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Biomes Affect Baking Properties and Quality Parameters of Different Wheat Genotypes

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Abstract: Wheat (*Triticum aestivum* L.) is predominantly cultivated in the Atlantic Forest biome. However, the recent expansion of agricultural frontiers in Brazil has led to its introduction into the Savannah biome. The commercial and technological quality parameters of wheat are determined by the interaction between genotype and growing environment. In this context, the objective of this study was to evaluate the effects of six wheat genotypes cultivated in five distinct environments, three located in the Atlantic Forest biome and two in the Savannah biome. The results demonstrated that environmental conditions significantly influenced protein and starch contents, which in turn affected hectoliter weight and falling number. On the other hand, genotypic variation had a marked effect on thousand-grain weight, colorimetric parameters (L* and b*), water and sodium retention capacities, dough tenacity and extensibility, as well as gluten strength. Wheat genotypes cultivated in the Savannah biome exhibited superior baking performance and technological quality, characterized by elevated starch content, enhanced gluten strength (with the exception of the genotype *Feroz*), and greater dough tenacity (except for the genotype *Guardião*), when compared to those cultivated in the Atlantic Forest biome. These results highlight the potential for identifying more sustainable cultivation environments, considering the different biomes, for the production of wheat with superior nutritional and technological quality, promoting the efficient use of natural and economic resources throughout the production cycle.

Keywords: phenotype; wheat flour; alveograph; baking properties

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1. Introduction

Wheat (*Triticum* spp.) accounts for approximately 30% of global grain production. In Brazil, wheat production has increased by 76% over the past five years, reaching 9.5 million tons in 2022 [1]. Approximately 90% of the wheat cultivated in Brazil is grown in the Atlantic Forest biome, where the combination of adapted genotypes and region-specific management practices has contributed to favorable crop development. However, this region is also characterized by harsh winters, with low temperatures and frequent frosts that negatively impact wheat cultivation [2].

More recently, the Brazilian Savannah biome, located in the central region of the country, has become a focus for the expansion of wheat cultivation and the development of genotypes adapted to its specific conditions. The Savannah biome covers approximately 22% of Brazil's territory and holds around 19% of the nation's water resources, making it a strategic area for agricultural development [3]. Wheat cultivation in the Brazilian Savannah environment has proven to be a promising alternative, as both rainfed and irrigated systems, conducted in upland areas and during the off season, enable the production of wheat grains with high quality standards for breadmaking. Moreover, the use of no-tillage farming systems allows wheat to be sown following the harvest of soybean or corn, contributing to the diversification of the grain production chain and increasing farmers' profitability [4].

One of the main challenges in wheat breeding is the development of new genotypes that combine high yield and post-harvest quality, while also ensuring stability, adaptability, and sustainable production systems [5]. In this context, grain genetics can directly influence the technological and baking properties of wheat, as well as environmental interactions and processing responses, resulting in grains with distinct quality attributes and chemical composition [6].

Numerous studies have been conducted to investigate the influence of genotype and growing environment on wheat grain quality. However, no studies have been found that specifically address the effects of the interaction between genotypes and the environments of the Atlantic Forest and Savannah biomes, due to the recent introduction of wheat cultivation, particularly in the Brazilian Savannah. Therefore, the aim of this study was to evaluate the effects of six wheat genotypes (Destak, 1403, Madrepérola, Senna, Feroz, and Guardião) and five cultivation environments: three located in the Atlantic Forest biome (Arapoti, Arapongas, and Passo Fundo) and two in the Savannah biome (São Gotardo and Uberaba), on baking properties and technological quality parameters.

2. Materials and Methods

2.1. Sampling and Crop Management

The experiment was conducted during the 2021 growing season. Six wheat genotypes (Destak, 1403, Madrepérola, Senna, Feroz, and Guardião) were supplied by OR Sementes (Passo Fundo, Brazil). The genotypes were cultivated in five distinct environments, three of which were located in the Atlantic Forest biome: Arapoti (E1) (24°8′43″ S; 49°49′8″ W; average temperature: 24 °C; precipitation: 77 mm; Red Latosol; productivity of 3100 to 3300 (kg/ha), Arapongas (E2) (23°25′12″ S; 51°25′31″ W; average temperature: 27 °C; precipitation: 108 mm; ferralic soil; productivity of 2900 (kg/ha), and Passo Fundo (E3) (28°15′40″ S; 52°24′30″ W; average temperature: 24 °C; precipitation: 170 mm; clay soil; productivity of 3.000 (kg/ha). The remaining two environments were located in the Savannah biome: Uberaba (E4) (19°44′52″ S; 47°55′55″ W; average temperature: 24 °C; precipitation: 107 mm; sandy soil; productivity of 2000 to 3100 (kg/ha) and São Gotardo (E5) (19°18′40″ S; 46°02′56″ W; average temperature: 26 °C; precipitation: 89 mm; Red Latosol; average productivity of 3200 to 3400 (kg/ha). Wholemeal flour was obtained using a Perten mill equipped with a 35-mesh screen, while white flour was produced using a Chopin laboratory mill (Model CD1, Chopin Technologies, Villeneuve-la-Garenne, France). Figure 1 illustrates the geographical location of the wheat cultivation environments assessed in this study, aiming to enhance the spatial characterization of the biomes under investigation.

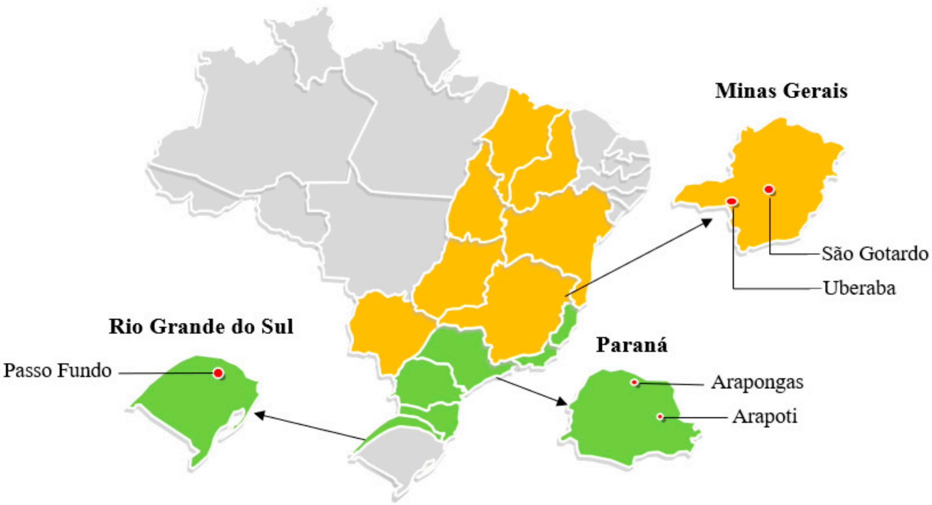

Figure 1. Geographical distribution of Brazilian biomes (Atlantic Forest shown in green and Savanna in yellow), along with the cultivation environments where the wheat genotypes were evaluated.

The field experiments were conducted under rainfed conditions, without supplemental irrigation. Soil types varied between the two biomes. In the Savannah biome, soils are predominantly acidic (pH 4.0–5.0), with textures ranging from sandy to clayey. In the Atlantic Forest biome, soils are generally deep, well drained, acidic (pH 4.5–5.5), and relatively nutrient-poor due to intense leaching and rapid organic matter decomposition. Fertilization was carried out following recommendations based on local soil analyses. A base application of fertilizers formulated with nitrogen, phosphorus, and potassium was performed at sowing, and an additional nitrogen topdressing was applied during crop development to ensure adequate nutritional support. These standardized practices helped minimize environmental variability and improve comparability between sites.

2.2. Chemical Composition

The chemical composition of wheat grains was determined by near-infrared spectrometry (400 to 2500 nm)–NIRS (NIRS™ DS2500, FOSS, Hillerød, Denmark).

The chemical composition of wheat grains was analyzed using near-infrared reflectance spectroscopy (NIRS) in the wavelength range of 400 to 2500 nm, employing the NIRS™ DS2500 analyzer (FOSS, Denmark).

2.3. Wheat Defects

The incidence of grain defects was assessed in accordance with Normative Instruction No. 38, issued on 30 November 2010, by the Brazilian Ministry of Agriculture, Livestock, and Food Supply (MAPA). The proportions of burned, insect-damaged, and shrunken kernels were quantified and expressed as percentages [7].

2.4. Test Weight and Thousand-Grain Weight

Grain test weight was determined using a hectoliter weight scale (Dalle Molle, Brazil). The thousand kernel weight (TKW) was measured in accordance with the official rules for seed analysis [8].

2.5. Colorimetric Profile

The colorimetric profile of the wheat grains was evaluated using a colorimeter (Minolta CR-310, Osaka, Japan). The CIELAB color space parameters measured included L* (lightness, ranging from 0 = black to 100 = white), a* (positive values indicating redness and negative values indicating greenness), and b* (positive values indicating yellowness and negative values indicating blueness).

2.6. Solvent Retention Capacity

Solvent retention capacity (SRC) was determined according to AACC International Approved Method 56-11 [9]. For each test, 5 g of flour was suspended in 25 g of four different solvents: distilled water, 50% sucrose solution, 5% sodium carbonate solution, and 5% lactic acid solution.

2.7. Hagberg Falling Number and Alveograph

The falling number was determined using a Falling Number apparatus (Model FN 1800, Perten Instruments, Decatur, IL, USA), following AACC International Method No. 56-81.03 [10]. The viscoelastic properties of the flours were assessed using an alveograph (Model NG, Chopin, Paris, France), in accordance with AACC International Method No. 54-30.02 [10]. The evaluated parameters included dough tenacity (P), extensibility (L), and gluten strength (W).

2.8. Statistical Analysis

The experiment was conducted in a completely randomized design (CRD) in a 6×5 factorial scheme, consisting of six wheat genotypes and five cultivation environments, with three replicates. Statistical analyses were performed using analysis of variance (ANOVA), and when significant differences were detected ($p < 0.05$), means were compared using Tukey's test, employing the SAS 9.4M7 statistical software. Technological properties were evaluated based on both genotype and environmental effects using multivariate analysis. Principal component analysis (PCA scores) and heatmaps were conducted using MetaboAnalyst 5.0. The data were median-normalized, log-transformed, and Pareto-scaled prior to analysis.

3. Results

3.1. Chemical Composition

The results of the chemical composition analysis are presented in Table 1 and Table S1. The analysis of variance revealed significant effects ($p < 0.05$) of both genotype and growing environment on protein, lipid, starch, ash, and fiber contents. The highest protein levels were observed in the Arapoti and Uberaba environments. Among the genotypes, Madrepérola (16.82%), Senna (16.02%), and Feroz (17.39%) showed the highest protein contents when cultivated in Arapoti. Lipid content was highest in wheat cultivated in Uberaba (genotypes Destak, 1403, Madrepérola, Senna, and Guardião) and Arapoti (Destak and Senna). In Arapoti, the Destak genotype exhibited the highest lipid content (1.96%), while Guardião presented the lowest (1.26%). The highest starch contents were found in São Gotardo for genotypes Destak (62.44%), 1403 (62.29%), Madrepérola (61.46%), and Feroz (60.32%). The lowest starch content was observed in the Guardião genotype cultivated in Arapoti (51.39%). Within each environment, Destak had the highest starch content in Arapoti (57.99%), while in Arapongas, genotypes Destak (55.27%) and Guardião (55.63%) stood out. In Passo Fundo, Senna (57.47%) and Guardião (56.90%) showed the highest starch levels. The lowest fiber contents were recorded in Uberaba and São Gotardo. Notably, the Guardião genotype consistently exhibited high fiber levels across all cultivation environments.

Table 1. Chemical composition of wheat genotypes grown in different cultivation environments.

Environment	*Genotipes*					
	Destak	**1403**	**Madrepérola**	**Senna**	**Feroz**	**Guardião**
			Protein (%)			
Arapoti	15.70 ± 0.16 Ab	14.18 ± 0.03 Ac	16.82 ± 0.17 Aa	16.02 ± 0.30 Aa	17.39 ± 0.09 Aa	15.05 ± 0.20 Ab
Arapongas	13.75 ± 0.10 Ba	12.90 ± 0.11 Ba	13.37 ± 0.24 Ba	12.89 ± 0.08 Ca	13.94 ± 0.07 Ca	13.03 ± 0.03 Ba
Passo Fundo	14.86 ± 0.46 ABab	13.56 ± 0.30 Bb	13.53 ± 0.18 Bb	14.10 ± 0.12 Bb	15.08 ± 0.10 Ba	13.58 ± 0.12 Bb
Uberaba	15.12 ± 0.01 Aa	14.03 ± 0.01 Ab	14.06 ± 0.10 Bb	15.96 ± 0.06 Aa	15.10 ± 0.08 Ba	14.95 ± 0.04 Aa
São Gotardo	13.15 ± 0.03 Bb	12.47 ± 0.03 Bc	12.85 ± 0.26 Bc	14.71 ± 0.03 Ba	13.50 ± 0.05 Cb	13.81 ± 0.07 Bb
			Lipid (%)			
Arapoti	1.96 ± 0.03 Aa	1.65 ± 0.06 Bb	1.65 ± 0.12 Bb	1.69 ± 0.05 Ab	1.60 ± 0.04 Ab	1.26 ± 0.07 Cc
Arapongas	1.51 ± 0.06 Cb	1.70 ± 0.05 Ba	1.42 ± 0.01 Bb	1.48 ± 0.05 Bb	1.58 ± 0.07 Ab	1.45 ± 0.01 Bb
Passo Fundo	1.51 ± 0.04 Ca	1.77 ± 0.04 Ba	1.57 ± 0.07 Ba	1.61 ± 0.06 Ba	1.65 ± 0.08 Aa	1.51 ± 0.01 Ba
Uberaba	1.84 ± 0.02 Aa	1.88 ± 0.02 Aa	1.91 ± 0.04 Aa	1.74 ± 0.02 Ab	1.60 ± 0.08 Ab	1.59 ± 0.03 Ac
São Gotardo	1.67 ± 0.03 Ba	1.65 ± 0.01 Ba	1.57 ± 0.01 Ba	1.65 ± 0.05 Ba	1.51 ± 0.04 Aa	1.44 ± 0.00 Ba
			Starch (%)			
Arapoti	57.99 ± 0.30 Ca	52.92 ± 0.13 Cc	51.39 ± 0.20 Dd	55.29 ± 0.80 BCb	52.65 ± 0.53 Cc	53.48 ± 0.21 Cc
Arapongas	55.27 ± 0.14 CDa	53.75 ± 0.18 Cb	53.47 ± 0.24 Cb	54.14 ± 0.23 Cab	53.98 ± 0.66 Cb	55.63 ± 0.74 Ba
Passo Fundo	53.19 ± 0.13 Bb	53.51 ± 0.25 Cb	54.28 ± 0.30 Cb	57.47 ± 0.32 Ba	53.78 ± 0.07 Cb	56.90 ± 1.91 Ba
Uberaba	59.53 ± 0.13 Ba	59.55 ± 0.13 Ba	59.15 ± 0.11 Ba	59.41 ± 0.22 Aa	57.97 ± 0.11 Bb	59.75 ± 0.74 Aa
São Gotardo	62.44 ± 0.32 Aa	62.29 ± 0.18 Aa	61.46 ± 0.29 Aab	60.20 ± 0.08 Aa	60.32 ± 0.13 Aa	60.46 ± 0.12 Aa
			Ashes (%)			
Arapoti	1.41 ± 0.12 Ce	1.49 ± 0.03 Cd	1.64 ± 0.02 Bb	1.60 ± 0.03 Cc	1.70 ± 0.03 Ba	1.65 ± 0.01 Bb
Arapongas	1.59 ± 0.09 Ba	1.47 ± 0.03 Ce	1.67 ± 0.02 Ab	1.56 ± 0.01 Dc	1.58 ± 0.00 Da	1.54 ± 0.01 Ed
Passo Fundo	1.59 ± 0.02 Bb	1.53 ± 0.02 Bd	1.65 ± 0.02 Ba	1.55 ± 0.03 Dc	1.65 ± 0.02 Ca	1.56 ± 0.02 Dc
Uberaba	1.70 ± 0.02 Ad	1.63 ± 0.02 Ae	1.64 ± 0.02 Be	1.84 ± 0.02 Aa	1.77 ± 0.02 Ab	1.74 ± 0.02 Ac
São Gotardo	1.59 ± 0.01 Bc	1.53 ± 0.01 Be	1.68 ± 0.05 Ab	1.70 ± 0.04 Ba	1.56 ± 0.02 Ed	1.61 ± 0.02 Cc
			Fibers (%)			
Arapoti	2.50 ± 0.01 Cc	2.61 ± 0.05 Ab	2.66 ± 0.02 Bb	2.70 ± 0.05 Ab	2.53 ± 0.03 Cc	2.85 ± 0.02 Aa
Arapongas	2.69 ± 0.01 Ba	2.66 ± 0.02 Aab	2.75 ± 0.01 Aa	2.64 ± 0.02 Ab	2.64 ± 0.03 Bb	2.78 ± 0.08 Aa
Passo Fundo	2.76 ± 0.03 Aa	2.59 ± 0.05 Ab	2.74 ± 0.04 Aa	2.64 ± 0.07 Aab	2.76 ± 0.06 Aa	2.74 ± 0.09 Aa
Uberaba	2.51 ± 0.03 Cb	2.40 ± 0.06 Bc	2.49 ± 0.07 Cb	2.46 ± 0.02 Bc	2.45 ± 0.01 Dc	2.64 ± 0.03 Ba
São Gotardo	2.24 ± 0.03 Dc	2.11 ± 0.01 Cd	2.28 ± 0.02 Dc	2.51 ± 0.04 Ba	2.38 ± 0.06 Db	2.57 ± 0.02 Ba

Comparison between growing locations is indicated by uppercase letters within rows, while comparison among genotypes is indicated by lowercase letters within columns.

3.2. Wheat Defects

The results of the wheat defect analysis are presented in Table 2 and Table S1. The analysis of variance (ANOVA) revealed significant effects ($p < 0.05$) of both genotype and cultivation environment on the incidence of burned, insect-damaged, and shrunken grains. The highest incidence of burned grains was observed in the São Gotardo environment across all genotypes, with the Senna genotype showing the greatest proportion (8.98%). In contrast, the other environments exhibited lower levels of burned grains. A similar trend was found for insect-damaged grains, with São Gotardo also presenting the highest levels of damage. Regarding shrunken grains, the highest incidence occurred in Arapongas, particularly in the Destak (9.15%) and Senna (7.49%) genotypes. The lowest levels of burned grains were recorded in the Uberaba environment.

3.3. Test Weight and Thousand-Grain Weight

The results of the test weight and thousand-grain weight analyses are presented in Tables 2 and S1. The analysis of variance revealed significant effects ($p < 0.05$) of both genotype and cultivation environment on hectoliter weight and thousand-grain weight. The highest test weights were recorded for the Madrepérola genotype in São Gotardo (80.10 g hL^{-1}), and for the Feroz and Guardião genotypes in Arapongas (80.12 and 80.60 g hL^{-1}, respectively), Passo Fundo (79.42 and 79.74 g hL^{-1}), and São Gotardo (79.95 and 81.04 g hL^{-1}). Conversely, the lowest test weights were observed for the Destak genotype in Arapongas (77.63 g hL^{-1}) and Passo Fundo (77.03 g hL^{-1}); for the Senna genotype in Arapongas (76.41 g hL^{-1}) and Uberaba (75.92 g hL^{-1}); for the Feroz genotype in Uberaba (75.32 g hL^{-1});

and for the Guardião genotype in Arapoti (78.50 g hL^{-1}) and Uberaba (76.79 g hL^{-1}). The 1403 genotype also exhibited low test weight values in multiple environments. Regarding thousand-grain weight, the Guardião genotype consistently exhibited the highest values across all cultivation environments. In contrast, the lowest thousand-grain weights were observed in the Destak, 1403, and Madrepérola genotypes, particularly when cultivated in Passo Fundo and Uberaba.

3.4. Colorimetric Profile

The results of the colorimetric profile analysis are presented in Tables 2 and S1. The analysis of variance indicated significant effects ($p < 0.05$) of both genotype and cultivation environment on the a*-value (red–green) and b*-value (yellow–blue) color parameters. No significant differences were observed for the L*-value (lightness) parameter across genotypes and environments. For the b*-value (yellowness) parameter, significant variation was identified among environments. The highest b*-value for the Destak genotype was recorded in São Gotardo (14.01), while genotype 1403 exhibited the highest b*-values in Uberaba (14.68) and São Gotardo (15.12). No significant differences in b*-values were observed among the other genotypes across environments. When comparing genotypes, the highest b*-value in Passo Fundo was recorded for genotype 1403 (13.94), while in São Gotardo, genotypes Destak (14.01) and 1403 (15.12) showed the highest values. In contrast, the Madrepérola genotype consistently exhibited the lowest b*-values across all environments (Table 3). The a*-values showed minimal variation among samples, ranging from −1.33 to −0.05.

Table 2. Defects, test weight, thousand-grain weight, and colorimetric profile of flours of wheat genotypes grown in different cultivation environments.

Environment	*Genotipes*					
	Destak	**1403**	**Madrepérola**	**Senna**	**Feroz**	**Guardião**
			Burned grain (%)			
Arapoti	0.16 ± 0.01 Db	0.33 ± 0.01 Ca	0.12 ± 0.01 Cc	0.00 ± 0.00 Ed	0.35 ± 0.07 Ba	0.00 ± 0.00 Dd
Arapongas	0.12 ± 0.01 Db	0.05 ± 0.01 Dc	0.15 ± 0.01 Cb	0.05 ± 0.01 Dc	0.00 ± 0.00 Dd	0.57 ± 0.05 Ba
Passo Fundo	0.28 ± 0.01 Ca	0.00 ± 0.00 Dd	0.18 ± 0.01 Cb	0.11 ± 0.01 Cc	0.15 ± 0.01 Cb	0.09 ± 0.00 Cc
Uberaba	0.58 ± 0.03 Bc	0.55 ± 0.02 Bd	0.53 ± 0.04 Bd	0.66 ± 0.01 Bb	0.35 ± 0.01 Be	0.52 ± 0.04 Ba
São Gotardo	1.48 ± 0.03 Ac	0.98 ± 0.01 Ae	2.56 ± 0.08 Ac	8.98 ± 0.02 Aa	0.89 ± 0.01 Af	5.03 ± 0.03 Ab
			Grain damaged by insects (%)			
Arapoti	0.22 ± 0.01 Bb	0.26 ± 0.02 Cb	0.22 ± 0.01 Cb	0.07 ± 0.03 Bc	0.03 ± 0.00 Dc	0.00 ± 0.00 Dd
Arapongas	0.11 ± 0.01 Ca	0.00 ± 0.00 Dc	0.12 ± 0.01 Da	0.04 ± 0.00 Bb	0.02 ± 0.01 Db	0.10 ± 0.00 Ca
Passo Fundo	0.11 ± 0.01 Cb	0.00 ± 0.00 Dc	0.49 ± 0.01 Ba	0.00 ± 0.00 Cc	0.15 ± 0.01 Cb	0.10 ± 0.00 Cb
Uberaba	0.08 ± 0.01 Cd	0.55 ± 0.02 Ba	0.05 ± 0.00 Ee	0.16 ± 0.01 Ac	0.23 ± 0.00 Bb	0.23 ± 0.01 Bb
São Gotardo	1.48 ± 0.03 Ab	0.98 ± 0.01 Ac	2.51 ± 0.16 Aa	0.00 ± 0.00 Ce	0.43 ± 0.04 Ae	0.53 ± 0.01 Ad
			Shrunken grain (%)			
Arapoti	1.75 ± 0.07 Bb	1.49 ± 0.01 Bc	1.20 ± 0.01 Dd	2.49 ± 0.01 Ba	0.78 ± 0.04 Ce	2.52 ± 0.02 Ca
Arapongas	9.15 ± 0.07 Aa	3.15 ± 0.07 Ad	4.96 ± 0.04 Ac	7.49 ± 0.02 Ab	3.48 ± 0.04 Ad	3.63 ± 0.18 Ad
Passo Fundo	0.99 ± 0.01 Ce	1.36 ± 0.01 Cd	3.03 ± 0.01 Ba	2.20 ± 0.01 Cc	0.55 ± 0.00 Df	2.80 ± 0.00 Bb
Uberaba	0.38 ± 0.01 Db	0.25 ± 0.00 Dc	0.21 ± 0.01 Ec	0.09 ± 0.00 Ed	0.51 ± 0.01 Da	0.33 ± 0.01 Eb
São Gotardo	0.25 ± 0.00 Ec	0.26 ± 0.01 Dc	1.47 ± 0.04 Cb	1.46 ± 0.05 Db	1.65 ± 0.07 Ba	1.42 ± 0.03 Db
			Test weight ($kg{\cdot}hL^{-1}$)			
Arapoti	80.00 ± 0.13 Aa	79.09 ± 0.43 Ab	77.05 ± 0.34 Bc	79.35 ± 0.30 Ab	78.20 ± 0.53 Bb	78.50 ± 0.22 Bb
Arapongas	77.63 ± 0.21 Bc	79.28 ± 0.24 Aab	78.64 ± 0.10 Bb	76.41 ± 0.26 Bd	80.12 ± 0.04 Aa	80.60 ± 0.39 Aa
Passo Fundo	77.03 ± 0.25 Bc	79.33 ± 0.19 Aa	78.05 ± 0.53 Bb	79.34 ± 0.67 Aa	79.42 ± 0.119 Aa	79.74 ± 0.38 Aa
Uberaba	79.76 ± 0.41 Aa	80.12 ± 0.16 Aa	78.52 ± 0.16 Bb	75.92 ± 0.51 Bd	75.32 ± 0.18 Cd	76.79 ± 0.51 Bc
São Gotardo	80.68 ± 0.18 Aa	80.92 ± 0.16 Aa	80.10 ± 0.42 Aa	79.29 ± 0.11 Aa	79.95 ± 0.27 Aa	81.04 ± 0.11 Aa

Table 2. *Cont.*

Environment	Genotipes					
	Destak	1403	Madrepérola	Senna	Feroz	Guardião
			Thousand-grain weight (g)			
Arapoti	35.14 ± 0.41 Ab	31.89 ± 0.39 Ac	38.40 ± 0.22 Ab	41.80 ± 0.18 Aa	36.80 ± 0.33 Ab	44.79 ± 0.38 Aa
Arapongas	33.41 ± 0.52 Ab	30.14 ± 0.78 Ab	34.85 ± 0.25 Bb	33.15 ± 0.68 Bb	35.04 ± 0.33 Ab	43.64 ± 0.34 Aa
Passo Fundo	28.68 ± 0.47 Cc	27.18 ± 0.37 Bc	28.99 ± 0.37 Cc	39.01 ± 0.39 Aa	32.66 ± 0.19 Bb	41.16 ± 0.14 Aa
Uberaba	30.80 ± 0.27 Bb	28.37 ± 0.42 Ab	29.79 ± 0.10 Cb	38.01 ± 0.32 Aa	32.95 ± 0.20 Bb	39.85 ± 0.54 Aa
São Gotardo	33.72 ± 0.43 Ab	32.09 ± 0.42 Ab	33.95 ± 0.42 Bb	37.46 ± 0.22 Ab	34.23 ± 0.14 ABb	40.41 ± 0.87 Aa
			Value L*			
Arapoti	88.77 ± 2.83 Aa	85.20 ± 6.16 Aa	92.70 ± 1.27 Aa	86.44 ± 3.23 Aa	90.05 ± 2.29 Aa	89.87 ± 6.32 Aa
Arapongas	89.64 ± 0.92 Aa	90.25 ± 1.48 Aa	88.56 ± 4.61 Aa	89.43 ± 5.02 Aa	91.99 ± 1.98 Aa	91.71 ± 0.88 Aa
Passo Fundo	89.41 ± 1.89 Aa	88.11 ± 0.59 Aa	92.65 ± 4.61 Aa	86.72 ± 3.41 Aa	85.74 ± 3.91 Aa	86.28 ± 6.25 Aa
Uberaba	87.85 ± 1.08 Aa	89.25 ± 1.50 Aa	89.96 ± 1.47 Aa	88.15 ± 3.33 Aa	89.52 ± 1.52 Aa	85.87 ± 4.49 Aa
São Gotardo	88.50 ± 1.78 Aa	91.17 ± 3.85 Aa	86.46 ± 4.17 Aa	84.62 ± 0.57 Aa	85.60 ± 0.85 Aa	85.91 ± 3.18 Aa
			Value a*			
Arapoti	−0.25 ± 0.13 Aa	−0.43 ± 0.09 Ba	−0.88 ± −1.05 Aa	−0.96 ± 0.07 Ba	−0.39 ± 0.10 Aa	−0.48 ± 0.08 Ba
Arapongas	−0.58 ± 0.07 Bc	−0.92 ± 0.06 Cd	−1.05 ± 0.07 Ad	−0.31 ± 0.10 Ab	−0.31 ± 0.04 Ab	−0.05 ± 0.07 Aa
Passo Fundo	−0.75 ± 0.06 Ca	−1.14 ± 0.03 Cb	−1.25 ± 0.04 Ab	−1.10 ± 0.12 Bb	−0.87 ± 0.05 Ca	−0.75 ± 0.04 Ca
Uberaba	−0.75 ± 0.05 Ca	−0.86 ± 0.27 Ca	−1.25 ± 0.07 Ac	−1.32 ± 0.05 Bc	−1.08 ± 0.07 Db	−1.08 ± 0.08 Db
São Gotardo	−0.29 ± 0.11 Aa	−0.19 ± 0.08 Aa	−1.33 ± 0.07 Ad	−0.44 ± 0.10 Ab	−0.53 ± 0.02 Bb	−0.89 ± 0.06 Cc
			Value b*			
Arapoti	13.18 ± 0.79 Ba	13.12 ± 1.03 Ba	8.06 ± 0.47 Ac	10.58 ± 1.40 Ab	11.35 ± 0.09 Aab	12.27 ± 0.25 Aa
Arapongas	12.68 ± 0.50 Ba	13.94 ± 0.65 Ba	9.52 ± 0.71 Ab	11.68 ± 0.43 Aa	11.30 ± 0.42 Aa	12.56 ± 0.54 Aa
Passo Fundo	12.20 ± 0.52 Bb	13.94 ± 0.29 Ba	9.23 ± 1.03 Ac	10.68 ± 0.73 Ab	11.19 ± 0.82 Ab	12.65 ± 0.72 Ab
Uberaba	12.02 ± 0.84 Ba	14.68 ± 1.17 ABa	9.80 ± 0.60 Ab	12.03 ± 0.50 Aa	12.88 ± 0.79 Aa	13.10 ± 0.78 Aa
São Gotardo	14.01 ± 0.40 Aab	15.12 ± 0.68 Aa	10.70 ± 1.43 Ac	12.33 ± 0.47 Ab	12.92 ± 0.62 Ab	13.13 ± 0.24 Ab

Comparison between growing locations is indicated by uppercase letters within rows, while comparison among genotypes is indicated by lowercase letters within columns.

Table 3. Solvent retention capacity (SRC), Hagberg falling number, tenacity, extensibility, and strength of gluten of wheat genotypes grown in different cultivation environments.

Environment	Genotipes					
	Destak	1403	Madrepérola	Senna	Feroz	Guardião
			SRC—Water (%)			
Arapoti	94.14 ± 15.01 Ca	105.51 ± 3.48 Aa	105.20 ± 3.22 Ba	88.44 ± 0.93 Ca	105.61 ± 1.61 Aa	103.53 ± 7.45 Aa
Arapongas	125.61 ± 1.61 Aa	88.28 ± 0.97 Bc	128.00 ± 3.78 Aa	122.76 ± 5.38 Aa	93.96 ± 0.05 Ab	98.12 ± 4.86 Ab
Passo Fundo	134.56 ± 6.98 Aa	88.66 ± 4.33 Bc	87.50 ± 1.22 Dc	107.03 ± 1.54 Bb	104.15 ± 2.61 Ab	98.28 ± 1.60 Ab
Uberaba	117.86 ± 0.15 Ba	103.28 ± 10.76 Ab	92.38 ± 1.29 Cb	81.14 ± 0.22 Dc	94.24 ± 6.54 Ab	109.59 ± 5.07 Ab
São Gotardo	102.95 ± 5.73 Ca	94.53 ± 0.99 Ab	92.88 ± 0.57 Cb	95.52 ± 2.46 Cb	85.42 ± 1.28 Bc	109.33 ± 5.66 Aa
			SRC—Sodium carbonate (%)			
Arapoti	103.73 ± 2.08 Aa	135.16 ± 1.25 Aa	114.07 ± 1.89 B Aa	114.90 ± 1.78 Aa	140.94 ± 4.90 Aa	119.52 ± 0.34 Aa
Arapongas	110.30 ± 4.69 C Aa	103.73 ± 0.82 C Aa	129.15 ± 1.75 Aa	134.84 ± 10.19 Aa	117.31 ± 134.57 Aa	126.53 ± 0.71 Aa
Passo Fundo	125.55 ± 3.24 Aa	106.53 ± 2.94 Aa	108.60 ± 4.07 Aa	128.47 ± 0.77 Aa	126.72 ± 5.09 Aa	122.89 ± 3.21 Aa
Uberaba	108.54 ± 1.75 Aa	112.36 ± 2.66 Aa	106.05 ± 1.69 Aa	106.51 ± 0.10 Aa	124.28 ± 0.45 Aa	131.79 ± 1.49 Aa
São Gotardo	114.66 ± 0.50 Aa	107.81 ± 0.95 Aa	117.59 ± 0.01 Aa	117.46 ± 0.46 Aa	107.86 ± 1.22 Aa	141.65 ± 13.25 Aa
			SRC—Sucrose (%)			
Arapoti	105.63 ± 11.68 Aa	127.84 ± 4.19 Aa	108.61 ± 79.94 Aa	108.73 ± 11.58 Aa	105.09 ± 1.38 Aa	107.30 ± 3.77 Aa
Arapongas	119.25 ± 13.95 Aa	113.57 ± 6.33 Aa	125.02 ± 32.33 Aa	123.60 ± 3.74 Aa	108.58 ± 3.01 Aa	109.95 ± 5.42 Aa
Passo Fundo	128.59 ± 10.88 Aa	104.63 ± 15.95 Aa	100.98 ± 1.61 Aa	226.56 ± 145.61 Aa	111.78 ± 0.46 Aa	121.15 ± 0.22 Aa
Uberaba	116.12 ± 1.52 Aa	125.18 ± 1.61 Aa	102.76 ± 2.30 Aa	93.21 ± 1.80 Aa	121.73 ± 9.11 Aa	127.59 ± 12.53 Aa
São Gotardo	129.48 ± 3.11 Aa	107.91 ± 7.87 Aa	115.04 ± 0.69 Aa	110.58 ± 10.85 Aa	94.11 ± 2.74 Aa	129.72 ± 4.66 Aa
			SRC—Lactic acid (%)			
Arapoti	135.50 ± 8.70 Dc	163.12 ± 3.66 Bb	182.37 ± 10.51 Ba	182.62 ± 7.70 Aa	179.59 ± 5.42 Aa	146.08 ± 9.53 Ab
Arapongas	202.06 ± 0.88 Aa	179.06 ± 5.25 Bb	205.09 ± 8.68 Aa	153.88 ± 5.83 Bb	161.16 ± 1.36 Ab	166.08 ± 9.53 Ab
Passo Fundo	186.48 ± 7.10 Ba	168.14 ± 4.13 Bb	181.50 ± 0.67 Ba	152.65 ± 0.41 Bb	152.70 ± 1.61 Bb	166.54 ± 0.27 Ab
Uberaba	163.72 ± 9.22 Ba	159.07 ± 1.83 Ca	132.73 ± 1.39 Db	173.56 ± 6.06 Aa	182.49 ± 10.27 Aa	158.51 ± 0.60 Aa
São Gotardo	147.63 ± 1.51 Cc	201.38 ± 1.40 Aa	159.29 ± 0.98 Cc	188.50 ± 5.13 Ab	172.12 ± 13.04 Ab	153.53 ± 5.50 Ac

Table 3. *Cont.*

Environment	Genotipes					
	Destak	1403	Madrepérola	Senna	Feroz	Guardião
			Hagberg Falling number (s)			
Arapoti	477.50 ± 9.19 Aa	400.50 ± 36.06 Bb	447.50 ± 4.95 Ab	483.00 ± 15.56 Aa	396.50 ± 14.85 Bb	407.00 ± 12.73 Ab
Arapongas	457.50 ± 7.78 Aa	426.50 ± 9.19 Bb	360.50 ± 0.71 Bc	336.50 ± 6.36 Cd	336.00 ± 1.41 Cd	374.00 ± 15.56 Bc
Passo Fundo	454.00 ± 9.90 Aa	371.00 ± 15.56 Cc	354.50 ± 13.44 Bc	402.00 ± 1.41 Bb	397.00 ± 9.90 Bb	400.00 ± 11.31 Ab
Uberaba	444.00 ± 49.50 Ab	559.50 ± 34.65 Aa	343.50 ± 7.78 Bc	445.50 ± 16.26 Bb	463.00 ± 16.97 Ab	427.00 ± 19.80 Ab
São Gotardo	442.00 ± 26.87 Aa	451.50 ± 20.51 Ba	460.00 ± 24.04 Aa	427.00 ± 19.80 Ba	366.50 ± 28.99 Bb	444.50 ± 2.12 Aa
			Tenacity (mm)			
Arapoti	119.50 ± 2.52 Bb	117.00 ± 10.12 Bb	64.25 ± 3.00 Ac	102.50 ± 9.94 Bb	97.00 ± 3.61 Bb	160.25 ± 5.29 Ba
Arapongas	91.00 ± 8.08 Ba	98.00 ± 3.79 Ca	58.75 ± 0.00 Ac	80.00 ± 2.00 Bab	70.50 ± 9.17 Cb	103.50 ± 3.51 Da
Passo Fundo	118.00 ± 7.37 Ba	123.00 ± 9.29 ABa	46.25 ± 1.53 Cb	97.25 ± 1.00 Ba	127.50 ± 6.24 Aa	102.25 ± 10.69 Da
Uberaba	112.75 ± 5.03 Bc	125.50 ± 1.73 Bc	56.75 ± 1.15 Ad	138.75 ± 0.58 Ab	125.75 ± 1.53 Ac	203.25 ± 1.53 Aa
São Gotardo	128.50 ± 1.53 Ab	136.25 ± 6.11 Ab	51.25 ± 0.58 Bd	106.25 ± 4.16 Bc	125.00 ± 3.06 Ab	141.67 ± 0.58 Ca
			Extensibility (mm)			
Arapoti	83.75 ± 4.62 Aa	69.25 ± 4.93 Aa	103.50 ± 13.20 Ba	97.25 ± 15.95 Aa	93.50 ± 6.24 Aa	50.50 ± 3.51 Cb
Arapongas	89.50 ± 10.44 Aa	66.75 ± 8.62 Ab	69.00 ± 14.43 Cab	112.25 ± 5.86 Aa	107.75 ± 14.36 Aa	65.75 ± 5.20 Bb
Passo Fundo	77.25 ± 10.15 Abc	43.75 ± 1.53 Bd	84.50 ± 2.08 Cb	122.50 ± 5.51 Aa	117.50 ± 13.00 Aa	61.00 ± 4.04 Bc
Uberaba	89.00 ± 2.89 Ac	70.50 ± 7.23 Ac	154.00 ± 5.51 Aa	99.50 ± 2.31 Ab	78.75 ± 1.73 Bc	48.50 ± 3.46 Cd
São Gotardo	89.25 ± 2.08 Ac	67.50 ± 1.15 Ad	141.50 ± 6.03 Aa	108.75 ± 4.62 Ab	85.50 ± 6.24 ABc	83.00 ± 2.65 Ac
			Strength of gluten (10^{-4} J)			
Arapoti	313.50 ± 19.30 Ba	270.25 ± 28.01 Bc	218.50 ± 2.00 Bc	305.25 ± 58.64 Cb	331.50 ± 20.07 Ba	306.75 ± 18.15 Bb
Arapongas	263.00 ± 36.69 Ca	229.00 ± 27.15 Ca	154.50 ± 4.55 Ba	291.75 ± 11.15 Ca	249.75 ± 46.87 Ba	229.00 ± 4.93 Ca
Passo Fundo	278.25 ± 44.19 Cc	210.75 ± 19.97 Cc	149.25 ± 3.21 Bd	349.00 ± 2.34 Bb	441.00 ± 18.72 Aa	204.00 ± 24.34 Cc
Uberaba	320.50 ± 13.43 Bb	276.75 ± 23.76 Bc	248.75 ± 11.72 Ac	416.50 ± 3.61 Aa	323.00 ± 6.03 Bb	364.00 ± 15.04 Ab
São Gotardo	362.25 ± 3.79 Aa	312.50 ± 8.39 Ab	219.00 ± 8.89 Bc	355.75 ± 2.31 Ba	316.50 ± 3.61 Bb	358.00 ± 7.55 Aa

Comparison between growing locations is indicated by uppercase letters within rows, while comparison among genotypes is indicated by lowercase letters within columns.

3.5. Solvent Retention Capacity

The results of the solvent retention capacity (SRC) analysis are presented in Table 3 and Table S1. The analysis of variance revealed significant effects ($p < 0.05$) of both genotype and cultivation environment for SRC-water and SRC-lactic acid. However, no significant differences were observed for SRC-sodium carbonate and SRC-sucrose. The highest SRC-water values for the Destak genotype were recorded in Arapongas (125.61%) and Passo Fundo (134.56%). Similarly, elevated values were observed for the Madrepérola (128.00%) and Senna (122.73%) genotypes in Arapongas. In contrast, the lowest SRC-water values were observed for the 1403 genotype in Arapongas (88.28%) and Passo Fundo (88.66%), for Madrepérola in Passo Fundo (87.50%), for Senna in Uberaba (81.14%), and for Feroz in São Gotardo (85.42%). For the Guardião genotype, no significant variation in SRC-water was observed among the different environments, indicating a more stable hydration capacity under varying cultivation conditions.

The highest SRC-lactic acid values were observed in the Destak genotype cultivated in Arapongas (202.06%), in the 1403 genotype in São Gotardo (201.38%), and in the Madrepérola genotype in Arapongas (205.09%). In contrast, the lowest values were recorded for the Destak genotype in Arapoti (135.50%), for the 1403 genotype in Uberaba (159.07%), for Madrepérola in Uberaba (132.73%), and for Feroz in Passo Fundo (152.70%). No significant differences were observed in the lactic acid SRC values for the Guardião genotype across the environments studied, suggesting greater stability of this trait in response to environmental variation.

3.6. Hagberg Falling Number

The results of the falling number analysis are presented in Table 3 and Table S1. The analysis of variance showed significant effects ($p < 0.05$) of genotype and environment on falling number. The highest falling number in the 1403 genotype was found in Uberaba (559.5 s), in the Madrepérola genotype in Arapoti (447.50 s) and São Gotardo (460.00 s), in the Senna genotype in Arapoti (483.00 s), in the Feroz genotype in Uberaba (463.00 s), while the lowest values in the 1403 genotype were found in Passo Fundo (371.00 s), and in the Senna, Feroz and Guardião genotypes in Arapongas (336.50, 336.00, and 374.00 s, respectively). For the genotype Destak no significant differences were found among the growing environments.

The results of the falling number analysis are presented in Table 3 and Table S1. The analysis of variance revealed significant effects ($p < 0.05$) of both genotype and cultivation environment on falling number values. The highest falling number was observed for the 1403 genotype in Uberaba (559.5 s), followed by the Madrepérola genotype in Arapoti (447.5 s) and São Gotardo (460.0 s), the Senna genotype in Arapoti (483.0 s), and the Feroz genotype in Uberaba (463.0 s). Conversely, the lowest falling number values for the 1403 genotype were recorded in Passo Fundo (371.0 s), and for the Senna, Feroz, and Guardião genotypes in Arapongas (336.5 s, 336.0 s, and 374.0 s, respectively). No significant differences in falling number values were observed for the Destak genotype across the different environments, indicating greater stability of enzymatic activity associated with this trait.

3.7. Alveography

The results of the alveograph analysis are presented in Table 3 and Table S1. The analysis of variance revealed significant effects ($p < 0.05$) of both genotype and environment on tenacity, extensibility, and gluten strength. The highest tenacity values were observed in the genotype Destak grown in São Gotardo (128.50 mm), in genotype 1403 in Passo Fundo (123.00 mm) and São Gotardo (136.50 mm), and in genotypes Senna and Guardião cultivated in Uberaba (138.75 mm and 203.25 mm, respectively). In contrast, the lowest tenacity values were recorded for genotype 1403 in Arapongas (98.00 mm), Madrepérola in Passo Fundo (46.25 mm), Feroz in Arapongas (70.50 mm), and Guardião in Arapongas (103.50 mm) and Passo Fundo (102.25 mm). Regarding extensibility, the highest values were found for Madrepérola in Uberaba (154.00 mm) and São Gotardo (141.50 mm), and for Guardião in São Gotardo (83.00 mm). The lowest extensibility values were observed for 1403 in Passo Fundo (43.75 mm), Madrepérola in Arapongas (69.00 mm) and Passo Fundo (84.50 mm), Feroz in Uberaba (78.75 mm) and São Gotardo (85.50 mm), and Guardião in Arapoti (50.50 mm) and Uberaba (48.50 mm). For genotypes Destak and Senna, no significant differences in tenacity or extensibility were observed across the different cultivation environments.

The highest gluten strength values were observed in genotypes Destak and 1403 when cultivated in São Gotardo, with values of 362.25 and 312.50 $\times 10^{-4}$ J, respectively. Genotypes Madrepérola and Senna showed the highest values in Uberaba (248.75 and 416.50 $\times 10^{-4}$ J, respectively), while Feroz exhibited its highest gluten strength in Passo Fundo (441.00 $\times 10^{-4}$ J). For Guardião genotype, the highest values were recorded in Uberaba (364.00 $\times 10^{-4}$ J) and São Gotardo (358.00 $\times 10^{-4}$ J). In contrast, the lowest gluten strength values for Destak (263.00 and 278.25 $\times 10^{-4}$ J), 1403 (229.00 and 210.75 $\times 10^{-4}$ J), and Guardião (229.00 and 204.00 $\times 10^{-4}$ J) were found in Arapongas and Passo Fundo, respectively. Additionally, the Senna genotype exhibited lower values in Arapoti (305.25 $\times 10^{-4}$ J) and Arapongas (291.75 $\times 10^{-4}$ J).

4. Discussions

4.1. Chemical Composition

Protein concentration in wheat grains is influenced by both abiotic factors during cultivation and genetic characteristics of the genotypes, directly affecting the rheological and technological quality of the flour [11]. Protein is recognized as the primary determinant of wheat flour quality [12]. Temperature and water availability are critical environmental variables, as they significantly affect the rate and duration of grain filling, thereby influencing protein deposition in the endosperm [11]. The cultivation environments of Arapoti (Atlantic Forest biome) and Uberaba (Savannah biome) exhibited high protein levels, demonstrating favorable adaptability for the genotypes evaluated. Although lipids represent a minor and highly variable component in wheat grains, their quantity and composition are essential for determining the functional and nutritional properties of wheat-based products [13]. Elevated lipid contents were observed in the Destak genotype in Arapoti (1.96%) and in the Madrepérola genotype in Uberaba (1.91%), suggesting higher nutritional potential due to the presence of polyunsaturated fatty acids and tocopherols. Starch, the predominant component of wheat grains, is a key determinant of flour yield and significantly contributes to the quality of the end-use product [14]. The higher starch contents observed in grains produced in São Gotardo indicate the suitability of this environment for cultivating wheat with high flour extraction potential.

4.2. Wheat Defects

The elevated levels of burned and insect-damaged grains observed in the São Gotardo environment may be attributed to a higher incidence of pests during the crop cycle. The presence of such defects significantly compromises the technological and nutritional quality of wheat-derived products. According to a study conducted by [15], the intensification of defects in soybean grains led to a substantial deterioration in functional quality. The authors reported a decrease in soluble protein content from 17.10% to 1.64%, a reduction in protein extraction yield from 40.20% to 8.60%, and an increase in acidity from 3.60 to 52.20 mg KOH g^{-1}, as well as an increase in lipase activity from 2.47% to 26.86% lipolysis, when comparing defect-free soybeans with burned soybeans. These findings highlight the significant negative impact that grain defects can have on the physicochemical properties of raw materials. Shrunken grains are characterized by the predominance of the outer layers, resulting from incomplete grain filling [7]. Their formation is often associated with environmental stresses, particularly thermal and water stress, as well as nutrient deficiencies in the soil during the cultivation period [16]. The elevated incidence of shrunken grains observed in the Arapongas environment is likely a consequence of adverse field conditions, which negatively impacted grain development. This, in turn, compromises both flour yield and quality.

4.3. Test Weight and Thousand-Grain Weight

The test weight (TGW) (or hectolitre weight) is the measure that indicates the specific weight of the grain; this unit of measurement is used as a marketing parameter in several countries and is also related to the potential yield of flour [17]. The lowest test weights in Uberaba in the Senna (75.92 kg hL^{-1}), Feroz (75.32 kg hL^{-1}), and Guardião (76.79 kg hL^{-1}) genotypes and in Arapongas in the Senna genotype (76.41 kg hL^{-1}) suggest that these genotypes were subjected to thermal or water stress during grain filling [18]. For the other genotypes, the test weight ranged from 77.03 to 81.04 kg hL^{-1}, similar to the results of [18] who analyzed the quality parameters of 15 wheat genotypes grown in Sonora, Mexico. These authors observed a variation in the test weight of 77.2–80.7 kg hL^{-1}, indicating adequate grain filling. In general, the highest thousand-grain weight values were found in the Guardião genotype (39.85 to 44.79 g) and the lowest in the 1403 genotype (27.18 to 32.09 g) and are related to the specific characteristics of these genotypes. A study carried out by [19] analyzed the grain yield of elite wheat genotypes under water stress and irrigation. These authors reported that under irrigated conditions, the weight of a thousand grains varied from 36.6 to 47.9 g, while under non-irrigated conditions, it varied from 26.4 to 40.6 g. The genotypes with the highest TGW in both systems showed some resistance to drought. These results indicate that the Guardião genotype may have better adaptability to the climatic conditions in the environments reported in the current study.

4.4. Colorimetric Profile

There is currently no established correlation in the literature between b*-value and the baking properties or technological quality parameters of wheat flour. However, flour color remains a critical quality attribute, significantly influencing consumer acceptance both of the flour and of the final baked products. The L*-value, which reflects flour brightness, is known to be influenced by the milling process and the flour's degree of refinement, including factors such as ash content, protein levels, pigment concentration, and the amount of damaged starch [20]. In the present study, no statistically significant differences in L*-value were observed among genotypes or cultivation environments, although values ranged from 84.62 to 92.70. The b*-value, which indicates the yellow hue of the flour, is primarily associated with carotenoid content [21]. These naturally occurring yellow pigments influence the crumb color of baked products and are often considered undesirable in bread production, particularly in regions where a whiter crumb is preferred. The consistently lower b*-values observed in the Madrepérola genotype suggest its potential suitability for producing flours with high consumer acceptance regarding crumb color.

4.5. Solvent Retention Capacity

The solvent retention capacity (SRC) test evaluates the ability of wheat flour (*Triticum aestivum* L.) to retain different solvents, serving as an effective tool to assess key technological and compositional attributes such as pentosan content, starch damage, gluten strength, and overall water absorption capacity [22]. Among these, water retention capacity is directly associated with the flour's ability to absorb water, a critical factor in the development of dough viscoelasticity and, consequently, in bread yield and quality [23]. Technologically, water plays a multifaceted role in dough formation by promoting gluten development, regulating dough consistency, dissolving salts, hydrating starch for improved digestibility, and enabling enzymatic activity [24]. In this study, the highest SRC-water values were generally observed in the Destak genotype, regardless of the cultivation environment, suggesting greater potential for water absorption and dough strength. The SRC with sodium carbonate reflects the degree of starch damage in the flour and is indicative of grain hardness. On the other hand, the sucrose SRC is associated with the presence and properties of water-soluble arabinoxylans (pentosans) and gliadins, which influence the functionality and extensibility of the dough matrix [25].

In the present study, no significant differences were observed in the retention capacities of sodium carbonate and sucrose across the evaluated genotypes and cultivation environments. The lactic acid SRC is commonly used as an indicator of glutenin content, a key protein associated with gluten strength and dough elasticity, both of which directly impact bread-making performance [25]. Flours exhibiting SRC-lactic acid values above 100% are generally considered suitable for bread production, as they are indicative of strong gluten-forming potential. In contrast, flours with values below 100% are typically associated with weaker gluten and are more appropriate for biscuit manufacturing [26]. According to the results obtained in this study, all genotypes, regardless of cultivation environment, presented SRC-lactic acid values exceeding 100% (ranging from 132.73% to 205.09%), thereby demonstrating suitability for bread-making applications.

4.6. Hagberg Falling Number

The falling number measures the activity of the α-amylase enzyme, where low values indicate low enzymatic activity, and high values indicate high enzymatic activity [27]. The enzymatic activity can be classified as low (≥351 s), ideal (201–350 s), and high (≤200 s). The optimal falling number value depends on the purpose of the flour, where for the manufacture of pasta, the falling number must be greater than 350 s, for the manufacture of bread and fermented biscuits, between 225 and 275 s, and for the manufacture of cakes and sweet biscuits, between 200 and 250 s [27]. In the present study, only the Madrepérola genotype cultivated in Uberaba, and Senna and Feroz cultivated in Arapongas presented a falling number lower than 350. For the other genotypes, according to the falling number (>350 s), they are suitable for manufacturing mass.

The falling number test evaluates the activity of the α-amylase enzyme, where lower values indicate higher enzymatic activity, and higher values reflect reduced enzyme activity [27]. Enzymatic activity is typically classified as low (≥351 s), optimal (201–350 s), or high (≤200 s). The optimal range of falling number values depends on the intended use of the flour: for pasta production, values above 350 s are preferred; for bread and leavened biscuit production, values between 225 and 275 s are ideal; and for cakes and sweet biscuits, values should range from 200 to 250 s [27]. In the present study, only the Madrepérola genotype grown in Uberaba and the Senna and Feroz genotypes grown in Arapongas showed falling number values below 350 s. For all other genotypes, falling number values exceeded 350 s, indicating their potential suitability for pasta production.

4.7. Alveography

Tenacity is the quality parameter that measures the resistance of the gluten mass and is associated with the glutenin content [28]. The highest tenacity values observed in the Guardião genotype suggest better adaptability of this genotype to growing conditions, mainly in the Uberaba (203.25 mm) and Arapoti (160.25 mm) environments. As for the Madrepérola genotype, the lowest values of tenacity (46.25–64.25 mm) were observed, making the gluten mass less resistant. Extensibility, on the other hand, is related to the fraction of gluten called gliadins and is associated with the ability to extend the dough without breaking it [29]. The lowest extensibility values were found in genotype 1403 (Passo Fundo) and in Guardião genotype (Arapoti and Uberaba) which suggests a low adaptability of these genotypes in these environments, resulting in low-quality bread. Wheat flour is graded according to gluten strength as medium ($<200 \cdot 10^{-4}$ J), medium strong (201 to $300 \cdot 10^{-4}$ J), and strong (301 to $400 \cdot 10^{-4}$ J). Gluten strength is directly related to baking capacity and quality, where medium strong and strong gluten is indicated for bread production, and medium gluten is used for the production of confectionery and biscuits [26]. Only for the Madrepérola genotypes cultivated in Arapongas and Passo Fundo, a gluten strength lower than $200 \cdot 10^{-4}$ J (average) was observed, making them unsuitable for the production of bread. In general, all treatments obtained adequate gluten strength values for bread production. The identification of the adaptability of new genotypes to cultivation in the Brazilian Savannah biome for bread production represents a significant advancement in the expansion of globally productive agricultural areas, particularly in the context of climate change, which threatens crop stability in traditionally productive regions such as Southern Brazil.

4.8. Global Overview of Differences in Baking Properties and Quality Parameters of Wheat Genotypes Cultivated in the Atlantic Forest and Savannah Biomes by Multivariate Analysis

The main differences in baking properties and quality parameters among the genotypes grown in different Brazilian biomes were observed through multivariate analysis. The graphical representation of the unsupervised principal component analysis PCA score and the heatmap of each genotype is shown in Figures 2 and 3.

The first two principal components (PC) of the PCA of the wheat genotypes Destak, 1403, Madrepérola, Senna, Feroz, and Guardião explain 76.8, 85.3, 81.1, 76.5, 69.9, and 85.2% of the total variability among the baking properties and quality parameters in the growth environments, respectively, confirming the variations in the wheat characteristics cultivated in different locations. In the PCA-score analysis, it was also possible to observe that wheat grains cultivated in Atlantic Forest biome (E1, E2, and E3) differed from grains cultivated in Savannah biome (E4 and E5), mainly in genotypes 1, 2, 3 (Figure 2A,C,E), and 4 (Figure 2A). In the heatmap analysis, it was observed that genotype Destak cultivated in Atlantic Forest biome showed a tendency to increase fiber, L*-value, and solvent retention capacity in water and lactic acid; however, when it was cultivated in Savannah biome, an increased in TGW, gluten strength, starch, test weight, and ash was observed (Figure 3A). The genotype 1403 showed higher contents of protein and shrunken grains when cultivated in Atlantic Forest, while when it was cultivated in Savannah biome, higher values of burned grains, insect damaged, starch, gluten strength, test weight, and TGW were detected (Figure 2D). An increase in fiber and solvent retention capacity in lactic acid were observed in genotype Madrepérola cultivated in Atlantic Forest, though the contents of starch, b*-value, extensibility, and gluten strength were higher in grains grown in the Savannah biome (Figure 2F). In addition, genotype Senna grown in the Atlantic Forest area stood out for the highest fiber values, and when grown in the Savannah area, it showed greater values of starch, but also insect damage, lipid, burned grains, b*-value, tenacity, ash content, and gluten strength (Figure 3B). Genotype Feroz cultivated in the Atlantic Forest biome showed higher values of fiber, extensibility, lipid, insect damage, and lower values of starch and b*-value when cultivated in the Savannah biome (Figure 3D). Genotype Guardião showed higher values for shrunken grain, L*-value, and fiber content when grown in Atlantic Forest, whereas when it was cultivated in the Savannah biome, it showed higher tenacity, gluten strength, falling number, solvent retention capacity in water, sucrose and sodium carbonate, insect damage, lipid, and starch (Figure 3F).

In general, wheat genotypes grown in Atlantic Forest demonstrated a tendency in increased fiber and L*-values, whereas when they were cultivated in the Savannah biome, the contents of starch, protein, properties of gluten (gluten strength and tenacity), burned grain, and insect-damaged grain tended to be higher (Figure 4A). As shown in Figure 4B, a positive correlation between gluten strength, tenacity, and a*-value was observed. Starch content, burned grain, and insect-damaged grain also showed a positive correlation. Solvent retention capacity in water, sucrose, and sodium carbonate demonstrated a positive correlation. In addition, other important interactions between the technological properties of wheat genotypes were observed, as shown in Figure 4C. For instance, there is a strong positive correlation between gluten strength and tenacity, and a negative correlation between tenacity and extensibility. Starch content showed a negative correlation with fiber and shrunken grains, while fiber content and shrunken grains demonstrated a positive correlation. Burned grains also showed a strong positive correlation with insect damage and starch content.

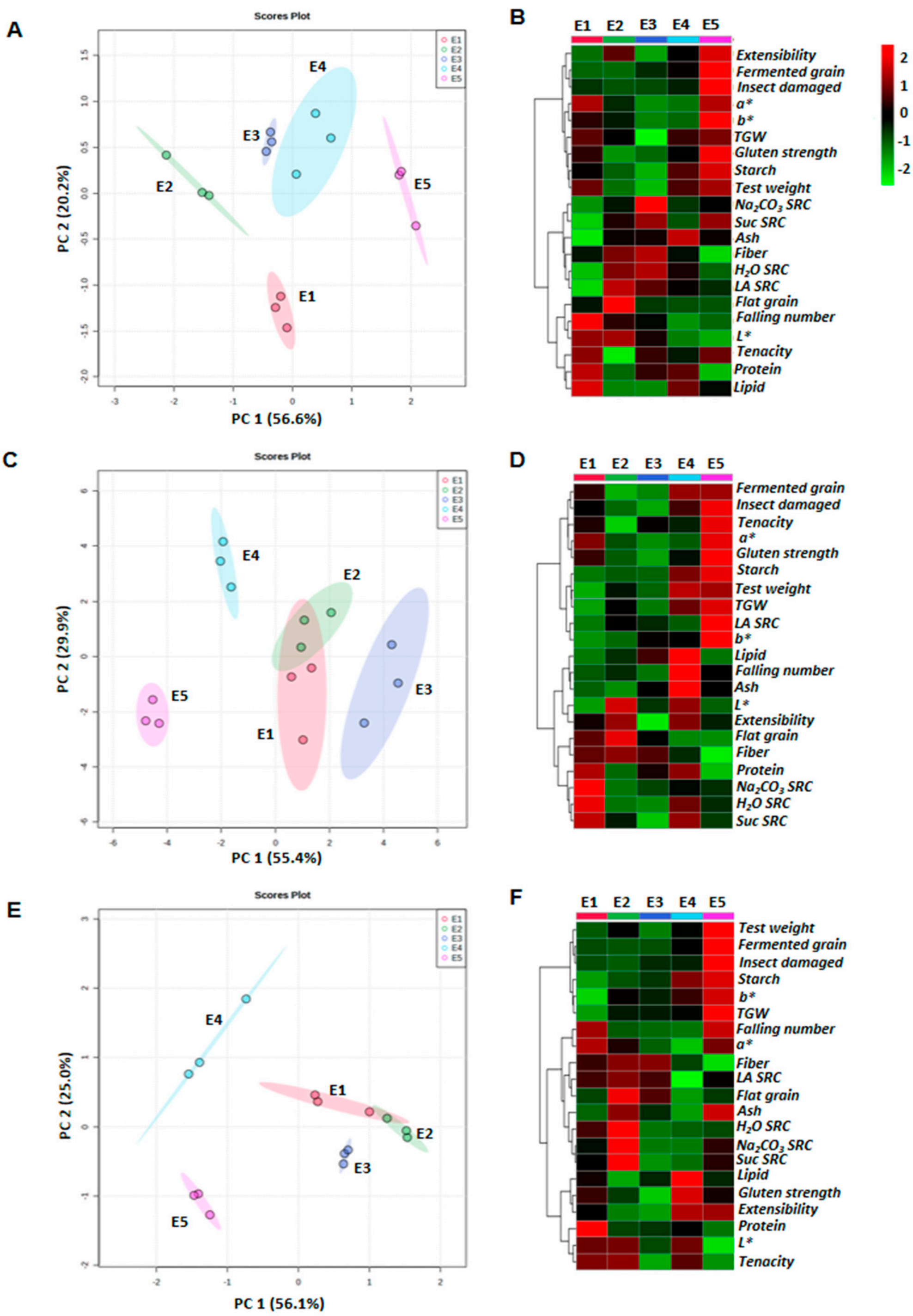

Figure 2. Comparison of baking properties and quality parameters of wheat genotypes grown in different Brazilian environments. Graphical representation of unsupervised principal component analysis PCA score and heatmap representing the major sources of variability in baking properties and quality parameters in genotype Destak (**A**,**B**), genotype 1403 (**C**,**D**), and genotype Madrepérola (**E**,**F**), respectively. The color scale represents the variation in the relative concentration of the physicochemical parameters, from high (red) to low (green) content. E1, Arapoti; E2, Arapongas; E3, Passo Fundo; E4, Uberaba; E5, São Gotardo.

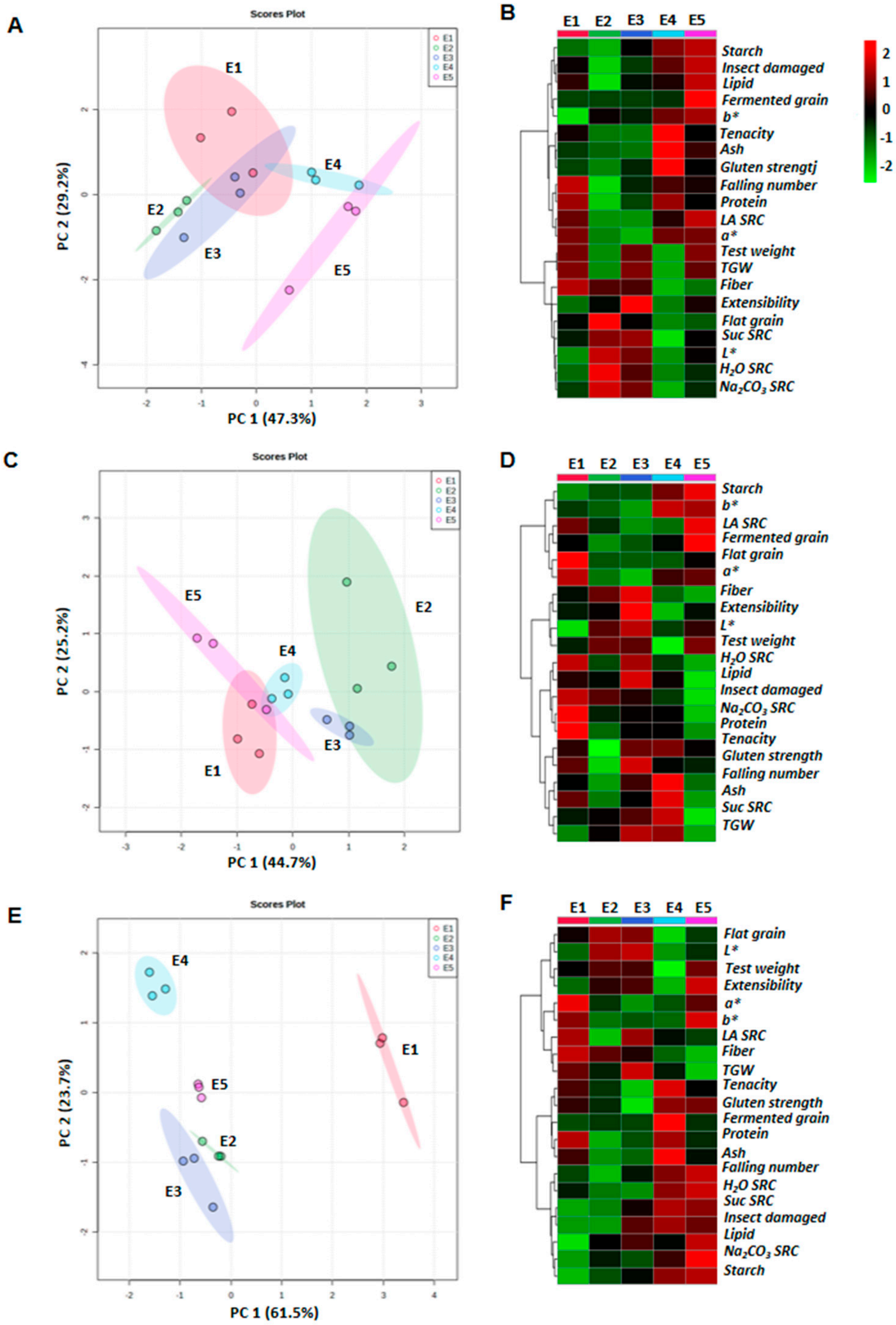

Figure 3. Comparison of baking properties and quality parameters of wheat genotypes grown in different Brazilian environments. Graphical representation of unsupervised principal component analysis PCA score and heatmap representing the major source of variability in baking properties and quality parameters in genotype Senna (**A**,**B**), genotype Feroz (**C**,**D**), and genotype Guardião (**E**,**F**), respectively. The color scale represents the variation in the relative concentration of the physicochemical parameters, from high (red) to low (green) content. E1, Arapoti; E2, Arapongas; E3, Passo Fundo; E4, Uberaba; E5, São Gotardo.

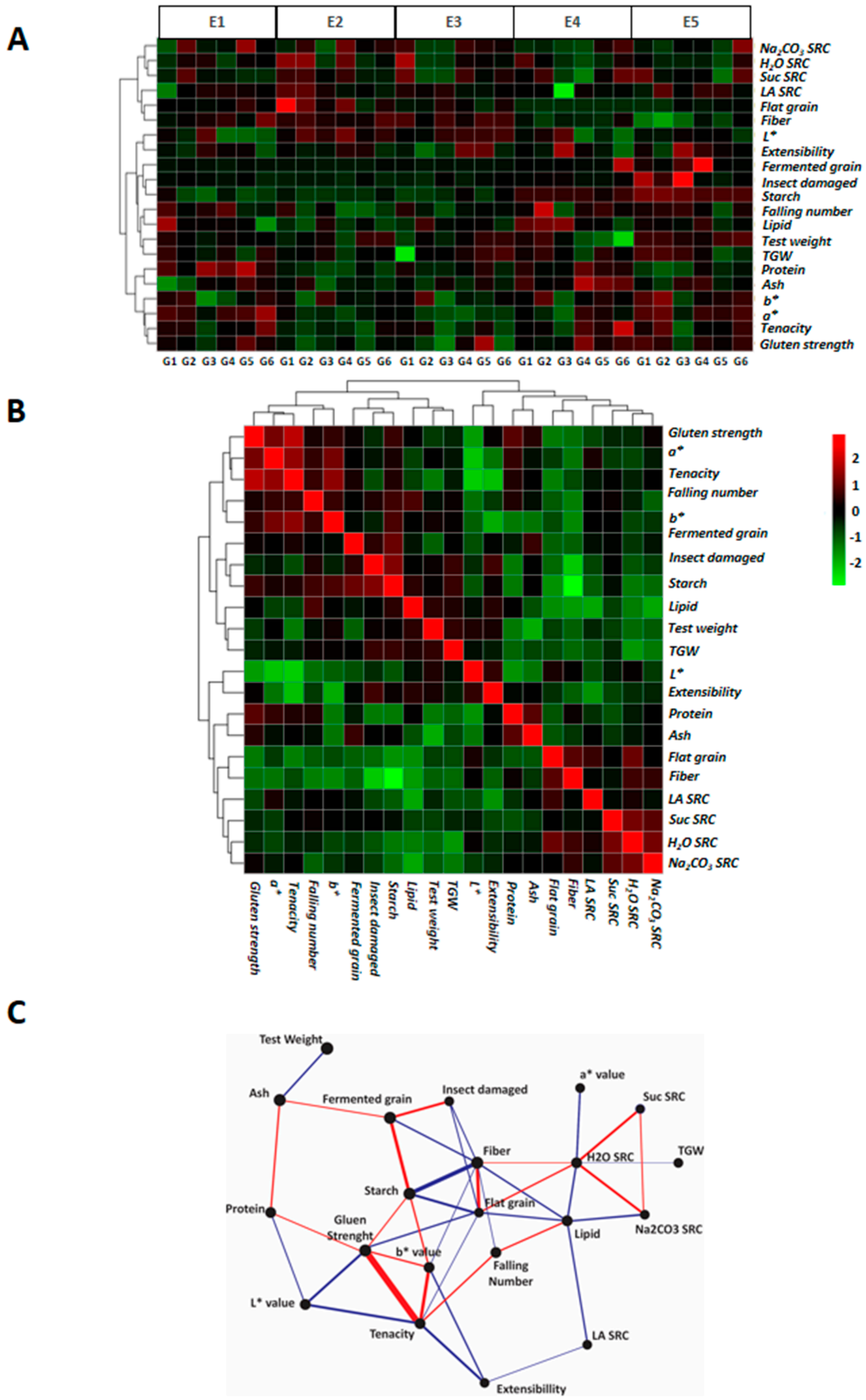

Figure 4. Comparison of baking properties and quality parameters of wheat genotypes grown in different Brazilian environments. Graphical representation heatmap analysis (**A**), Pearson's correlation heatmap (**B**) and Debiased Sparse Partial Correlation (DSPC) network (**C**) representing the major source of variability in baking properties and quality parameters in genotypes Destak (G1), 1403 (G2), Madrepérola (G3), Senna (G4), Feroz (G5), and Guardião (G6). The color scale of heatmaps represents the variation in the relative concentration of the baking properties and quality parameters, from high (red) to low (green) content. In DSPC network, the red lines indicate positive correlations, while the blue lines represent negative correlations. The line thickness is proportional to the magnitude of the correlation. E1, Arapoti; E2, Arapongas; E3, Passo Fundo; E4, Uberaba; E5, São Gotardo.

5. Conclusions

The results indicated that the Destak, 1403, Madrepérola, and Senna genotypes exhibited superior agronomic and technological performance in the Brazilian Savannah, characterized by higher starch content in the grains, gluten strength, and dough tenacity, key attributes for breadmaking. In the Atlantic Forest biome, genotypes Destak, 1403, Senna, and Guardião stood out due to their higher protein content. The Madrepérola genotype, also cultivated in this biome, showed technological suitability for cookie production. These findings support the establishment of quality standards tailored to each biome, contributing to a more sustainable wheat production system through optimized resource use and increased productivity. Furthermore, strategies such as no-tillage farming, which enhances soil organic matter, while reducing erosion and crop rotation, thereby improving nutrient cycling and disrupting pest life cycles, should be considered to support wheat cultivation in the Savannah area. Given the Brazilian Savannah's proven potential for high-quality wheat production, particularly for breadmaking, breeding programs should prioritize genotypes such as Destak and Senna, while public policies should encourage the expansion of wheat cultivation in the region. These measures can mitigate environmental impacts and promote compensatory sustainability practices, ensuring that unavoidable damage is offset by responsible agricultural actions.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su17125236/s1, Table S1: Analysis of variance for baking properties and quality parameters of wheat genotypes grown in different environments.

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