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Correlation between spring barley performance constituents under arid conditions

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Abstract. Barley possesses unique dietary properties and is among the richest sources of phenolic compounds among cereal crops, which explains the growing interest in barley grain as a raw material for functional food production. The purpose of the study was to identify valuable starting material for the breeding of naked spring barley with pigmented grains. To achieve this, the level of productivity and its relationship with structural elements (spike length, number of grains per spike) and plant height were determined. The study involved seven accessions of naked barley with pigmented grains and the standard, hulled barley cultivar 'Avhur'. The naked barley accessions included yellow-grained cultivars 'CDC(Crop Development Centre) Hilose', 'CDC Alamo', and 'Mebere' (var. *nudum*); collection accession UA 0800645 (var. *nudimelanocrithum*, black grain), UA 0800663 (var. *viride*, green grain), and UA 0805462 (var. *daghestanicum*, gray-green grain); and the breeding line Violet 18-1207 (var. *nudidubium*, purple grain) developed at the Plant Breeding and Genetics Institute, NAAS. Statistical analysis was performed using ANOVA with post-hoc Fisher's LSD test and correlation analysis. A wide variability of productivity was demonstrated ($V = 26-47\%$), and a strong correlation was established between the productivity of the main spike and its structural elements ($r = 0.65-0.96$). As a result, a correlation cluster was identified: productivity \rightarrow number of grains per spike \rightarrow spike length. Considering the low variability of the trait "number of grains per spike" and its strong correlation with spike length, these traits were determined

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to be key indicators for selection aimed at high productivity. A source of long spikes was identified ('CDC Alamo', 10.6 cm), including sources of a large number of grains per spike ('CDC Alamo' and the breeding line Violet 18-1207, 26-28 grains). The identification of sources of valuable traits is essential for breeding aimed at increasing the yield of naked barley and ensuring food security, particularly under conditions of climate change

Keywords: naked barley; variability; primary spike; number of grains; plant height; weight of grains per spike; correlation cluster

Introduction

Resolution of the Cabinet of Ministers of Ukraine No. 684-r (2024) states that the main problems in nutrition that need to be solved have been identified at the global level, in particular: the availability of foods in sufficient quantities, their accessibility for all segments of the population, safety of foods for health, and rational nutrition. Barleys with pigmented caryopses are little spread in Ukraine, but it has long been a traditional food crop in countries of North Africa, the Middle East, China, and Tibet. Research by S. Iwatani & N. Yamamoto (2019) indicates that the concept of functional foods (FOSHU, Food of Specific Health Use), referring to foods with specific therapeutic effects on the human body, was introduced in Japan in 1991. Subsequent programmes in other countries have expanded barley diversity through breeding, resulting in new accessions and cultivars better suited for food production. For example, the study by M. Yirgu *et al.* (2022) concluded that in Ethiopia, there are many landraces with coloured grains and their dispersal depends on environmental conditions. Barleys with white caryopses are most widespread followed by accessions with purple, black, and grey grains. In terms of altitude, the dispersal of white-grained barleys tends to increase from low to high altitudes, while the dispersal of brown-grained accessions, vice versa, tends to increase from high to low altitudes.

Global food demand is predicted to grow, so it is necessary to increase agricultural production to ensure food security while minimising environmental impacts, especially in the context

of possible climate change. Understanding agronomic and biological characteristics of crops under water deficit is crucial to increase performance and yield potentials. K. Sato (2025) determined that agronomically important traits are often controlled by several interacting genes, requiring in-depth knowledge of genetics. To better understand contributions of genomic sequence variations to different traits, standardised phenotyping and systematic gene modification through genome editing have become widely used. This provides new strategies for improving traits through gene sequence-based barley breeding. M. Jayakodi *et al.* (2021) stated that Haplotype (haploid genotype)-based characterisation of Single Nucleotide Polymorphism copies from gene banks and breeding germplasm is a state-of-the-art approach to plant breeding. High-quality genome sequences are essential for haplotype analysis and association of barley sequence variations with phenotypic variations. The haploid genotype, as a region of DNA that is inherited as a single unit from parent to offspring, cannot always be determined by genotype. Haplotype determination is only possible through sequencing. Combined information gained from genomic sequences and systematic functional gene analysis provides new strategies for trait improvement through sequence-based barley breeding.

J.H. Czembor (2023) investigated that agromorphological characteristics of collection naked barley accessions as starting materials are crucial for the development of targeted breeding strategies that respond to changing environmental

conditions and demand for agricultural products, and are thus valuable resources for breeding programmes. This is all the more important given that the use of elite materials in breeding has led to cultivars becoming genetically homogeneous and more vulnerable to stresses such as droughts and elevated temperatures. In particular, narrowing and homogeneity of the barley gene pool are a challenge for breeders of stress-tolerant cultivars. It has been shown by S. Sakuma & T. Schnurbusch (2020) that over the past decades, breeders have raised the yield of barley grain mainly by increasing the number of grains per spike, a trait determined by the number of spikelets per spike and the number of fertile flowers, which emphasises the significance of spike architecture in improving yield potential.

The purpose of this study was to create starting materials for the breeding of naked barleys with pigmented caryopses and other valuable traits.

Materials and Methods

The experiments with barley plants were carried out in compliance with the requirements of the International Plant Protection Convention (2006) and in accordance with the Law of Ukraine No 4147-IX (2024). Based on the findings of other researchers, the Yuriev Plant production Institute of the National Academy of Agrarian Sciences of Ukraine (YPPI NAAS) determined the performance of the naked spring barley accessions and relationship between performance and its constituents (spike length, number of grains per spike) and plant height. Since naked barley yields little in breeding nurseries under arid conditions, assessment of genotypes by this trait would be incorrect; therefore the accessions were characterised by primary spike performance. Seven naked barley accessions with pigmented caryopses and the check cultivar (chaffy barley 'Avhur' (var. *nutans*) bred at the YPPI NAAS) were studied. The naked cultivars with yellow caryopses were 'CDC Hilose', 'CDC Alamo' and 'Mebere' (var. *nudum*); collection accession UA 0800645 (var.

nudimelanocrithum) has black caryopses; collection accession UA 0800663 (var. *viride*) has green caryopses; collection accession UA 0805462 (var. *daghestanicum*) has grey-green caryopses; and YPPI-bred line Violet 18-1207 (var. *nudidubium*) has purple caryopses.

The cultivars and collection accessions were grown in the YPPI NAAS scientific crop rotation fields in 2022-2024. The sowing was carried out with a cassette seeder SKS-6A (USSR) within optimal timeframes in 2023 and 2024; in 2022, the sowing was two weeks later than the optimal time because the Institute's fields were in the combat zone. The barley accessions were sown according to the breeding nursery scheme; each plot was 2 m², without replications; the check cultivar was placed after every 10 accessions. Plants with roots were harvested manually. To analyse performance constituents, 15-20 typical plants of each accession were selected. Data were statistically processed in STATISTICA-6: one-way analysis of variance (ANOVA) for pairwise comparison and post-hoc comparison of homogeneous groups using Fisher's LSD test. Different letters (a, b, c, d) indicate statistically significant differences among years and barley accessions. Boxplots (box-and-whisker plots) were used to visualise the original data. Such diagrams are convenient to show the median, mean, lower and upper quartiles, minimum and maximum, and outliers. Distances between different parts of the box allowed evaluating of dispersion degrees and data asymmetry and identifying outliers. The weather in the study years varied, enabling the comprehensive evaluation of the naked barley accessions (Fig. 1).

Data for April and 20 days of May 2022 are missing, since meteorological observations were impossible because the Russian invasion. Barley was sown later than usual, so the available meteorological data for 2022 fully correspond to the growing period of spring barley in this study. The April air temperature in the study years was 1.3-3.7°C higher than the long-term mean value; the May temperature was 0.5-0.3°C lower in 2022 and 2023 and 0.4 °C higher in 2024 than

the long-term mean value. In May, barley went through one of the critical phases – tillering; therefore it was especially demanding on growing conditions. In June, when barley went through the next critical phases, earing and filling, the air temperature was similar to the long-term mean value in 2023, but it exceeded the long-term mean value by 1.4-2.1°C in the other years. The July temperature was 1.5-4.6°C higher than the long-term mean value. Elevated air temperatures during this period are dangerous because they cause grain scorching, thereby significantly reducing yield. The amount of productive precipitation also had a negative impact on the naked barley performance at elevated temperatures (Fig. 2).

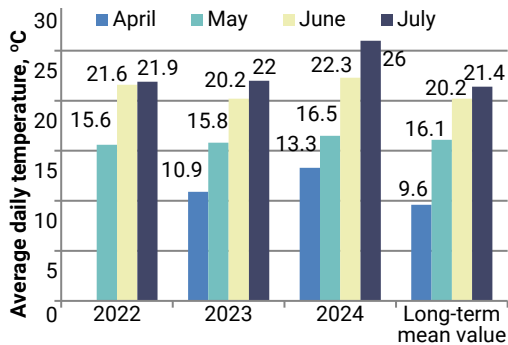


Figure 1. Mean daily air temperature in the study years compared to the long-term mean daily air temperature

Source: constructed by the authors based on data from the Kharkiv Regional Hydrometeorological Centre

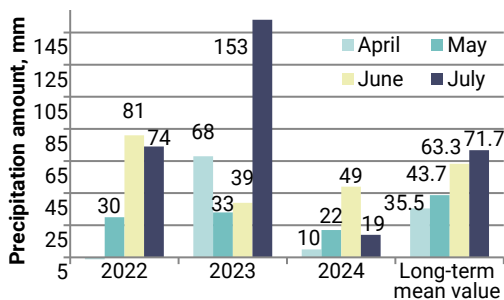


Figure 2. Monthly precipitation in the study years compared to the long-term mean value

Source: constructed by the authors based on data from the Kharkiv Regional Hydrometeorological Centre

Thus, in May (in all years of the study), the precipitation amount was smaller than the long-term mean value by 21.7-10.7 mm, which did not help productive tillering of barley. The June precipitation amount was bigger than the long-term mean value only in 2022, while it was 14.3-2.3 mm smaller in the other years. The July precipitation in 2022 and 2023 was more abundant than the long-term mean value, but the rains were torrential and unproductive, that is, a large amount of precipitation fell within several days and the moisture quickly evaporated at elevated temperatures. 2024 had particularly harsh conditions: high temperatures and continuous drought throughout the entire growing period of barley. This had a severely negative impact on the performance and yield, but simultaneously allowed assessing the accessions for drought tolerance.

Results and Discussion

It was found that the primary spike performance was significantly lower in 2024^b (1.42 g) than in 2022 and 2023 (1.81-1.86 g, group ^a), which was explained by an abnormally harsh weather (a prolonged drought combined with high temperatures: the mean daily temperature in June-August reached 32°C). These observations are consistent with data by S.G. Thabet *et al.* (2020) where 121 accessions of the world collection were tested under arid conditions, the outcome was a significant decline in levels of agronomic traits related to barley yield, i.e., spike length, awn length, the numbers of spikelets and grains per spike, and thousand-grain weight. M.A.E.-H. Attia *et al.* (2022) noted that the negative impact of water deficit during the earing and filling phases of naked 'Giza 129', 'Giza 130', and 'Giza 131' on the barley yield and performance and the numbers of spikelets and grains per spike and thousand-grain weight made the greatest contributions to yield. In this study, ANOVA revealed significant differences in all elements of the plant structure depending on growing conditions. The post-hoc comparison showed that the plant height in 2023^b (63 cm) was significantly different from that in 2022^a (55 cm) and 2024^a (54 cm) (Fig. 3).

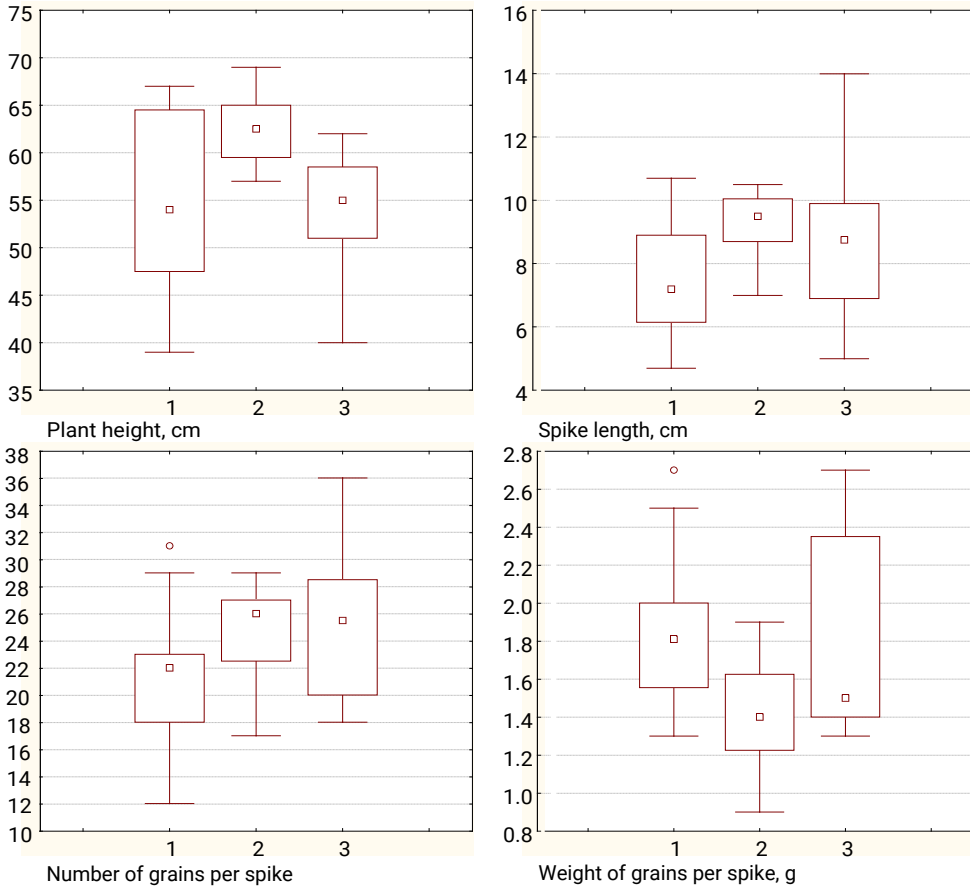


Figure 3. Inter-year variability of the elements of barley plants structure, 2022-2024

Note: study years: 1 – 2022, 2 – 2023, 3 – 2024

Source: constructed by the authors

The spike length in 2022^a (7.5 cm) was significantly different from that in 2024^b (9.3 cm), while the 2023^{ab} value was intermediate (8.7 cm). The number of grains was fewer in 2022^b (21 grains) compared to 2023^a and 2024^a (25 grains). Thus, 2022 was the worst year for the expression of the “spike length” and “number of grains” traits in naked spring barley, which is attributed to the late sowing because of hostilities at the scientific crop rotation site in the 2022 spring. However, this allowed assessing the responses of different naked barley accessions to late sowing. The coefficient of variation of the weight of grains from the primary ear (CV) was 26% in ‘Avhur’, 29% in line

Violet 18-1207, 30% in accession UA 0805462, 34% in accession UA 0800663 and ‘Meber’, 36% in ‘CDC Hilose’, 44% in ‘CDC Alamo’, and 47% in accession UA 0800645. That is, the variability of the primary spike performance was high, as the coefficients of variation exceeded 20% in all accessions. This is consistent with the data by C. Massman *et al.* (2022) that genotype made a greater contribution to thousand-grain weight and plant height than “genotype x environment” interaction, but the “genotype x environment” factor had a five-fold stronger effect on performance variance than genotype. The naked cultivars turned out to be less adaptable to changes of growing

conditions than the chaffy check cultivar ('Avhur'); they responded with greater trait variability to such changes. A trait variability range can be estimated by "whiskers" length on a "box", where the

"whiskers" ends are the limits of a statistically representative sample (without outliers). There were also significant inter-genotype differences in all elements of the plant structure (Fig. 4).

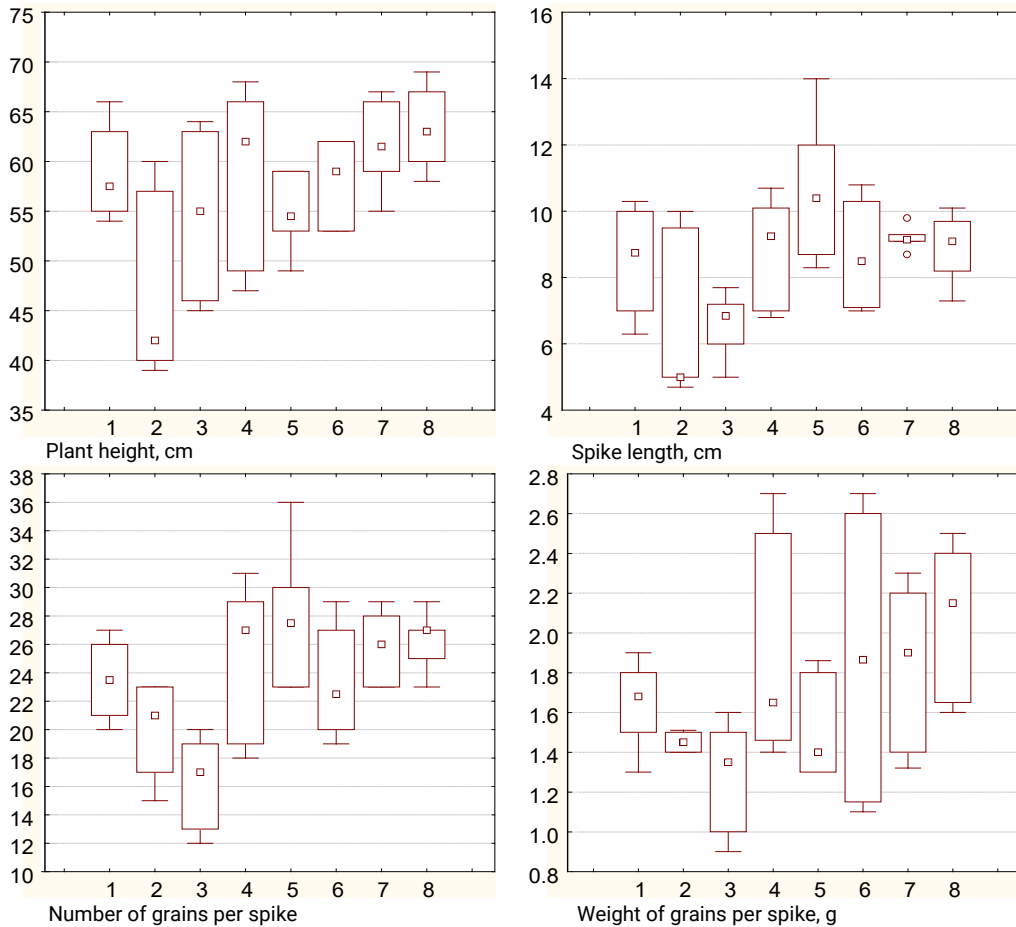


Figure 4. Inter-genotype variability of the elements of barley plants structure, 2022-2024

Note: barley accessions: 1 – Avhur, 2 – UA 0800645, 3 – UA 0800663, 4 – CDC Hilose, 5 – CDC Alamo, 6 – Mebere, 7 – UA 0805462, 8 – Violet 18-1207

Source: constructed by the authors

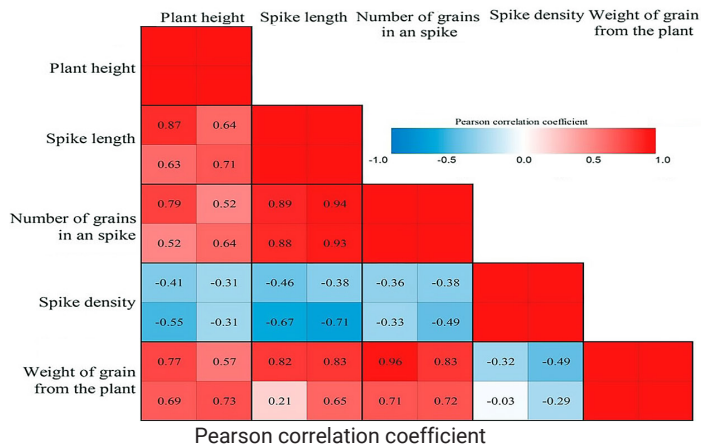
The post-hoc comparison showed that the plant height in UA 0800645^c (47 cm) was significantly different from that in all other accessions, this is explained by the fact that accession UA 0800645 is erectoid and belongs to var. *nudimelanocrithum*. Line Violet 18-1207^b (63 cm) was also taller than accession 'UA 0800663'^a and 'CDC Alamo'^a (55 cm). Other accessions were

classified as group ^{ab} with a plant height of 58–62 cm. The spikes in accessions UA 0800645^c and UA 0800663^c (6.5-6.6 cm) were significantly shorter than those in the other accessions, and 'CDC Alamo'^b (10.6 cm) also had longer spikes than 'Avhur'^a and 'Mebere'^a (8.5-8.7 cm). The other accessions were classified as group ^{ab} with a spike length of 8.9–9.2 cm.

The number of grains per spike was the maximum in 'CDC Alamo'^b (28 grains); 'Avhur'^{ac}, 'Mebere'^{ac} (23–24 grains), and 'CDC Hilose'^{ab}, accession UA 0805462^{ab}, and line Violet 18-1207^{ab} (25–26 grains) had similar numbers of grains in their primary spikes. Accession UA 0800663^d (16 grains) was significantly different from all accessions; accessions UA 0800645^{cd} was at the level of 'Avhur'^{ac}, 'Mebere'^{ac}. As to weight of grains from the primary spike, there were only significant differences between line Violet 18-1207^b (2.08 g) and accessions UA 0800663^c (1.28 g) and UA 0800645^{ac} (1.45 g). The other accessions were classified as groups ^{ab,ac} and ^{abc} (1.45-1.89 g).

Thus, in terms of the primary spike performance, 'CDC Alamo' (var. *nudum*) and line Violet 18-1207 (var. *nudidubium*) were the best accessions, while accessions UA 0800645 (var.

nudimelanocrithum) and UA 0800663 (var. *viride*) showed the lowest performance. Based on the results of ANOVA and boxplot comparison, it was concluded that spike length and the number of grains per spike are the determinants of the performance of naked barley plants. Spike density is a trait that little depends on the weather during cultivation. In this study, this parameter did not significantly change over the years. Among the studied accessions, erectoid accession UA 080064 with a dense spike (14 segments per 4 cm) stood out conspicuously, while the other accessions were classified as loose (10-12 segments per 4 cm). There was a strong correlation between the primary spike performance and the number of grains per spike in all years of the study: the coefficient of correlation was from 0.71 in 2024 to 0.96 in 2022 (Fig. 5).



Correlation coefficients for different years and mean values

2022	2023
2024	Mean

Figure 5. Correlations between the performance constituents in the naked barley accessions
Source: constructed by the authors

The primary spike performance also depended on spike length ($r=0.65-0.83$) and plant height ($r=0.69-0.77$). The number of grains per spike was significantly correlated with spike length and the latter was closely correlated with plant height. Of all the studied traits, only spike density was negatively correlated with other traits, including weight of grains per plant. It is worth noting that there

was a strong negative correlation between spike density and spike length ($r=0.69-0.77$). This is explained by the fact that there was accession UA 0800645 (var. *nudimelanocrithum*), which is erectoid, i.e., has shortened internodes and very dense short spikes, in the sample analysed in this study.

A similar conclusion regarding negative correlation between performance and spike density

was drawn by C. Fan *et al.* (2024), who reported about a significant positive correlation between the number of nodes per rachis and spike length and a significant negative correlation between spike density and spike length. A genome-wide association study of agronomic traits in 431 spring barley accessions, including landraces and old cultivars from the Polish Gene Bank, failed to find a positive correlation between spike density and other agronomic traits (Karabach & Berezniak, 2021; Czembor & Czembor, 2022). The following correlation cluster was established: performance → number of grains per spike → spike length. However, spike length was closely correlated with plant height; therefore, plant height also significantly, though indirectly, affects performance through spike length (Fig. 6).

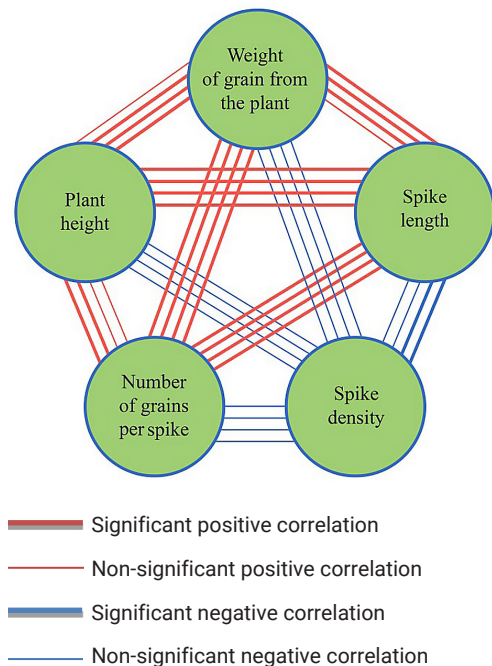


Figure 6. Correlation clusters of the performance constituents in the naked barley accessions
Source: constructed by the authors

Since such a correlation was unchanged for several years, one can affirm that performance-oriented selection can be driven by the

“spike length” and “the number of grains per spike” traits. This enables pre-harvest culling, facilitating and accelerating breeding algorithms. However, it should be noted that these conclusions are correct for the naked barley sample under study and specific growing conditions. In studies on other cultivars/accessions or/and in other environments, differing results can be obtained due to various compensatory effects of plants of different barley cultivars.

This data on the significant contribution of the number of grains in the primary spike to barley performance are consistent with R.A. Serrago *et al.* (2025). Thus, in order to create a database of barley yield and its constituents, in particular, the number of grains per spike and thousand-grain weight, scientific studies on barley in four journals (Field Crop Research, European Journal of Agronomy, Crop and Pasture Science) over 25 years were reviewed. It was found that the number of grains was more closely correlated with yield (86% of yield variability) than thousand-grain weight (13%).

According to V. Thirulogachandar & T. Schnurbusch (2021), determination of yield potential by the number of grains is a step towards increasing yields of cereals, including barley. To achieve this goal, it is extremely important to establish the maximum yield potential, which is determined by the number of spikelet buds per spike in. The number of and weight grains of per spike was also defined as the major constituents of barley performance. The researchers found that the inter-environmental factor and inter-genotype variability of performance were usually attributed to variations in the number of grains. Therefore, the performance potential fulfilment depends on how optimal environmental conditions are in the critical phase, when the number of grains per spike is determined.

Aarushi *et al.* (2023) investigated the impact of drought on barley and found that plant height and spike length varied greatly (40-60%) under stress, while the number of grains per spike changed little (about 11%). They also reported a

negative effect of drought on chlorophyll content, flag leaf area, plant height, and grain weight from the primary spike, whereas the trait “spike length” remained comparatively stable. T. He *et al.* (2023) noted that plant height and performance are complex traits and are influenced by numerous genes; therefore, the pleiotropic effects of these genes contribute to the positive correlation between these two traits. It was reported about correlations between spike length and the number of grains per spike, between spike length and weight of grains per spike, and between the number of grains per spike and weight grains per spike. Based on a positive regression, it was concluded that the number of grains per spike meant a larger weight of grains per spike. According to a study by N. Vasko *et al.* (2023), performance was strongly correlated with productive tillering capacity, weight of grains per spike, and spike length and moderately correlated with the number of grains per spike. Weight of grains per spike was significantly strongly correlated with spike length and the number of grains per spike; spike length was correlated with plant height.

Similar findings were obtained by G. Akdogan *et al.* (2025), who claimed that the number of grains per spike was one of the three major components that determine barley yield, along with the number of spikes per 1 m² and thousand-grain weight. According to their data, there was a strong positive correlation between the number of grains and weight of grains per spike ($r = 0.85$). Plant height was significantly positively correlated with all yield indicators, and as a result of predicting the effectiveness of breeding for increased harvest index, the number and weight of grains per spike turned out to be the most promising traits.

According to V. Kaur *et al.* (2022), plant height is an important trait for barley yield because shorter plants with stronger stems are less prone to lodging, while taller plants contribute to greater photosynthetic capacity. Their study showed a strong positive correlation of plant height with spike length, number of grains per spike, and

number of spikelet triplets per spike. Together with spike traits, plant height explained up to 78% of the total yield variance, highlighting its central role in determining performance. Data of K.T. Desta *et al.* (2024) are somewhat different, stating positive correlations between plant height and the number of grains per spike, between spike length and plant height and between spike length and awn length but a negative correlation between spike length and the number of grains per spike. Given the stability of spike length and number of stems per plant (bushiness) in environments with different degrees of drought, one can assume their potential as reliable selection criteria in breeding for drought tolerance. The analysis confirmed clear variability in plant structure elements among the studied naked barley accessions. Grain number and spike traits proved to be the main factors influencing differences in their performance.

Conclusions

The study of naked spring barley variability and performance correlations under arid conditions revealed significant relationships between performance and spike length ($r = 0.65-0.83$), between performance and grain number ($r = 0.71-0.96$), and between performance and grain weight per spike ($r = 0.73$). Performance was also indirectly related to plant height. The correlation pattern “performance → number of grains per spike → spike length” was established, with plant height and other performance constituents being closely positively correlated regardless of environmental conditions. The exception was spike density, which showed negative correlations with all other parameters under study. Considering the low variability of grain number per spike and the strong relationship between grain number and spike length ($r = 0.93$), these traits were determined as essential for high performance selection in naked spring barley. Sources of long spikes were identified: ‘CDC Alamo’ (10.6 cm); sources of high grain numbers were detected: ‘CDC Alamo’ (28 grains) and ‘CDC Hilose’, accession UA 0805462, and line Violet 18-1207 (25-26 grains).

Line Violet 18-1207 was also distinguished by grain weight per spike (2.08 g).

The revealed patterns provide a foundation for further research and breeding programmes. Statistical analysis identified valuable accessions suitable for use as starting materials in hybridisation. The stability of correlations across different environmental conditions confirmed the reliability of these traits as selection criteria. Identifying sources of valuable traits was found to be crucial for enhancing naked barley yield and addressing food security needs, particularly under climate change conditions. The introduction of naked barleys with pigmented caryopses was determined

to be promising for sustainable agricultural development in medium and small enterprises.

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Conflict of Interest

None.

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Кореляція елементів продуктивності ярого ячменю в посушливих умовах

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Анотація. Ячмінь має унікальні дієтичні властивості та є одним з найбагатших джерел фенолових сполук серед зернових культур, тому зростає зацікавленість зерном ячменю як сировиною для продукції функціонального харчування. Метою дослідження було виділення цінного вихідного матеріалу для селекції голозерного ярого ячменю з кольоровим зерном. Для цього було визначено рівень продуктивності та її зв'язок із структурними елементами (довжиною колоса, кількістю зерен у колосі) і висотою рослини. Вихідним матеріалом були сім зразків голозерного ячменю з кольоровим зерном та стандарт – плівчастий ячмінь сорту 'Avhur'. Серед голозерних сорти з жовтим зерном 'CDC(Crop Development Centre) Hilose', 'CDC Alamo' та 'Mebere' (var. nudum), колекційні зразки UA 0800645 var. nudimelanocrithum (чорне зерно), UA 0800663 var. viride (зелене зерно), UA 0805462 var. daghestanicum (сіро-зелене зерно), лінія селекції IP НААН Violet 18-1207 var. nudidubium (фіолетове зерно). Статистичну обробку здійснено за дисперсійним аналізом ANOVA з апостеріорним порівнянням за Fisher LSD та кореляційним аналізом. Показано широку мінливість продуктивності ($V = 26-47\%$), встановлено тісну сильну кореляцію між продуктивністю головного колоса та елементами її структури ($r = 0,65-0,96$). У результаті виділено кореляційний кластер продуктивність \rightarrow кількість зерен у колосі \rightarrow довжина колоса. Враховуючи низьку мінливість ознаки кількість зерен у колосі та сильну кореляцію між кількістю зерен та довжиною колоса, встановлено, що ці ознаки є ключовими для добору на високу продуктивність. Визначено джерело довгоколосості сорт 'CDC Alamo' (10,6 см) та великої кількості зерен у колосі – сорт 'CDC Alamo' і лінія Violet 18-1207 (28-26 зерен). Виділення джерел цінних ознак є важливим для селекції на підвищення врожайності голозерного ячменю та задоволення потреб у продовольстві, особливо в умовах зміни клімату

Ключові слова: голозерний ячмінь; мінливість; головний колос; кількість зерен; висота рослини; маса зерна з колоса; кореляційний кластер