JMBFS
Journal of Microbiology, Biotechnology and Food Sciences
International peer-reviewed scientific online journal

Published by Faculty of Biotechnology and Food Sciences

THE IMPACT OF NON-STANDARD BARLEY QUALITY ON THE MALTING PROCESS AND ITS UTILIZATION POSSIBILITIES

Štefan Dráb, Miriam Solgajová, Andrea Mendelová, Ján Mareček, Blažena Drábová*

Address(es): Ing. Štefan Dráb, PhD.
Institute of Food Sciences, Faculty of Biotechnology and Food Sciences, Slovak University of Agriculture, Tr. A. Hlinku 2, 949 76 Nitra, Slovak Republic.

*Corresponding author: miriam.solgajova@uniag.sk

https://doi.org/10.55251/jmbfs.13952

ARTICLE INFO

Received 10. 2. 2026
Revised 18. 3. 2026
Accepted 25. 3. 2026
Published 1. 4. 2026

Regular article

OPEN ACCESS

ABSTRACT

Malting barley is a key ingredient in the production of malt, which is further used in the production of beer, a beverage with a long tradition in Slovakia. The production of high-quality malt depends on multiple factors, including variety, weather conditions, soil characteristics, water availability and appropriate processing. In recent years, the cultivation of malting barley in Slovakia has faced several agronomic and economic challenges, such as variable weather patterns, soil degradation trends and increasing production costs, which have contributed to a higher occurrence of barley with non-standard quality parameters. The aim of this study was to determine the technological quality of malting barley with non-standard protein content and to analyse the malting potential of the resulting malt samples. The results indicate that processing barley with elevated protein content may adversely affect key malt quality attributes, including friability, extract yield and the Kolbach index. These findings highlight the importance of monitoring the quality of incoming barley and adjusting malting parameters when processing raw material that deviates from standard quality requirements.

Keywords: malting barley, non-standard quality, malt, malting, protein content

INTRODUCTION

Barley is one of the most important agricultural crops worldwide with a wide range of uses and is particularly important in the feed and malting industries. Barley is the fourth most important cereal grown in the world after maize, wheat and rice **(Hoyle *et al.*, 2020)**. Barley grain is composed of dry matter (80-88%) and water (12-20%). The main components of dry matter are carbohydrates, nitrogenous substances, lipids, polyphenolic substances, inorganic substances and vitamins **(Pires-Bránik, 2015)**. Of the carbohydrates, starch is the most abundant at 65-68% as well as non-starch polysaccharides such as cellulose, hemicellulose, gum-like substances, and β-glucans **(Deme *et al.*, 2020)**. Starch is critical to extract formation from a malting perspective and is also a measure of barley quality. Starch undergoes the greatest physicochemical changes during the malting process **(Jiménez *et al.*, 2018)**. The most important hemicelluloses and gummy substances in barley grain are β-glucans. For malting barley, a low β-glucan and protein content and, conversely, a higher starch content in the grain is desirable. The β-glucans form a barrier to the entry of hydrolytic enzymes into the cells, thereby negatively affecting the rate of grain modification during malting **(Rani and Bhardwaj, 2021)**. Barley grain can contain 8 to 30% protein by weight of the total grain. This amount is referred to as the crude protein in the grain. The protein content is highly variable and influenced by many factors. Crude protein content is generally recognised as the most important indicator of the processing value of malting barley. The ideal crude protein content of malting barley should be around 10.7% **(Frančáková *et al.*, 2011)**. Producing high quality malting barley can be a challenge for growers and a decline in the production of this commodity has been noted in recent years **(Siller *et al.*, 2021)**. According to **Macák *et al.* (2023)**, several factors have contributed to the recent decline in malting barley cultivation in Slovakia, including fluctuations in weather conditions, periods of drought, temperature extremes and the generally less favourable economic position of barley compared with other crops. These factors have made it increasingly challenging for growers to consistently produce barley that meets the strict quality and volume requirements of maltsters. In parallel with reduced production, issues related to barley quality have become more frequent, with maltsters reporting a higher occurrence of non-standard barley exhibiting deviations from typical malting quality. The quality of malting barley is influenced by a range of agronomic factors such as variety, weather conditions, soil characteristics and fertilisation, as well as post-harvest handling including storage **(Schierhorn *et al.*, 2020)**. However, the final product - malt - is also influenced by the technology of its production **(Solgajová *et al.*, 2022)**. By modifying some technological steps (cleaning), it is possible to increase the quality of the barley itself, to promote its germination (addition of enzymes), or to a large extent to modify the malting technology so that the malt obtained is of higher quality despite the lower quality of malting barley (modification of steeping, air rest, modification of kilning, etc.) **(Yuqing *et al.*, 2016; Farzaneh *et al.*, 2017)**. Barley of non-standard quality may be defined as grain with unsatisfactory moisture content, insufficient or high protein content, biological or mechanical deterioration, mycotoxin or heavy metal content and poor/irregular germination. In view of the hygienic quality of the malt produced, barley with exceeded values of the parameters monitored in relation to possible negative effects on the health of the consumer cannot be used and the parameters in question must therefore be strictly always observed. Barley of non-standard quality is rarely processed into malt and results in inferior quality malt that can adversely affect the sensory, chemical and physical properties of beer **(Gupta *et al.*, 2010)**. **Badea and Wijekoon (2021)** reported that batches of poor quality barley are most commonly processed as: livestock feed, raw material for the production of a products other than malt, e.g. barley flour, barley extrudate, raw material for biomass or bioethanol production, conversion into fish feed.

The production of malt is one of the first and most important steps prior to the brewing process, and malt is one of the main raw materials used in the production of beer and is often referred to as the "heart" of beer, as it provides the beer with important extractables necessary for fermentation. However, it also contributes to the aroma, flavour and colour of the beer, which are its unique characteristics. The malting process has three main steps: steeping, germination and kilning **(Hoyle *et al.*, 2019)**. When processing barley of non-standard quality into malt, it is important to consider ecological and economic factors **(Badea and Wijekoon, 2021)**. It is therefore very important to be able to determine the real potential for malting quality of non-standard barley, and it is also of great importance to carry out further research into processing and malting technologies regarding the quality of the final product.

The aim of this work was to analyse technological quality of non-standard protein content malting barley and to determine the malting potential of produced malt samples and its utilization possibilities.

MATERIAL AND METHODS

Material

In total, 8 samples of the two-raw barley were analysed, including 5 samples of the winter barley variety Casanova and 3 samples of the spring barley variety Overture. Assessed varieties are currently among the most widely used in the malting industry in the Slovak Republic **(Dráb *et al.*, 2024)**. Samples were labelled

according to variety and sampling locality (Casanova A–E, Overture A–C). Barley originated from agricultural locations in western and southern Slovakia (Komárno, Nitra, Galanta) and northern Hungary (Pápa) from harvest year 2023, after overcoming dormancy. Samples were selected due to their non-standard protein content, exceeding the typical malting requirements. The selection criterion was crude protein content outside the optimal values such as: <10% and >12%. These levels classify barley as non-standard for malting due to the expected negative impact on modification and extract yield. Crude protein content is generally recognised as the most important indicator of the processing value of malting barley.

The malting potential was evaluated based on analyses of barley and subsequently malt samples. Before malting, the samples were cleaned to remove foreign matters as well as broken and immature grains. Micro-malting was conducted in a laboratory micro-malting plant (Ravoz, Olomouc, Czech Republic) provided by Research Institute AgroBioTech at Slovak University of Agricultural in Nitra. The weight of each malted sample was 1000 g. Grain fraction over 2.5 mm was used in the malting process.

Malting barley quality, malting of samples and malt analyses were determined according to the following methodologies of European Brewery Convention **(Analytica EBC, 2010)** and Middle European Brewing Analysis Commission methods **(MEBAK, 2011)**.

Micro Malting

The malting of the samples followed the MEBAK 1.5.3 (2011) methodology, while the malting process was modified to simulate the malting of the samples under operating conditions. Malting consisted of the following technological steps. The air steeping was conducted in the steeping box. During the steeping process, the samples were alternately steeped in water and then an air rest was performed after draining the steeping water. Two steeping cycles and air rests were performed. Barley was steeped for 1 day at 15 °C. The samples were submerged in water for 5 hours, followed by an air rest and an additional 4 hours of steeping to achieve a moisture content of 45%. At the end of the steeping process, the degree of steeping of the samples was checked by weighing, if the degree of steeping of the samples was not 45%, samples were individually sprinkled with the required amount of water. After steeping, barley was transferred to a box for germination. The total germination time was 120 hours. The temperature of the grain during germination was controlled at 17 °C. During this process, turning - removing the sample from the germination box, mixing and returning the sample to the box - was done every 12 hours. After the first day of germination, the degree of steeping of the samples was checked and, if necessary, the samples were sprinkled with individual amounts of water. The kilning process was performed on an electrically heated one-floor kiln. The samples were pre-dried at a temperature of up to 53 °C for 6 hours, after which the drying temperature was gradually increased to a finishing temperature of 82 °C for 8 hours, and this temperature was maintained for a further 3 hours. The samples were then cooled and the roots and sprouts formed were removed by a de-germination process.

Barley samples Analyses

Barley analyses were carried out according to the methodology (EBC, 2010) and (MEBAK, 2011), using the following methods: determination of barley moisture content (EBC Method 3.2), starch content (EBC Method 3.13), total nitrogen (EBC Method 3.3.1), hectolitre weight (MEBAK, 2011), first-class proportion over 2.5 mm (EBC Method 1.1.1), germination capacity (EBC Method 3.5.2).

Malt Analyses

Malt and wort analyses were carried out according to the methodology (EBC, 2010) and (MEBAK, 2011). Congress worts were prepared according to EBC Method 4.5.1. The technological parameters such as extract content (EBC 4.5.1), wort saccharification rate and filtration time (EBC 4.5.1), wort colour (EBC 4.7.1), haze of wort at 90° (EBC 9.29), wort viscosity (EBC 4.8), Kolbach index (EBC, 4.9.1), apparent final attenuation (EBC 8.6.2) were also analysed in the samples. In malted samples the friability (EBC 4.15), the malt moisture content (EBC 4.2) and total nitrogen (EBC Method 3.3.1), was also determined. Relative extract at 45°C was analysed by method (MEBAK 4.1.4.11) as well as wort clarity (MEBAK 3.1.4.2.6).

Statistical Analyses

The experiment was conducted in triplicate, referring to three analytical repetitions of each measured parameter, while micro-malting was carried out once per sample. The data were analysed using one-way analysis of variance (ANOVA), followed by Duncan's multiple range test. Statistical analyses were performed using Statistica version 12 (StatSoft Inc., Tulsa, OK, USA). Differences were considered statistically significant at $p < 0.05$.

RESULTS AND DISCUSSION

The winter barley variety Casanova and the spring barley variety Overture were selected for analysis based on their non-standard protein content, which classifies them as suboptimal for malting. The corresponding quality parameters of the barley samples are presented in Tables 1–2.

Technological quality of barley

In our dataset, the analysed barley samples differed markedly in parameters influencing their malting behaviour, and these differences were strongly driven by the protein content. Although moisture values of all samples remained within the commonly acceptable storage range (11.48-12.33%), the variation between Overture A (12.33%) and Casanova D (11.48%) showed that individual lots entered malting with different hydration levels, which likely influenced their subsequent steeping behaviour. **Rani and Bhardwaj (2021**) state that grain moisture is a key indicator especially for storage of barley. The authors recommend a moisture content of approximately 14% for short-term storage, while a lower moisture content of around 12% is considered suitable for long-term storage (**Lišková *et al.*, 2011)**; however, moisture levels should not decrease below 10%, as this may result in reduced germination capacity.

From the results we found that grain protein content influenced several technological parameters. Casanova A, with the highest protein content (13.93%; Table 1) consistently exhibited indicators of inferior malting suitability such as the lowest starch content, the lowest proportion of first-class grains, and reduced hectolitre weight. Conversely, Casanova B, the lowest protein sample (8.54%; Table 1) showed the highest starch content (58.48%) and a more favourable grain structure. These trends demonstrate that protein content was the principal factor determining overall raw material quality in our sample set, and the strength of the relationship is supported by the statistically strong negative correlation between protein and starch ($r = 0.9868$; Table 3). These findings are in line with authors **Boško *et al.* (2025)** who state that the optimal grain protein content ranges from 10 to 12%. **Hoyle *et al.* (2019)** state that a high protein content in barley can cause turbidity in beer, while too low protein content can cause defects in foaminess and fullness of beer. The starch content is crucial for the formation of the extract and is therefore an important measure of the quality of the barley. In malting barley, the starch content in grain dry matter is around 63-65% and should not be less than 60% (**Benková, 2009; Basařová *et al.*, 2015**). **Yu *et al.* (2017**) investigated the relationship between protein content, molecular structure and starch grain size in grain. The study showed that protein content was negatively correlated with starch content in grain, but the correlation between protein content and starch structure was not significant.

According to **Frančáková *et al.* (2011**); **Solgajová *et al.* (2022)** the value of the proportion of first-class grains should be above 85% for good quality malting barley. The results also showed that grain structure deteriorated with increasing protein content, as seen in the sharp drop in first-class grain proportion in Casanova A (65.53%; Table 1). This confirms that high protein barley in our study tended to have smaller and less uniform kernels. Although most samples met the >85% criterion for first-class grain proportion, the poorest-performing sample highlights the technological risk associated with high-protein lots, especially in years or regions with protein rich production conditions.

The hectolitre weight is mainly influenced by the weight and shape and the barley starch content. For barley, the average value of hectolitre weight ranges from 720 $g.dm^{-3}$ to 740 $g.dm^{-3}$ (**Basařová *et al.*, 2010**). **Aydoğan *et al.* (2017)** reported that the hectolitre weight in spring barley ranges from 650-780 $g.dm^{-3}$ however, grain with a lower hectolitre weight is no longer suitable for malting. Hectolitre weight followed a similar pattern. Overture B reached the lowest value (660.40 $g \cdot dm^{-3}$; Table 1) which places it close to the limit of acceptable malting quality. Given that hectolitre weight is closely linked to grain plumpness and starch accumulation, this again reflects the influence of protein-driven grain development. Casanova D, with a high hectolitre weight (733.23 $g \cdot dm^{-3}$), supports the interpretation that grain physical quality was strongly variety and protein dependent.

From biological parameters germination capacity was measured. Germination is one of the most important indicators for assessing malt quality because barley must germinate uniformly (**Fox and Bettenhausen, 2023**). **Osama *et al.* (2021**) state that barley germination is very important for malting purposes. At least 96% of the grains must germinate. The homogeneity of the grains is also important for synchronous germination of individual grains to occur (**Kunze, 2014**). All samples exhibited germination capacity above 98% (Table 1) indicating that despite significant variation in protein and starch composition, physiological viability was not compromised. This also confirms that the samples, although differing in technological quality, were all suitable for controlled micro-malting experiments.

Table 1 Means and homogeneous groups of technological parameters of barley samples based on Duncan's multiple range test

Barley parameters	Casanova A	Casanova B	Casanova C	Casanova D	Casanova E	Overture A	Overture B	Overture C
Crude protein (%)	13.93 ±0.08g	8.54 ±0.09a	9.02 ±0.04b	12.74±0.06e	9.94±0.08d	13.66±0.17f	9.33±0.09c	9.38±0.11c
Starch (%)	53.19±0.88a	58.48±0.75e	57.97±0.7de	54.71±0.16b	57.11±0.13c	53.05±0.38a	57.61±0.32cd	57.63±0.45cd
First class proportion (%)	65.53±0.55a	95.10±0.53e	94.00±1.06cd	98.20±0.60f	97.97±0.35f	93.57±1.29c	98.37±0.95f	89.77±0.95b
Hectolitre weight ($g.dm^{-3}$)	677.23±4.47bc	679.93±3.00bc	670.07±3.05ab	733.23±10.55d	684.33±5.85c	681.67±3.98c	660.40±9.75a	687.20±5.37c
Germination (%)	98.67±0.58a	99.00±0.00ab	99.67±0.58bc	98.67±0.58a	100.00±00c	99.67±0.58bc	98.50±0.50a	98.50±0.50a
Steeping degree - end of steeping (%)	39.67±0.58c	36.33±1.15a	39.67±0.58c	36.33±0.58a	40.33±1.15c	39.00±1.00bc	38.00±1.00b	36.33±0.58b
Steeping degree - first day germination (%)	42.33±1.15c	39.33±0.58ab	40.33±1.53abc	39.00±1.00a	41.33±1.53bc	40.67±0.58abc	41.33±1.53bc	38.67±1.53a
Steeping degree - end of germination (%)	38.33±1.53a	38.33±0.58a	38.67±1.53a	37.33±0.58a	37.33±1.15a	37.33±1.53a	38.33±0.58a	39.33±1.53a

Legend: different letters at mean represent statistically significant differences among varieties ($p<0.05$)

Steeping degree

The samples were subsequently malted in a micro-malting plant under conditions that simulated normal malting under operating conditions.

The steeping process revealed clear differences in water uptake between the analysed samples, and these differences closely reflected their protein composition. Although all samples were steeped under identical conditions, none of them reached the target moisture content (45%) after the standard steeping cycles, indicating that several lots required additional water to achieve sufficient hydration. The degree of steeping is an important indicator of hydration efficiency, as higher steeping levels promote more vigorous germination and increased production of simple sugars (**Rani and Bhardwaj, 2021**). This suggests that the starting material, especially its protein structure and kernel morphology, substantially influenced water absorption behaviour under micro-malting conditions.

Our results confirm a consistent trend that barley with lower protein content achieved a higher steeping degree, both after steeping and after the first day of germination (Table 1). This indicates that low-protein grains hydrated more readily and maintained more stable moisture distribution during early germination. In contrast, high-protein samples, particularly those from the Casanova variety, required additional moistening and still showed lower final steeping degrees. Such behaviour is consistent with the observation of **Prokeš (2000),** who reported that protein-rich barley absorbs water more slowly and often requires more intensive steeping to achieve sufficient proteolytic and cytolytic degradation.

The practical implication of this is that high-protein barley in our study reacted as a technologically more demanding raw material, requiring either longer steeping or more intensive moistening steps to ensure comparable hydration to low-protein barley. Without such adjustments, these lots are at higher risk of uneven germination and insufficient cytolytic and proteolytic activity, as also noted by **Prokeš (2000)**. The observed water-uptake behaviour therefore directly explains why high-protein samples in later stages of malting showed slower modification and higher residual moisture in finished malt. A further observation from our results is that post-steeping moistening had a clearly positive effect, as all samples showed an increased steeping degree after 24 hours of germination. This confirms that controlled post-steeping hydration can effectively compensate for initial deficiencies in water uptake, especially in protein-rich lots.

Overall, the steeping behaviour of the samples demonstrates that protein content was the primary parameter influencing hydration kinetics, and the differences observed already in the steeping stage forecasted several technological outcomes later documented in malt quality parameters. This also emphasises the importance of carefully controlled steeping procedures, as overly low or overly high moisture levels may impair germination dynamics, as also stated by **Mosher and Trantham (2016)**.

Technological quality of malt

The malt analyses confirmed that differences observed in the barley stage were carried through the entire malting process. A clear and consistent pattern was found across both varieties. Samples with higher protein content produced malt with higher residual moisture after kilning. This trend was evident in both cultivars, with Casanova A (4.33%) and Overture A (3.70%) - the highest-protein samples, also showing the highest malt moisture levels. This indicates that protein-rich kernels dried more slowly, likely because their denser endosperm structure retained more water during kilning. In our work we observed lower moisture content in spring barley varieties and higher moisture content in winter barley varieties (3.53-4.33%). Malt moisture content is one of the factors that affect the loss of aromatics, milling difficulties, reduced stability and foaming problems of beer (**Guido and Ferreira, 2023**). The moisture content of finished malt should not exceed 6% (**Kunze, 2014**). These findings suggest that the key controlling factor in our dataset was protein content rather than hydration behaviour during steeping. Variety had an additional effect: winter barley samples generally showed slightly higher malt moisture, consistent with their harder grain texture and slower moisture release that influence kilning efficiency. According to **Basařová *et al.* (2010)**, after kilning, the moisture content of the malt should be 3.5% for pale malts and 2% for dark malts. Higher malt moisture content may cause a reduction in extractability, storage problems and fermentation problems The barley growth habit may significantly influence the rate of water uptake during steeping and the rate of moisture removal during kilning (**Basařová *et al.*, 2015**), as winter barley varieties are generally harder than spring varieties, which can result in slower water absorption and desorption from the grain.

According to **Rydzak *et al.* (2023)**, controlling protein modification during malting and subsequent wort preparation is essential, as malt protein levels influence both modification and extract formation. The optimum malt protein content is generally considered to be 9.5–11.5% (**Basařová *et al.*, 2015**). In our study, malt protein values ranged from 7.74% to 13.68% and closely mirrored the protein levels of the corresponding barley samples, with a very strong correlation between barley and malt protein ($r = 0.9963$; Table 3). This indicates that the malting process did not substantially reduce the compositional differences between lots, and high-protein barley remained high-protein after germination and kilning. As noted by **Gupta *et al.* (2010)**, malting increases the soluble nitrogen fraction due to proteolytic activity, but the overall protein ranking of the samples typically remains unchanged. The technological implications of this are significant. High-protein samples in our study required modified malting conditions to achieve adequate modification, including more intensive steeping, slower moisture release during kilning and potentially lower germination temperatures to prevent excessive proteolysis. Such adjustments are in line with recommendations by **Rani and Bhardwaj (2021)**, who propose lower germination temperatures (8-15 °C) for high-protein malts to avoid undesirable reactions. In contrast, low-protein samples showed faster and more uniform drying, more efficient hydration, and lower final malt moisture - indicators of more favourable malting performance. **Rostovskaya *et al.* (2020)** similarly indicate that low-protein barley should be steeped more gently (often only once or twice) to avoid excessive nutrient loss, with germination temperatures typically maintained between 10 and 20 °C. Overall, the behaviour of the samples throughout the malting process confirms that protein content was the central determinant of malt technological quality in our study. The observed alignment between protein levels, hydration behaviour, and kilning performance demonstrates that nitrogen variability within a single harvest year can significantly influence malting efficiency and key malt parameters. As also highlighted by **Mathias *et al.* (2014)**, protein breakdown during germination alters the nitrogen profile of the grain, but high-protein barley nonetheless remains technologically demanding and must be processed carefully to prevent grain damage (**Rostovskaya *et al.*, 2020**). The negative influence of elevated grain protein on extract yield, previously reported by **Dráb *et al.* (2013)** and **Basařová *et al.* (2015)**, was fully confirmed in our results.

Table 2 Means and homogeneous groups of technological parameters of malt samples based on Duncan's multiple range test

Malting parameters	Casanova A	Casanova B	Casanova C	Casanova D	Casanova E	Overture A	Overture B	Overture C
Crude protein (%)	13.68±0.06f	7.74±0.05a	8.39±0.02b	12.52±0.40e	9.34±0.28d	12.69±0.22e	8.49±0.09b	8.92±0.12c
Extract of malt (%)	77.69±0.37a	83.81±0.25ef	82.88±0.26cd	80.28±0.55b	83.07±0.41de	82.26±0.51c	84.12±0.63f	82.86±0.48cd
Kolbach index (%)	25.55±0.54a	40.87±0.28f	41.55±0.62f	29.63±0.33b	36.58±0.41d	32.83±1.08c	38.63±0.63e	30.71±0.97b
Friability (%)	55.56±0.52a	85.96±0.92e	79.68±1.05d	61.28±0.32b	85.00±0.19e	78.04±0.36c	97.54±0.46f	80.10±0.49d
Relative extract 45 °C (%)	29.29±0.72b	27.59±0.43a	27.92±0.78a	32.79±0.43e	31.71±0.53c	37.30±0.60f	30.28±0.45b	31.80±0.63cd
Wort viscosity (mPa.s^{-1})	1.56±0.00e	1.51±0.00c	1.53±0.01d	1.67±0.01f	1.47±0.01b	1.75±0.00g	1.44±0.01a	1.55±0.01e
Wort haze 90° (EBC)	4.15±0.04b	8.48±0.05g	7.34±0.05d	7.48±0.02e	7.03±0.10c	3.48±0.03a	3.58±0.08a	8.11±0.06f
Wort colour (EBC)	5.03±0.05a	8.03±0.06h	7.14±0.04d	7.61±0.04e	7.85±0.04g	5.75±0.08b	5.93±0.04c	7.72±0.05f
Apparent final attenuation (%)	81.70±0.12b	81.91±0.49bc	81.90±0.32bc	80.62±0.36a	80.83±0.21a	82.83±0.11d	82.62±0.58cd	80.31±0.73a
Filtration time (min.)	18.33±1.53bc	17.67±0.58b	18.33±1.53bc	14.67±0.58a	20.33±1.53c	19.33±1.53bc	39.33±1.53e	31.33±1.53d
Saccharification (min.)	<15	<15	<15	<15	<10	<10	<10	<10

Legend: different letters at mean represent statistically significant differences among varieties ($p<0.05$)

Malt extract represents the soluble substances released from malt during mashing, including simple sugars and amino acids that support yeast nutrition, as well as more complex carbohydrates and proteins contributing to beer flavour, aroma and mouthfeel. Because extract yield is a central indicator of malt quality, its determination is critical for evaluating malting barley (**Fox and Bettenhausen, 2023**). As emphasised by **Li *et al.* (2008)**, extractability has major economic significance for brewers, and varieties capable of producing high extract are therefore preferred. Low extract yields are associated with operational inefficiencies, including prolonged brewhouse processing, poorer fermentation performance, turbidity formation, filtration challenges and potential off-flavours. Malts with high enzymatic activity and correspondingly high extract support both product quality and brewhouse yield (**Rani and Bhardwaj, 2021**). In our study, extract values clearly reflected differences in protein composition among samples. Overture B achieved the highest extract (84.12%), while Casanova A (the sample with the highest grain protein content) showed the lowest extract value (77.69%). This pattern is consistent with the established negative relationship between protein content and extract yield described by **Dráb *et al.* (2013)** and further supported by the strong extract–protein association noted by **Hartman (2013)**. Our results confirmed this relationship quantitatively, revealing a statistically significant negative correlation between protein content and malt extract ($r = -0.8292$; Table 3). A comparison between sample groups illustrates the technological relevance of this trend, samples with protein levels below 10% produced on average 83.35% extract, whereas samples exceeding 10% protein achieved only 80.08%. These findings demonstrate that protein content was a key determinant of saccharification efficiency within the sample set. While literature sources such as **Fox and Bettenhausen (2023)** and **Li *et al.* (2008)** describe the general technological and economic importance of extract, our data highlight how strongly extract yield can vary within a single harvest year when barley protein content fluctuates.

The saccharification is the time required for the starch to be converted into simple sugars during the mashing process. Good quality malt should be sugared in less than 10 minutes as enzymes initiate starch hydrolysis, longer duration is due to poor starch degradation (**Kumar *et al.*, 2013**).

Saccharification time mirrored the extract behaviour. Samples Casanova E, Overture A, Overture B and Overture C achieved saccharification within <10 minutes, meeting the expectations for well-modified malt, as noted by **Kumar *et al.* (2013)** and consistent with the acceptable 10-15 min range reported by **Frančáková *et al.* (2011)**. Samples with longer saccharification times (15 min) corresponded to higher protein content and poorer modification, demonstrating that protein-rich malts required more enzymatic effort to degrade starch into fermentable sugars.

Friability measurement is used to evaluate the degree of cell wall modification in malted grains and to identify malts that may cause problems in later brewing steps, such as clarification, mashing or filtration (**Schwartz and Jin, 2020**). Malt friability is generally expected to exceed 90% for well-modified malt (**Rani and Bhardwaj, 2021**). High friability values indicate sufficient degradation of structural components, including non-starch polysaccharides such as β-glucans, as documented by **Psota *et al.* (2018)** and **Solgajová *et al.* (2022).**

In our study, friability proved to be one of the most sensitive indicators of modification quality. Casanova A (the sample with the highest protein content) reached only 55.56% friability, demonstrating pronounced under-modification. This behaviour corresponds to the mechanism described by **Prokeš (2000)**, who reported that higher grain protein content increases kernel hardness and slows cytolytic degradation. Literature values for high-quality malts (>90% friability; **Psota *et al.*, 2018**; **Rani and Bhardwaj, 2021**) contrast sharply with the poor friability values observed in high-protein samples in our dataset. Our results also revealed a statistically significant negative correlation between protein content and friability ($r = -0.7774$; Table 3), demonstrating that protein acted as the main limiting factor in endosperm modification. This association is consistent with findings of **Bohačenko *et al.* (2021)** and agrees with technological observations by **Schwartz and Jin (2020)**, who noted that under-modified malts are more likely to cause lautering and filtration issues. Based on these findings, barley with elevated protein content should be steeped to a higher degree of steeping and allowed a longer germination period to achieve adequate modification and reach optimal friability values.

Relative extract at 45 °C, an indicator of proteolytic activity, showed pronounced deficiencies in several high-protein samples. Casanova A–C did not reach even 30%, indicating insufficient proteolysis. Although **Frančáková *et al.* (2012)**, **Dráb *et al.* (2013)** lists 37% as the desirable threshold, and **Psota *et al.* (2009)** report a link with the Kolbach index, our results did not confirm a significant correlation between these parameters (Table 3). This suggests that in these samples, proteolytic activity was limited primarily by poor hydration and slow modification rather than by the enzymatic system itself.

The Kolbach index indicates the ratio between the total nitrogen content of malt and the dissolved nitrogen content of the congress wort. The optimum value ranges from 38 to 42% (**Kreisz, 2009**). Authors **Amabile *et al.* (2014); Zavřelová *et al.* (2021**) indicates that for European breweries the Kolbach index should not exceed 40%, but for example American breweries require a value of at least 42%. Kolbach index values ranged widely (25.6–41.5%; Table 2) and reflected similar patterns as other indicators. High-protein samples such as Casanova A, Casanova D and Overture A exhibited values below 35%, which **Zavřelová *et al.* (2021)** associate with incomplete proteolytic modification. Conversely, Casanova C reached 41.55%, meeting the upper limit recommended by **Kreisz (2009)**. Our data confirm a strong correlation between extract and Kolbach index ($r = 0.8353$; Table 3) with a level of significance ($p < 0.05$), matching the positive correlation described by **Frančáková *et al.* (2011)**.

The apparent final attenuation represents a comprehensive indicator of malt quality. It reflects the proportion of malt extract that is utilizable by yeast, with particular emphasis on the content of fermentable sugars (**Kreisz, 2009**). **Prokeš *et al.* (2007**); **Zavřelová *et al.* (2021)** states that malts with a high apparent final attenuation, can provide beers with an empty taste. For pilsner malt, a typical apparent final attenuation is 78-82%. All samples reached acceptable apparent final attenuation values typical for pilsner malt (79–82%), consistent with the ranges suggested by **Frančáková *et al.* (2012)**. The fact that attenuation remained within the optimal range even in high-protein samples indicates that fermentable sugar composition was less affected by protein variability than extract and modification parameters.

Viscosity plays an important role in the production, it is mainly influenced by the content of high molecular weight substances in the wort (polysaccharides, β-glucans). If grains with high protein content are less hydrated and germinated during the malting process, it results in poorer grain modification of non-starchy polysaccharides and an increase in wort viscosity (**Blšáková *et al.*, 2022**). Viscosity results were favourable in all samples, but one sample Overture A reached the critical upper limit (1.75 mPa·s^{-1}), which corresponds to incomplete β-glucan degradation as noted by **Jin *et al.* (2013)** and **Deme *et al.* (2020)**. Authors reported that viscosity is commonly regarded as an indirect indicator of β-glucan degradation as elevated values are associated with impaired wort flow during lautering. Malts producing laboratory wort viscosities exceeding 1.75 mPa·s^{-1} are therefore considered to exhibit insufficient modification. All other samples fell within acceptable ranges (1.44-1.67 mPa·s^{-1}; Table 2), consistent with the guidance of **Basařová *et al.* (2015)** and **Solgajová *et al.* (2022)**.

Filtration rate is one of the traditional parameters used to assess malt quality. It is evaluated during wort filtration, which under standard conditions should be completed within 1 hour. Filtration time of up to 2 hours is classified as slow, while filtration exceeding 2 hours is considered poor (**Frančáková *et al.*, 2011**). Filtration was completed within 60 minutes for all samples (Table 2), indicating satisfactory modification from a lautering perspective, as defined by **Prokeš *et al.* (2007)** and **Frančáková *et al.* (2011)**. Authors reported that fast filtration is a sign of good modification of the barley grain and perfect mashing of the malt.

Clear malt worts are indicative of well-modified barley grain and properly kilned malt (**Prokeš *et al.*, 2007**). Wort clarity was acceptable in most samples; only Casanova B and Overture C exceeded the haze threshold of 8 EBC units. This aligns with the sensory and quality thresholds described by **Psota *et al.* (2018)**. Authors state that turbidity values exceeding 8 EBC units are characteristic of opalescent malts. Importantly, no significant correlation was found between protein content and haze (Table 3), suggesting that turbidity was driven more by sample-specific attributes than by protein alone.

Table 3 Correlation matrix of analysed parameters in barley, malt, and wort

Parameters	Crude protein content-barley (%)	Starch content-barley (%)	Hectolitre weight-barley (g.dm^{-3})	First-class proportion (%)	Moisture content - malt (%)	Protein content - malt (%)	Malt extract in dry matter (%)	Kolbach index (%)	Friability (%)	Relative extract 45°C (%)	Viscosity (mP.s^{-1})	Wort turbidity 90° (EBC)	Wort turbidity 13° (EBC)	Filtration rate (min.)
Starch content-barley (%)	**-0.9868**													
Hectolitre weight-barley (g.dm^{-3})	0.4187	-0.2831												
First-class proportion (%)	-0.5236	0.5906	0.1943											
Moisture content-malt (%)	0.4037	-0.3817	0.3115	-0.5592										
Crude protein-malt (%)	**0.9963**	-0.9789	0.4533	-0.5511	0.4355									
Malt extract in dry matter (%)	**-0.8292**	0.8096	-0.3897	0.7991	-0.6922	-0.8599								
Kolbach index (%)	**-0.7990**	0.7616	-0.4818	0.5900	-0.2674	-0.8372	**0.8353**							
Friability (%)	**-0.7774**	0.7391	-0.5820	0.6615	-0.7438	-0.8181	0.9492	0.7905						
Relative extract 45°C (%)	0.5613	-0.5470	0.3551	0.2332	-0.4023	0.5348	-0.0671	-0.4114	-0.1042					
Viscosity (mP.s^{-1})	0.7127	-0.7019	0.5250	-0.0617	0.2305	0.7129	-0.3921	-0.4803	-0.5268	0.7517				
Wort turbidity 90° (EBC)	-0.5013	0.5764	0.4474	0.3259	0.1600	-0.4504	0.2025	0.2385	-0.0357	-0.4099	-0.2036			
Wort turbidity 13° (EBC)	-0.4608	0.5325	0.4539	0.2592	0.2674	-0.4066	0.1358	0.2149	-0.1108	-0.4438	-0.1541	0.9901		
Filtration rate (min.)	-0.4275	0.4150	-0.4816	0.2457	-0.6505	-0.4387	0.4774	0.1590	0.6440	-0.0289	-0.4933	-0.3377	-0.3830	
Saccharification (min.)	0.1301	-0.1027	0.2769	-0.3881	0.9534	0.1651	-0.4779	-0.0265	-0.5741	-0.5767	0.0619	0.3926	0.4900	-0.6458

Effective malting of barley samples with non-standard protein content requires above all an individualised technological approach, including careful adjustment of steeping intensity, germination conditions and kilning parameters to achieve adequate malt modification. In addition, the results suggest that protein-rich barley lots should not be used as single-source malts but rather incorporated into blends with low-protein malts to achieve balanced modification and optimal extract. Breweries can use these data to adjust mashing, filtration, or nitrogen management strategies when handling variable-quality malt supplies. Overall, strategic blending malts represents an effective way to mitigate the negative technological impacts associated with high-protein barley.

Although micro-malting cannot fully replicate the heat and airflow conditions of industrial systems, it remains an essential and widely accepted method for reliably predicting malt behaviour under controlled conditions. Micro-malting provides the only practical way to assess the technological risks of non-standard raw materials. Thus, the observed trends in hydration, modification and extract are directly relevant for industrial practice, even if absolute values may differ at full scale.

CONCLUSION

This study assessed the technological quality of malting barley with non-standard protein content and the malting potential of the resulting malts. The sample with the highest protein content (Casanova A) exhibited the lowest starch content and failed to meet the required proportion of first-class grains, while all samples achieved excellent germination capacity (>98%). Hectolitre weight values ranged from 660.4 to 733.2 g·dm^{-3}, reflecting substantial variation in grain physical quality. During micro-malting, clear relationships emerged between protein content and malt quality. Higher-protein samples consistently retained more moisture after kilning, and protein level significantly affected malt friability, indicating limited endosperm modification in protein-rich lots. Malt extract values were within the optimal range except for Casanova A, which showed reduced extractability in line with its elevated protein content. Most samples exhibited low proteolytic activity, as indicated by relative extract at 45 °C, and the Kolbach index ranged from 25.6% to 41.5%, with high-protein samples showing the lowest values. Wort viscosity exceeded acceptable limits only in Overture A, while final attenuation and haze values met technological requirements in nearly all cases.

Overall, the findings of this study demonstrate that non-standard barley with elevated protein content negatively influences grain hydration, malt drying behaviour, modification degree, extract formation and proteolytic indicators. Effective malting of such material therefore requires an individualised technological approach, including careful adjustment of steeping intensity, germination conditions and kilning parameters to achieve adequate modification. The results also highlight the practical relevance of raw-material segregation based on protein level. Mixing barley lots with contrasting protein contents before malting may reduce modification uniformity within the malt batch. To ensure consistent technological performance and meet malt specifications, post-malting blending of finished malts is preferable to blending raw barley prior to processing. This approach enables breweries and maltsters to compensate for variability in barley quality while maintaining stable extract yield, modification level and overall processing performance.

Acknowledgements: This work was supported by the Research and Development Agency under contract No.APVV-24-0266.

REFERENCES

Amabile, R. F., Faleiro, F. G., Capettini, F., Sayd, R. M., Peixoto, J. R., & Guercia, R. F. (2014). Characterization and genetic variability of barley accessions (*Hordeum vulgare* L.) irrigated in the savannas based on malting quality traits. *Journal of the Institute of Brewing, 120*(4), 404–414. https://doi.org/10.1002/jib.179

Aydoğan, S., Şahin, M., Göçmen Akçacık, A., Demir, B., Hamzaoğlu, S., & Kara, İ. (2017). Evaluation of quality properties of barley genotypes in different locations. *Selçuk Journal of Agriculture and Food Sciences, 31*(2), 8–13. https://doi.org/10.15316/SJAFS.2017.13

Badea, A., & Wijekoon, C. (2021). Benefits of barley grain in animal and human diets. In A. Goyal (Ed.), *Cereal grains*. IntechOpen. https://doi.org/10.5772/intechopen.97053

Basařová, G., Psota, V., Šavel, J., Basař, P., Paulů, R., Kosař, K., Dostálek, P., Basařová, P., Kellner, V., Mikulíková, R., & Čejka, P. (2015). *Sladařství: Teorie a praxe výroby sladu* (1st ed.). Havlíček Brain Team.

Basařová, G., Šavel, J., Basař, P., & Lejsek, T. (2010). *Pivovarství: Teorie a praxe výroby piva* (1st ed.). Vysoká škola chemicko-technologická.

Benková, M. (2009). Porovnanie vybraných ukazovateľov technologickej kvality starších a súčasných odrôd sladovníckeho jačmeňa. *Kvasný Průmysl, 55*(9), 255–259. https://doi.org/10.18832/kp2009021

Blšáková, L., Gregor, T., Mešťánek, M., Hřivna, L., & Kumbár, V. (2022). The use of unconventional malts in beer production and their effect on wort viscosity. *Foods, 11*(1), 31. https://doi.org/10.3390/foods11010031

Bohačenko, I., Psota, V., Hartmann, J., & Musilová, M. (2021). Combined effect of high temperature and drought on yield and malting quality of barley. *Czech Journal of Food Sciences, 39*(1), 17–22. https://doi.org/10.17221/146/2019-CJFS

Boško, R., Garčárová, M., & Psota, V. (2025). Kvalita zrna sladovníckeho jačmeňa v ČR, úroda 2024. *Kvasný Průmysl, 71*(1), 968–979. https://doi.org/10.18832/kp2025.71.968

Deme, G. D., Asfaw, B. T., & Gari, M. T. (2020). Evaluation of malting potential of different barley varieties. *Journal of Water Pollution & Purification Research, 6*(3), 24–35. https://doi.org/10.37591/jowppr.v6i3.787

Dráb, Š, Krajčovič, T., Svorad, M. (2024). *Barley year book* 2024 (1st ed.). Editor: Posta V., Praha : Výzkumný ústav pivovarský a sladařský, ISBN : 978-80-88613-41-1

Dráb, Š., Psota, V., Frančáková, H., Sachambula, L., Hartmann, J., & Tokár, M. (2013). Závislosť kvality sladu na odrode a ročníku. *Kvasný průmysl,* 59(7–8), 181–189. https://doi.org/10.18832/kp2013018
European Brewery Convention Analysis Committee. (2010). *Analytica EBC*. Fachverlag Hans Carl.
Farzaneh, V., Ghodsvali, A., Bakhshabadi, H., Zare, Z., & Carvalho, I. S. (2017). The impact of germination time on selected parameters through the malting process. *International Journal of Biological Macromolecules, 94*(A), 663–668. https://doi.org/10.1016/j.ijbiomac.2016.10.052
Fox, G. P., & Bettenhausen, H. M. (2023). Variation in quality of grains used in malting and brewing. *Frontiers in Plant Science, 14*, 1172028. https://doi.org/10.3389/fpls.2023.1172028
Frančáková, H., Líšková, M., Bojňanská, T., & Mareček, J. (2011). Effect of milling softness on basic technological parameters of wort. *Potravinárstvo, 5*(1), 39–42. https://doi.org/10.5219/111
Frančáková, H., Líšková, M., Bojňanská, T., & Mareček, J. (2012). Germination index as an indicator of malting potential. *Czech Journal of Food Sciences, 30*(4), 377–384. https://doi.org/10.17221/314/2010-CJFS
Guido, L. F., & Ferreira, I. M. (2023). The role of malt on beer flavour stability. *Fermentation, 9*(5), 464. https://doi.org/10.3390/fermentation9050464
Gupta, M., Abu-Ghannam, N., Gallaghar, E. (2010). Barley for brewing: Characteristic changes during malting, brewing and applications of its by-product. *Comprehensive Reviews in Food Science and Food Safety, 9*(3), 318–328. https://doi.org/10.1111/j.1541-4337.2010.00112.x
Hartman, I. (2013). The effect of agrotechnological characters of barley grain on malt quality. *Kvasný Průmysl, 59*(10-11), 284–287. https://doi.org 10.18832/kp2013028
Hoyle, A., Brennan, M., Jackson, G. E., & Hoad, S. (2019). Increased grain density of spring barley is associated with an increase in grain nitrogen. *Journal of Cereal Science, 89*, 102797. https://doi.org/10.1016/j.jcs.2019.102797
Hoyle, A., Brennan, M., Pitts, N., Jackson, G. E., & Hoad, S. (2020). Relationship between specific weight of spring barley and malt quality. *Journal of Cereal Science, 95*, 103006. https://doi.org/10.1016/j.jcs.2020.103006
Jiménez, B., Contreras-Jiménez, B., Del Real, A., Millan-Malo, B. M., Gaytán-Martínez, M., Morales-Sánchez, E., Rodríguez-García, M. E. (2018). Physicochemical changes in barley starch during malting. *Journal of the Institute of Brewing, 125*(1), 10–17. https://doi.org/10.1002/jib.547
Jin, Z., Li, X. M., Gao, F., Sun, J. Y., Mu, Y. W., & Lu, J. (2013). Proteomic analysis of differences in barley malts with distinct filterability. *Journal of Proteomics, 93*, 93–106. https://doi.org/10.1016/j.jprot.2013.05.038
Kreisz, S. (2009). Malting. In H. M. Eßlinger (Ed.), *Handbook of brewing: Processes, technology, markets* (pp. 147–164). Wiley-VCH.
Kumar, D., Kumar, V., Verma, R. P. S., Kharub, A. S., & Sharma, I. (2013). Quality parameter requirement and standards for malt barley – A review. *Agricultural Reviews, 34*(4), 313–317. https://doi.org/10.5958/j.0976-0741.34.4.018
Kunze, W. (2014). *Technology brewing and malting* (5th ed.). VLB Berlin.
Li, Y., Schwarz, P. B., Barr, J. M., & Horsley, R. D. (2008). Factors predicting malt extract within a single barley cultivar. *Journal of Cereal Science, 48*(2), 531–538. https://doi.org/10.1016/j.jcs.2007.12.004
Líšková, M., Frančáková, H., & Mareček, J. (2011). Zmeny v obsahu hrubého proteínu v sladovníckom jačmeni vplyvom pozberového dozrievania. Journal of Central European Agriculture, 12(1), 92–102. https://hrcak.srce.hr/file/105415
Macák, M., Korczyk-Szabó, J., Hromadová, Ľ., & Habán, M. (2023). Options for evaluating the yield response of malting barley varieties to environmental conditions in the Slovak Republic. *Journal Central European Agriculture, 24*(1), 169–177. https://doi.org/10.5513/JCEA01/24.1.3742
Mathias, T. R. dos S., Mello, P. P. Moretzsohn de, & Sérvulo, E. F. C. (2014). Nitrogen compounds in brewing wort and beer: A review. *Journal of Brewing and Distilling, 5*(2), 10–17. https://doi.org/10.5897/JBD2014.0042
Mitteleuropäische Brautechnische Analysenkommission (MEBAK). (2011). *Raw materials: Barley, adjuncts, malt, hops and hop products*. MEBAK, Freising-Weihenstephan, 341 pp.
Mosher, M., & Trantham, K. (2016). The "food" for the brew. In M. Mosher & K. Trantham, *Brewing science: A multidisciplinary approach* (pp. 125–156). Springer. https://doi.org/10.1007/978-3-319-46394-0_5
Osama, S. K., Kerr, E. D., Yousif, A. M., Phung, T. K., Kelly, A. M., Fox, G. P., et al. (2021). Proteomics reveals commitment to germination in barley seeds is marked by loss of stress response proteins and mobilisation of nutrient reservoirs. *Journal of Proteomics, 242*, 104221. https://doi.org/10.1016/j.jprot.2021.104221
Pires, E., & Brányik, T. (2015). *Biochemistry of beer fermentation*. Springer. https://doi.org/10.1007/978-3-319-15189-2
Prokeš, J. (2000). Technologický význam dusíkatých látek v ječmeni a sladu. *Kvasný Průmysl, 46*(10), 277–279. https://doi.org/10.18832/kp2000023
Prokeš, J., Vaculová, K., & Milotová, J. (2007). Vybrané sladovnické parametry nových přírůstků z kolekce genetických zdrojů jarního ječmene. *Kvasný Průmysl, 53*(6), 162–167. https://doi.org/10.18832/kp2007007
Psota, V., Skulilová, Z., & Hartmann, J. (2009). The effect of the barley variety, location and year crop on the haze of congress wort. *Czech Journal of Food Sciences, 27*(3), 158–164. https://doi.org/10.17221/156/2008-CJFS
Psota, V., Svorad, M., & Musilová, M. (2018). The barley varieties registered in the Slovak Republic after harvest 2017. *Kvasný Průmysl, 64*(3), 111–116. https://doi.org/10.18832/kp201818
Rani, H., & Bhardwaj, R. D. (2021). Quality attributes for barley malt: The backbone of beer. *Journal of Food Science, 86*(8), 3322–3340. https://doi.org/10.1111/1750-3841.15858
Rostovskaya, M. F., Boyarova, M. D., & Klykov, A. G. (2020). Effect of various barley steeping conditions on the content of albuminous substances in the malt. *Food Processing: Techniques and Technology, 50*(2), 319–328. https://doi.org/10.21603/2074-9414-2020-2-319-328
Rydzak, L., Vasiukov, K., Kobus, Z., & Natoniewski, M. (2023). Modification of the malting process of barley grains of different varieties by vacuum impregnation and its effect on selected wort parameters. *Processes, 11*(10), 2830. https://doi.org/10.3390/pr11102830
Schierhorn, F., Hofmann, M., Adrian, I., Bobojonov, I., & Müller, D. (2020). Spatially variable climate change impacts on wheat and barley yields in Kazakhstan. *Journal of Arid Environments, 178*, 104164. https://doi.org/10.1016/j.jaridenv.2020.104164
Schwarz, P., & Jin, Z. (2020). Advances in postharvest storage and handling of barley: Methods to prevent or reduce mycotoxin contamination. In G. Fox & C. Li (Eds.), *Achieving sustainable cultivation of barley*. Burleigh Dodds Science. https://doi.org/10.19103/AS.2019.0060.15
Siller, A., Hashemi, M., Wise, C., Smychkovich, A., & Darby, H. (2021). Date of planting and nitrogen management for winter malt barley production in the Northeast USA. *Agronomy, 11*(4), 797. https://doi.org/10.3390/agronomy11040797
Solgajová, M., Dráb, S., Mendelová, A., Kolesárová, A. a Mareček, J. (2022). Quality assessment of spring barley varieties intended for malting process. *Journal of Microbiology, Biotechnology and Food Sciences, 12*(Special Issue). https://doi.org/10.55251/jmbfs.9250
StatSoft, Inc. (2013). Statistica (data analysis software system), version 12. StatSoft, Inc., Tulsa, OK, USA.
Yu, W., Tan, X., Zou, W., Hu, Z., Fox, G. P., Gidley, M. J., & Gilbert, R. G. (2017). Relationships between protein content, starch molecular structure and grain size in barley. *Carbohydrate Polymers, 155*, 271–279. https://doi.org/10.1016/j.carbpol.2016.08.078
Yuqing, H., Cai, S., Ye, L., Hu, H., Li, C., & Zhang, G. (2016). The effects of GA and ABA treatments on metabolite profile of germinating barley. *Food Chemistry, 192*, 928–933. https://doi.org/10.1016/j.foodchem.2015.07.090
Zavřelová, M., Psota, V., Matušinsky, P., Musilová, M., & Némethová, M. (2021). Hodnotenie sladovníckej kvality genetických zdrojov jarného jačmeňa z rôznych oblastí pôvodu. *Kvasný Průmysl, 67*(1), 392–402. https://doi.org/10.18832/kp2021.67.392