-limited yield potential (YW). [Color figure can be viewed at wileyonlinelibrary.com]

water absorption values in both 2018 and 2019, as summarized in Table 1. Since optimal water absorption of over 60% is generally recommended for hard winter wheat flour, our results suggest the management practices, such as IFP and YW, effectively promote protein accumulation, which can significantly increase the water absorption in wheat flour.

As shown in Figure 1, the average value of dough development time in 2018 was higher than in 2019, and a similar trend was found for the dough stability value. This variation could be due to the lower precipitation in 2018, which reduced the risk of fungal diseases and improved the dough quality to some extent (Bastos et al. 2020). The traits associated with flour mixing, particularly dough stability, were highly variable across different environmental conditions. Other factors including wheat genotype also significantly influenced the DoughLAB parameters (Supporting Information S1: Table S3). A similar result was found in a study by Dencic et al. (2011) showing that high cultivar variability in water absorption and high genotype and management variability in dough development time were observed for the dough mixing attributes (Rozbicki et al. 2015). Thus, wheat flour characteristics can be improved due to the increase in the protein content, caused by enhanced management intensity.

The location × management × genotype (L × M × G) interaction had significant effect on flour pasting parameters, as shown in Supporting Information S1: Figure S4. The peak (2669–3080 cP) and breakdown viscosity values (659–1103 cP) were widely affected by this interaction (Supporting Information S1: Table S3). The pasting quality (the peak and breakdown viscosity) of flour from Hutchinson generally exhibited lower value than the samples from other locations. For example, the samples under EI treatments grown in Belleville (2969 cP) and Leoti (2921 cP) exhibited significantly greater ($p < 0.05$) peak viscosity compared to Hutchinson (2693 cP), which may be explained by the different soil types or weather conditions experienced in the three locations. The 2018 samples generally had higher average falling number values than the corresponding 2019 samples. For example, in Leoti, the average falling number under IFP treatment was 719 s in 2018, compared to 516 s in 2019. Falling numbers are affected by precipitation patterns. A previous study indicated that climatic conditions could contribute to unexpectedly low falling number, particularly during rainy or extremely humid conditions (Janic et al. 2024). In our study, the lower falling number in 2019 may be a consequence of higher in-season precipitation in 2019 that led to the increased potential for sprouting. According to Table 2, the available water amount (AW) during the growing season was significantly correlated with the falling number values ($p < 0.05$). Still, we note that the levels in this study are still well above the threshold below which millers have concerns with falling numbers. In a previous study, the varying environment was considered as a crucial factor for the differences in falling number among spring-sown wheat cultivars (Yong, et al. 2004) which is consistent with our findings.

3.4 | Agronomic and Genotype Effects on Bread Quality

The bread quality, in particular specific volume, was significantly influenced by the interaction between year and genotype (Y–G), while other interactions were not significant (Table S3). Based on the ANOVA results, the highest average value of specific volume was 5.9 $cm^3\,g^{-1}$ found in 2018 WB-Grainfield samples, while 2018 WB4458 samples (5.1 $cm^3\,g^{-1}$) had significantly lower specific volume than the other samples (Figure 2). The interaction of year, location, and genotype (Y × L × G) significantly affected crumb cell volume, which ranged from 4.8 (2018 WB4458 sample in Hutchinson) to 5.6 (2019 WB-Grainfield sample in Belleville). The Y × L interaction was significant for bread texture, such as crumb hardness, which ranged from 263 g (2019 Belleville) to 360 g (2018 Hutchinson). Moreover, a significant management effect was observed for specific volume (Supporting Information S1: Table S3). The enhanced management practices promoted wheat loaf volume, especially with the improved application of nitrogen fertilizer, which exhibited significantly higher specific volume (5.8 $cm^3\,g^{-1}$) than the conventional FP (5.3 $cm^3\,g^{-1}$), as illustrated in Table 1. This finding differed from a previous report that nitrogen fertilizer application had less impact on bread quality (e.g., loaf volume) compared to cultivar and location selection from spring wheat irrigated trials (Souza et al. 2004), but agrees with recent findings for HRWW in Kansas (Raj et al. 2023). Rozbicki et al. (2015) also indicated that managing fertilizer application to target specific end-use quality traits, such as bread volume, can be challenging. Nevertheless, the Y × L interaction was considered critical for crumb hardness (Munaro et al. 2020), which agreed with our result.

3.5 | Correlations Among the Analyzed End-Use Traits

Pearson's correlation coefficients were calculated to evaluate the relationships between various end-use traits (Table 2). When it comes to the weather data, it is interesting to find that the photothermal quotient (PQ) during the critical period significantly correlated with some key parameters of end-use traits such as dough stability and bread specific volume ($p < 0.05$). There was also a significant correlation ($p < 0.05$) between available water for entire season (AW) and falling number (FN). Additionally, wheat grain yield (YD) significantly correlated with many important grain quality traits (i.e., HI and TW) ($p < 0.01$). The negative correlation between yield and protein concentration was expected, and likely helps to explain the negative correlation between yield and dough strength and stability. The kernel diameter of the wheat showed a positive correlation with both the kernel weight ($r = 0.98$) and test weight ($r = 0.38$), consistent with the results of spring wheat observed by Studnicki et al. (2016). The result showed that HI was positively correlated with protein content ($r = 0.69$) significantly. There were significant correlations observed between the protein content and flour characteristics. For example, a positive correlation was noticed between the protein content and wet gluten ($r = 0.75$), water absorption ($r = 0.57$), and dough stability ($r = 0.41$), respectively. Wheat proteins, particularly gluten-forming proteins, contribute to the unique rheological properties of the flour-water system (Lollato, Figueiredo, et al. 2019), and relate to the dough and other end-use qualities (Chen et al. 2018, 2019).

A significant correlation also occurred between the WG and dough mixing quality (e.g., water absorption), as well as the bread characteristics (e.g., specific volume). This finding agreed with previous result that the wet gluten content was correlated

TABLE 2 | Pearson correlation coefficients for the relationships between the examined end-use traits.

	AW	PQ	YD	HI	KD	KW	TW	PC	WG	WA	DT	DS	PV	FV	SB	FN	SV	NC	CV
PQ	0.20																		
YD	−0.26	0.54																	
HI	−0.39	−0.87*	−0.37**																
KD	0.67	0.17	0.22	−0.55**															
KW	0.55	0.12	0.30*	−0.54**	0.98**														
TW	−0.50	−0.46	0.33*	0.11	0.38**	0.46**													
PC	−0.55	−0.41	−0.28*	0.69**	−0.66**	−0.69**	−0.20												
WG	−0.64	0.06	0.02	0.42**	−0.44**	−0.47**	−0.13	0.75**											
WA	0.50	−0.67	−0.18	0.52**	−0.03	−0.05	−0.06	0.57**	0.38**										
DT	−0.22	−0.82*	−0.28*	0.58**	−0.44**	−0.38**	−0.07	0.39**	0.09	0.25									
DS	−0.35	−0.93**	−0.37**	0.66**	−0.46**	−0.41**	0.11	0.41**	0.11	0.17	0.78**								
PV	−0.43	0.56	0.19	−0.21	−0.35**	−0.32*	−0.20	0.01	0.18	−0.41*	0.08	−0.04							
FV	−0.89*	0.13	0.09	0.08	−0.57**	−0.53*	0.07	0.30*	0.35**	−0.30*	−0.01	0.10	0.64**						
SB	−0.20	0.42	−0.09	0.01	−0.63**	−0.65**	−0.63**	0.34**	0.36**	−0.19	0.16	0.01	0.63**	0.44**					
FN	−0.83*	−0.43	−0.23	0.63**	−0.68**	−0.66**	0.10	0.65**	0.54**	0.06	0.29*	0.45**	0.18	0.63**	0.29*				
SV	−0.09	0.86*	0.20	0.04	−0.47**	−0.44**	−0.47**	0.23	0.30*	0.07	0.04	−0.15	0.44**	0.24	0.56**	0.14			
NC	−0.01	0.64	0.02	0.08	−0.53**	−0.54**	−0.52**	0.29*	0.30*	−0.04	0.10	−0.01	0.36**	0.19	0.68**	0.18	0.73**		
CV	0.11	0.98**	0.25	−0.09	−0.14	−0.13	−0.34**	0.05	0.18	0.15	−0.22	−0.41**	0.13	0.06	0.19	−0.04	0.68**	0.20	
CH	−0.58	−0.83*	0.01	0.27*	−0.01	0.05	0.58**	−0.02	−0.09	−0.23	0.31*	0.48**	−0.20	0.12	−0.21	0.27*	−0.55**	−0.30*	−0.64**

Abbreviations: AW, available water for entire season; BD, break down viscosity; CH, crumb hardness; CV, cell volume; DS, dough stability; DT, development time; FN, falling number; FV, final viscosity; HI, hardness index; KD, kernel diameter; KW, kernel weight; NC, number of cells; PC, flour protein content; PQ, photothermal quotient for critical period; PV, peak viscosity; SB, setback viscosity; SV, specific volume; TW, yest weight; WA, eater absorption; WG, wheat gluten content; YD, wheat grain yield.

*Significant correlation at the 0.05 probability level.

**Significant correlation at the 0.01 probability level.

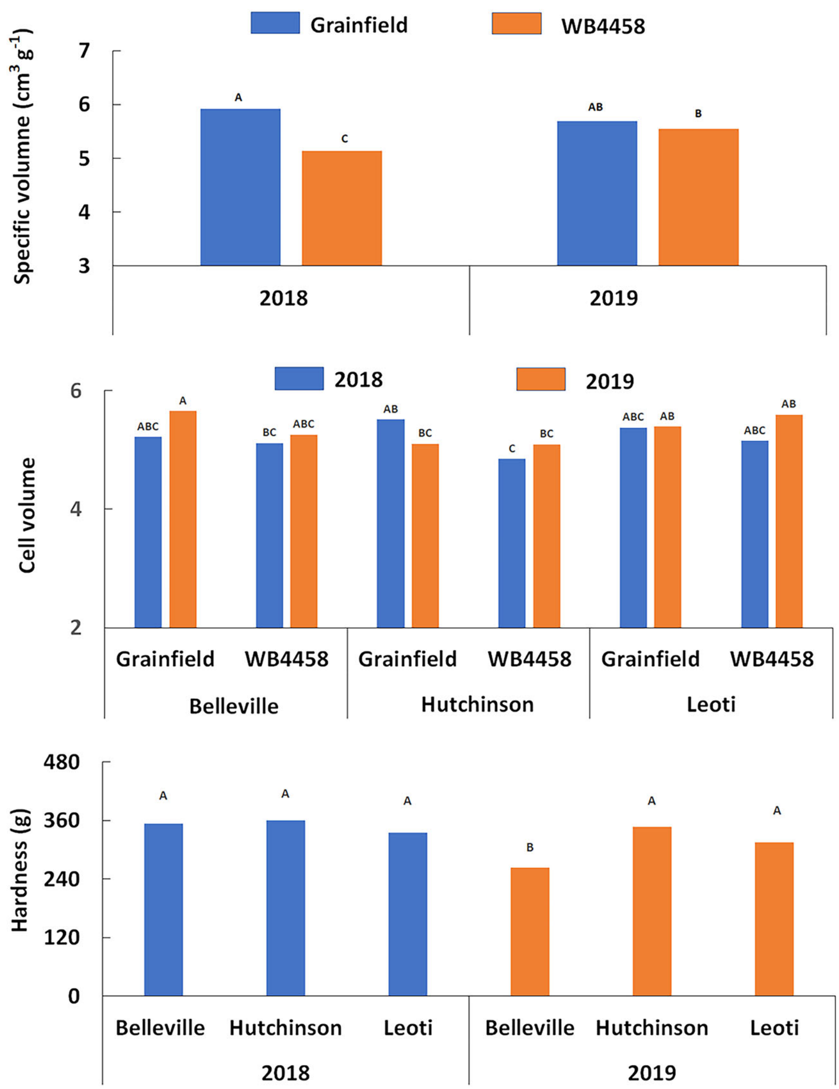

FIGURE 2 | Effect of interaction on bread end-use quality by the year × genotype (Y × G) on specific volume ($cm^3\ g^{-1}$); the year × location × genotype (Y × L × G) on cell volume (CV); the year × location (Y × L) on crumb hardness (g). $^{A\text{–}C}$Bars with different letters differ significantly ($p < 0.05$). EF, enhanced fertility; EI, economical intensification; FP, farmer practice; IFP, increased foliar protection; YW, water-limited yield potential. [Color figure can be viewed at wileyonlinelibrary.com]

with the dough rheological properties (Chen, Ehmke, et al. 2018). When flour is hydrated and manipulated, an elastic and polymeric network of gluten is formed, which provides the dough strength and structure. It has been reported that gluten, especially high and low molecular weight glutenin subunits, strongly affects the function and texture of baked goods from wheat (Ooms and Delcour 2020). In addition, several positive correlations were found among the analyzed bread quality traits, for instance, the specific volume was highly positively correlated with the number of cells ($r = 0.73$) and cell volume ($r = 0.68$), similar to previous reports (Szafranska et al. 2008; Vazquez et al. 2012). The associations between the flour pasting property (e.g., the peak and setback viscosity) and the baking traits such as specific volume were observed in our study, supporting findings from earlier studies (Dencic et al. 2011). However, this contrasts with another literature on bread traits (Mladenov et al. 2001), where the bread-making quality was not significantly correlated to the flour mixing parameters. This discrepancy may be due to differences in wheat genotypes, processing conditions, or experimental methodologies across studies.

4 | Conclusion

Wheat quality traits from field experiments conducted in three Kansas locations over 2 years with two wheat cultivars under five management intensities revealed the multilateral effects of wheat genotypes, crop management, and environment on primary quality indices of HRWW kernel and flour, as well as the bread-making properties. Management intensity allowed for greater grain yield irrespective of variety interaction in five out of six environments, simultaneously impacting grain quality, flour, and dough characteristics. Grain kernel characteristics varied significantly from the interaction of wheat cultivars, year, location, and management, while there was greater variability for flour quality related to these factors and their interactions. Wheat genotype, environment, and field management play a large role in determining more desirable wheat quality traits. The end-use quality of wheat responded positively to increases in management input-intensity, especially with enhanced fertility with in-furrow starter fertilizer and fungicide application; however, the extent of improvement is also dependent on wheat genotypes and environments. Although several consistent interaction effects from field management were observed for the majority of grain and flour characteristic traits, the trend for bread quality traits was still not very clear. In the present study, no significant correlations were identified between the weather data (i.e., available water amount) and grain yield and flour quality. Thus, the effect of integrated management on grain quality needs to be further investigated. Significant associations were identified among some of the wheat quality traits, such as the positive correlation between the protein content and the rheological parameters of wheat flour. The protein quality parameters such as wet gluten content could act as a rapid and valuable tool for predicting the end-use suitability. Our findings suggest that wheat end-use quality can be greatly improved by optimizing management strategies for specific, well-characterized production environments. These insights can contribute to the development of quality-based bread wheat production systems not only in Kansas but also in other wheat-growing regions globally.

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Conflicts of Interest

The authors declare no conflicts of interest.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.