

Research Article

Functional Quality of Brazilian Barley: How Temperature and Rainfall Modulate β -Glucan and Dietary Fiber Levels

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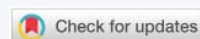
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Keywords: Barley cultivars; Genetic factors; Bioactive compounds; β -glucan; Dietary fiber



Abstract

The objective of this study was to evaluate the impact of genotype and growing environment on the β -glucan and dietary fiber (DF) content of whole grain barley cultivars grown in Brazil. Cultivars BRS 225, BRS 195, and MN 743 were cultivated during the 2008 and 2009 crop years across two distinct locations (Passo Fundo and Victor Graeff). Analytical quantification followed AACC protocols for moisture, protein, and fiber fractions, while β -glucan was determined using the McCleary enzymic method. Significant differences ($p < 0.05$) were identified among genotypes and environments regarding β -glucan, total dietary fiber (TDF), soluble dietary fiber (SDF), and insoluble dietary fiber (IDF). Environmental variables, specifically air temperature, insolation, and rainfall, played a decisive role in fiber accumulation. Higher air temperatures and increased insolation were positively correlated with β -glucan levels, whereas rainfall generally exerted a negative influence. The substantial variation observed within the same location across different years underscores the necessity of considering both genetic potential and specific climatic windows to optimize the functional and nutritional quality of Brazilian barley.

Introduction

The investigation of natural products containing bioactive compounds is critical, given their role in modulating human physiology and delaying the onset of chronic degenerative diseases [1,2]. Cereal grains serve as primary sources of these constituents, with barley (*Hordeum vulgare* L.) being specifically recognized for its high concentration of dietary fiber (DF) and other health-promoting molecules [3-5]. Of particular interest are the mixed linkage (1,3)-(1,4)- β -D-glucans (β -glucan), which constitute a significant portion of barley's soluble fiber fraction. These compounds have been clinically linked to the reduction of plasma cholesterol, improved lipid metabolism, attenuation of the glycemic response, and a potential decrease in cancer risk [6-9].

Barley is a premier source of bioactive compounds, primarily (1,3;1,4)- β -D-glucan and total dietary fiber, which are recognized for their role in reducing glycemic index and serum cholesterol. The accumulation of these non-starch polysaccharides is a complex interplay between genetic potential and environmental stressors during the crop cycle.

Despite its robust nutritional profile, the chemical composition of barley is subject to considerable variability dictated by the interaction between genotype and environmental conditions, presenting a significant challenge for industrial processors and end-users [10,11]. Although barley is recognized as an ecologically plastic species, the specific influence of regional Brazilian macroclimates on its fiber fractions requires precise characterization to ensure nutritional consistency [3].



To bridge this knowledge gap, the 2008 and 2009 crop years provide an essential historical baseline for evaluating this plasticity, as they featured distinct meteorological contrasts ranging from optimal isolation to excessive rainfall. Specifically, the 2008 season represented a climatic ideal for fiber synthesis, marked by elevated temperatures and solar radiation, while the 2009 season mimicked the extreme rainfall patterns that have since become more frequent in Southern Brazil and worldwide due to shifting climatic cycles. Understanding these foundational genotype-environment (G \times E) interactions is therefore critical for developing the predictive models and management strategies needed to maintain grain functional quality in the current agricultural landscape.

This study provides an essential historical baseline required to understand the ecological plasticity of barley under high climatic variability. This period serves as a critical reference point for observing the crop's physiological resilience to meteorological anomalies, establishing a technical foundation for comparing contemporary harvest quality trends across divergent geographical regions.

Recent advancements in cereal science have highlighted how weather-induced stress dictates nutrient deposition. Khaleghdoust, et al. [12] and Karaman, et al. [13] have demonstrated that climatic fluctuations trigger specific biochemical pathways, such as the differential regulation of sucrose synthase and cellulose synthase-like (CslF) genes, which determine the final ratio of starches to fibers in the cereal endosperm. Environmental variables, particularly the timing of precipitation relative to anthesis, act as the primary drivers for nutrient translocation efficiency.

Thus, the objective of this study was to determine the effects of air temperature, isolation degree, and rainfall amount on the β -glucan and DF contents in whole grain barley cultivars grown in Brazil, thereby identifying the environmental parameters that maximize grain quality.

Materials and methods

Materials

The experimental design utilized Brazilian whole grain barley cultivated across varied environmental sites. Meteorological monitoring focused on the critical grain-filling stage (July in the Southern Hemisphere), tracking mean temperature departures and cumulative rainfall. The study evaluated three barley cultivars: BRS 225, BRS 195, and MN 743. Samples were obtained from the 2008 and 2009 crop years, utilizing three replications from field trials coordinated by Embrapa Trigo in Passo Fundo. Experimental sites were located in Victor Graeff (VG) and Passo Fundo (PF), Rio Grande do Sul, Brazil. Sowing was performed in the first half of June. Harvesting was executed in the last week of October (Victor Graeff) and the second week of November (Passo Fundo).

Meteorological data, including air temperature (measured specifically at 12 a.m.), insolation degree, and rainfall, were sourced from the National Institute of Meteorology [14].

Tests on Barley Samples

Moisture and protein (N \times 6.25) were determined according to AACC Methods 44-01, 46-12, and 55-10 [15]. The analytical quantification of β -glucan was quantified via the McCleary Enzymic Method [16] [16] using Megazyme assay kits. This procedure involved the enzymatic depolymerization of β -glucan using endo-(1,3)-(1,4)- β -glucan 4-glucanohydrolase (lichenase), followed by hydrolysis to glucose with purified β -D-glucosidase, with subsequent glucose quantification via the glucose oxidase-peroxidase method. TDF and its fractions were determined using the enzymatic-gravimetric approach AACC Method 32-07 [15]. Samples underwent sequential enzymatic digestion using heat-stable α -amylase (Novo Nordisk A/S, Bagsvaerd, Denmark), amyloglucosidase, and protease (Sigma, St. Louis, MO, USA). SDF was precipitated with ethyl alcohol, and TDF residues were corrected for protein, ash, and blank values. SDF was calculated as the difference between TDF and IDF.

Statistical analysis

Data were processed using the System for Analysis and Separation Averages in Agricultural Experiment (SASM-Agri, version 4) [17]. Mean differences were analyzed using Scott-Knott's test and the Least Significant Difference (LSD) test at a significance level of $p < 0.05$.

Results

Fiber composition by location and genotype

The analytical results for fiber fractions and β -glucan content are summarized in Table 1 (Passo Fundo) and Table 2 (Victor Graeff).

Descriptive analysis of fiber content

Statistically significant differences in TDF were localized

Table 1: β -glucan and total dietary fiber contents in Passo Fundo (PF).

Barley lines (L)	β -glucan (%)	TDF (%)	Soluble fiber (%)	Insoluble fiber (%)
2008				
BRS 195	2.64 a	24.91 b	7.03 a	17.87 b
BRS 225	2.74 a	27.42 a	4.82 c	22.60 a
MN 743	2.76 a	25.47 b	5.83 b	19.64 b
Mean value	2.71	25.93	5.89	20.04
Std. dev.	0.06	1.32	1.11	2.39
2009				
BRS 195	1.30 b	22.72 b	4.25 d	18.47 b
BRS 225	1.43 b	26.37 a	3.73 d	22.64 a
MN 743	1.72 b	28.85 a	5.73 b	23.12 a
Mean value	1.48	25.98	4.57	21.41
Std. dev.	0.22	3.08	1.04	2.56

Means with the same letter within a column are not significantly different ($p < 0.05$) by LSD analysis. A Dry weight basis.

**Table 2:** β -glucan and total dietary fiber contents in Victor Graeff (VG).

Barley lines (L)	β -glucan (%)	TDF (%)	Soluble fiber (%)	Insoluble fiber (%)
2008				
BRS 195	1.65 d	24.05 a	7.13 a	16.92 b
BRS 225	2.61 b	23.70 a	6.36 b	17.34 b
MN 743	3.31 a	25.52 a	4.05 d	21.47 a
Mean value	2.52	24.42	5.85	18.58
Std. dev.	0.83	0.97	1.60	2.51
2009				
BRS 195	1.64 d	25.13 a	7.50 a	17.64 b
BRS 225	1.42 e	25.63 a	4.54 d	21.10 a
MN 743	1.82 c	22.68 a	5.34 c	17.33 b
Mean value	1.63	24.48	5.79	18.69
Std. dev.	0.20	1.58	1.53	2.09

Means with the same letter within a column are not significantly different ($p < 0.05$) by LSD analysis. A Dry weight basis.

to Passo Fundo (Table 1), where the highest values were recorded in MN 743 (2009) and BRS 225 (2008/2009). In Victor Graeff (Table 2), no significant differences were observed among cultivars for TDF. Regarding SDF, BRS 195 consistently demonstrated the highest contents across both locations and years. IDF values were significantly higher in MN 743 (2009) and BRS 225 (2008/2009) in PF, while in VG, the samples MN 743 (2008) and BRS 225 (2009) exhibited the highest insoluble fractions.

Environmental correlations

In Passo Fundo, the mean β -glucan content was significantly higher in 2008 (2.71%) compared to 2009 (1.48%), a trend directly corresponding to the higher mean air temperatures and more intense insolation recorded during the 2008 growth cycle [14]. Recent studies, such as Khaleghdoust, et al. [12], reinforce these findings by demonstrating that annual weather conditions have a more profound impact on β -glucan levels than nitrogen fertilization, confirming the primacy of environmental factors over chemical management. A similar positive correlation between temperature and β -glucan was observed in Victor Graeff, where higher average temperatures promoted higher accumulation across genotypes (2.52% mean in 2008 vs. 1.63% in 2009). Notably, isolation data for Victor Graeff was unavailable and could not be correlated. Rainfall exhibited a distinct negative correlation with β -glucan content in both regions. In PF, the 2009 crop year, characterized by significantly higher rainfall, resulted in a marked decrease in β -glucan (1.48%) compared to the drier 2008 year. This negative trend was consistent in VG, with the single exception of BRS 195 in 2009, which maintained stable levels despite increased precipitation [14]. This phenomenon is supported by contemporary evidence suggesting that excessive precipitation during the grain-filling period can lead to the leaching of glucose, the primary precursor of β -glucans, from the flag leaf and awns, or cause structural polymer degradation. Furthermore, thermal stress during grain filling affects the duration of nutrient deposition. Higher temperatures favor the synthesis of specific fiber polymers, while extreme heat may shorten the filling window, impacting grain weight and

final bioactive concentration [18]. The 2008–2009 Brazilian data reveal that when early-season conditions are warm and dry, followed by timely rainfall during the vegetative phase, barley yields stabilize but undergo significant chemical reorganization.

Discussion

Climate variance

The β -glucan levels identified in this study are consistent with the known range for barley (2.5% to 11.3%), which typically exceeds the concentrations found in oats, rye, or wheat [4,19]. Our data confirms that the synthesis of these compounds is a highly plastic trait influenced by the synergy of genetics and environment [4,11]. The positive correlation between air temperature and β -glucan accumulation aligns with the findings of Ehrenbergerová, et al., suggesting that thermal levels during the grain-filling stage are critical for enzymatic pathways involved in fiber synthesis [20]. The negative impact of rainfall on β -glucan content corroborates the mechanisms proposed by Aastrup, who suggested that precipitation may degrade established β -glucans or inhibit their synthesis. Furthermore, rainfall may lead to the leaching of glucose, a critical metabolic precursor for β -glucan synthesis, from the flag leaf and awns [21]. High precipitation is also known to reduce grain viscosity, which is positively correlated with the water-soluble β -glucan fraction [21,22]. These observations are supported by findings in Finnish oats, where cold, rainy weather suppressed β -glucan levels [22], and Montana barley studies, where hot, dry years yielded maximum concentrations [23,24]. Our results also indicate that TDF levels often mirror IDF trends; specifically, in PF during 2009 (high rainfall/low isolation), TDF remained high primarily due to an increase in the insoluble fraction, even as soluble β -glucans decreased. According to Khaleghdoust et al., environmental factors account for up to 90% of the variance observed in barley fiber synthesis. This scenario confirms that while genetics define the potential range of the crop, environmental conditions during the critical grain-filling stage act as the ultimate determinants of bioactive compound concentration [12]. Excessive rainfall, for example, inhibits β -glucan synthesis through two primary mechanisms: first, precipitation causes the leaching of glucose, the essential metabolic precursor for fiber synthesis, from the flag leaves and awns; second, rain can physically degrade established polymers or inhibit enzymatic synthesis pathways [25]. During the 2009 crop year in Passo Fundo, a metabolic “compensation effect” was identified: despite the drop in soluble β -glucan levels caused by excessive rain and low isolation, total dietary fiber (TDF) levels remained high, reaching 28.85% in cultivar MN 743. This occurs because environmental stress forces the plant to shift carbon allocation toward the insoluble dietary fiber (IDF) fraction, prioritizing the maintenance of the grain’s structural integrity over the synthesis of soluble bioactives. Thus, temperature and rainfall operate as the



primary modulators of fiber synthesis and the subsequent dilution of bioactive compounds by starch accumulation. Recent studies indicate that climate fluctuations regulate the activity of sucrose synthase, an enzyme that, under lower and favorable temperatures, prioritizes the conversion of sucrose into amylopectin. This biochemical prioritization results in higher starch content and significantly lower gelatinization temperatures, observed as 2 to 3 °C lower in cooler years, while a simultaneous reduction occurs in the synthesis of cell wall polysaccharides, such as fibers [12,13].

Integrated Results: Genotype and Environmental Effects on Barley Fiber and β -Glucan

1. Overview of nutritional composition analysis

This study provides a rigorous evaluation of the nutritional and bioactive profiles of whole grain barley cultivars (BRS 225, BRS 195, and MN 743) grown under diverse environmental conditions in southern Brazil. Our analysis focused on the concentrations of total dietary fiber (TDF), soluble dietary fiber (SDF), insoluble dietary fiber (IDF), and β -glucan. Statistical evaluation using Scott-Knott's test and the Least Significant Difference (LSD) method revealed significant differences ($p < 0.05$) across genotypes, geographical locations, and crop years. These findings underscore the complex interplay between genetic potential and environmental variables, specifically temperature, rainfall, and isolation, in determining the final biochemical composition of the grain.

2. Cultivar performance in passo fundo

In the Passo Fundo location, the fiber composition demonstrated significant inter-annual and genotypic variance. The quantitative results, expressed on a dry weight basis, are detailed in Table 1. A comprehensive Passo Fundo data profile indicates that the highest TDF values were achieved by MN 743 in crop year 2009 and BRS 225 in both crop years 2008 and 2009. Conversely, the lowest TDF concentrations were recorded for BRS 195 across both years and MN 743 in crop year 2008. Regarding soluble fractions, BRS 195 reached the maximum SDF content in crop year 2008. A significant shift in β -glucan accumulation was observed between years. The 2008 crop year yielded a significantly higher mean than the 2009 crop year. The 2009 Passo Fundo crop year serves as a definitive "stress case." The extreme water/thermal imbalance likely triggered a robust antioxidant response. According to Rolim et al., such stress induces the upregulation of Superoxide Dismutase (SOD), Catalase (CAT), and Ascorbate Peroxidase (APX) to mitigate oxidative damage. This is accompanied by an "osmotic adjustment" where the plant diverts metabolic resources toward soluble sugars and amino acids, often at the expense of endosperm β -glucan accumulation [18].

3. Cultivar performance in Victor Graeff

The nutritional data from the Victor Graeff trials, presented in Table 2, revealed a distinct pattern of environmental

stability for certain fiber components compared to Passo Fundo. Notably, no statistically significant differences ($p < 0.05$) were observed for TDF among cultivars in Victor Graeff. This suggests a higher degree of environmental stability for total fiber in this region. However, β -glucan content remained highly variable, with MN 743 achieving the maximum value in crop year 2008. BRS 195 consistently demonstrated the highest SDF values across both 2008 and 2009. The highest IDF concentrations in this location were observed in MN 743 (2008) and BRS 225 (2009).

4. Environmental and climatic impact analysis

Synthesizing the meteorological data with the biochemical results confirms that environmental conditions during the grain-filling period are decisive factors in barley quality.

- **Temperature and Insolation:** A strong positive correlation exists between higher mean air temperatures, intense solar radiation, and β -glucan synthesis. This was explicitly demonstrated in Passo Fundo during crop year 2008, where elevated temperature and isolation averages favored higher β -glucan content. In Victor Graeff, higher air temperatures similarly stimulated β -glucan accumulation; however, due to the lack of available insolation data for that site, a direct correlation with sunlight could not be established.
- **Rainfall and Biochemical Degradation:** High rainfall levels exerted a predominantly negative influence on β -glucan content in both locations (the sole exception being BRS 195 in Victor Graeff during 2009). This decline is likely due to the mechanical and biochemical effects of precipitation, which can degrade β -glucans, inhibit their synthesis, or lead to the leaching of glucose, the primary metabolic precursor for β -glucan, from the flag leaf and awns.
- **Interaction and Fraction Drivers:** The study identified that specific climatic profiles favor different fiber fractions. Crop year 2009, marked by higher rainfall and reduced isolation, was characterized by increased TDF and IDF content. Analysis suggests that the insoluble fraction (IDF) serves as the primary driver for TDF fluctuations. Conversely, crop year 2008, featuring higher temperatures and more intense isolation, favored the accumulation of soluble dietary fiber and β -glucan.

Statistical compliance and notation

All comparative assessments regarding the performance of cultivars (e.g., "highest" or "lowest") are strictly corroborated by the statistical groupings indicated by Tables 1 and 2, determined via Scott-Knott's test and LSD analysis. All claims of significance are maintained at the $p < 0.05$ level. These results confirm that while the genotype establishes



the baseline potential for nutritional quality, environmental factors, particularly the temperature/isolation to rainfall ratio, play a decisive role in the final expression of bioactive compounds in Brazilian barley.

Limitations and future directions

This study acknowledges certain contextual limitations, including the focus on two specific crop years and the regional scope within Southern Brazil. Furthermore, the unavailability of isolation data for Victor Graeff prevented a direct correlation analysis between solar radiation and grain quality at that specific site. Future research should expand this assessment to include newer Brazilian cultivars and investigate the impact of modern extreme weather events, such as intensified El Niño and La Niña oscillations, on the functional stability of barley bioactive compounds.

Conclusion

This study confirms that environmental and genetic factors interact to determine the functional fiber profile of barley grown in Brazil. Climatic variables are particularly influential: higher air temperatures and insolation promote the accumulation of soluble β -glucans, whereas excessive rainfall negatively impacts these bioactive components. The significant inter-annual variation observed at the same geographical locations highlights the importance of identifying specific climatic windows to maximize grain quality. These findings provide a framework for breeding and management strategies aimed at enhancing the nutritional value of Brazilian barley for human consumption. In summary, the temperature-to-rainfall ratio is established as the decisive modulator of the functional quality of Brazilian barley. While high cumulative solar irradiance and elevated temperatures are essential parameters for maximizing glucan levels, excessive rainfall acts as the primary inhibitor of this process, either through the leaching of metabolic precursors (such as glucose) or by shifting carbon allocation toward the synthesis of insoluble structural fibers at the expense of soluble fractions. As future directions, to address the biochemical degradation induced by climatic variability, subsequent research must incorporate transcriptomic analysis of Cellulose Synthase-Like (CslF) enzymes, which are primarily responsible for β -glucan synthesis in the endosperm. It is critical to determine whether excessive rainfall causes mere physical leaching or triggers the genetic down-regulation of CslF genes. Furthermore, testing modern cultivars under controlled stress conditions to simulate extreme El Niño scenarios will be essential for ensuring the nutritional stability and food security of high-quality functional grains in the contemporary agricultural landscape.

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Ethical and conflict of interest statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The integrity of the data and the accuracy of the analyses are the sole responsibility of the authors.

Author contributions statement

According to the affiliations and the scope of the study, the contributions were distributed as follows:

Aline Sobreira Bezerra (ASB): Conceptualization, experimental design, data collection, laboratory analyses, and writing of the original draft of the manuscript.

José Laerte Nörnberg (JLN): Technical supervision, academic guidance, and critical review of the manuscript.

Leandro Machado de Carvalho (LMC): Technical supervision, academic guidance, and review of the document.

Simoní da Ros (SR): Support in the interpretation of functional data, laboratory analyses, and final English language revision.

Euclides Minella (EM): Coordination of field trials at EMBRAPA Trigo and provision of barley samples.

Data availability statement

The meteorological data used in the study (temperature, precipitation, and insolation) were obtained from the National Institute of Meteorology (INMET). All analytical data regarding fiber composition and β -glucan supporting the findings of this study are included in the results tables within the manuscript.

Statistical Validation Details

Data were processed using the SASM-Agri (version 4) software. The adopted statistical procedures were:

Procedures: One-way analysis of variance (ANOVA) was performed to evaluate the effects of genotype and environment.

Mean tests: Significant differences between means were identified and located using the Scott-Knott test and the Least Significant Difference (LSD) test.

Significance level: All analyses were maintained at a confidence level of $p < 0.05$.

Assumptions: The analyses were based on standard assumptions of normality and homogeneity of variance required by parametric tests applied in agricultural experiments.



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