UDC 633.11+575.21

# YIELD AND TRAITS OF LEAVES ASSIMILATION SURFACE OF WINTER WHEAT

**G. O. Priadkina*, N. M. Makharynska, D. V. Konovalov**

*Institute of Plant Physiology and Genetics of the National Academy of Sciences of Ukraine,*
*31/17, Vasylkivska Str., Kyiv, Ukraine, 03022*

*E-mail: galpryadk@gmail.com*, nadjavasko@ukr.net, davidkonovalov@ukr.net*

*ORCID: https://orcid.org/0000-0002-4548-1747, https://orcid.org/0000-0002-9987-6437,*
*https://orcid.org/0000-0003-1254-2926*

Received / Received / Accepted July 19, 2023

**Aim**. To determine markers of drought tolerance based on the analysis of the traits leaves assimilation surface in 6 varieties of winter wheat with near drought tolerance under conditions of field drought in the Forest-Steppe of Ukraine. **Methods**. Traits of leaves assimilation surface was determined used field, morphometric, phenological and spectrophotometric methods. **Results**. Under conditions of field drought during the grain filling period the dry weight of flag leaf and of all green leaves of the main shoot of 2 high-yielding varieties (Kyivska 17 and Horodnytsia) at anthesis and milk ripeness were higher, than that of 4 others on average over 3 years. The specific weight of the flag leaves of the main shoot and chlorophyll content slightly differed in the studied varieties. The variability of the dry weight of flag leaf and of all green leaves of the main shoot of winter wheat varieties at anthesis and at milk ripeness was greater than the variability of their chlorophyll content it was found. A close correlation between the dry weight of flag leaf at anthesis and at milk ripeness, as well as all green leaves, with the yield (r = 0.658–0.837) was established. **Conclusions.** The higher yield of winter wheat varieties with a higher leaf dry weight under drought conditions may be due to the formation of a more amount of photoassimilates, which can be used both for root growth (water deficit avoidance strategy) and for the storage of reserved assimilates in the stem (strategy of create reserves for further filling of grain). The dry weight of flag leaf of the main shoot at anthesis can be used as a morphometric marker of drought tolerance, given the close correlation with the yield and the simplicity and convenience of determinations in the field.

**Key words:** *Triticum aestivum* L., field drought, leaf weight, chlorophyll.

**DOI:**

## INTRODUCTION

Global food security in today world requires increased food production. On this purpose the most important for mankind are grain crops. Wheat (*Triticum aestivum* L.) is the second (after rice) most important and widespread food cereal crop in the world (Dowla et al, 2018). It provides about 20 % of total calories and the similar portion of total protein for the world's population (Braun et al, 2010; Nemati et al, 2022).

At the same time, current climate trends indicate that main abiotic limiting factors for wheat production worldwide are drought and increasing air temperatures. Drought constrains wheat production worldwide and reduces its yield by 10–50 % (Zulkiffal et al, 2021; Zandalinas et al, 2021). This problem is also relevant for Ukraine (Balabukh, 2023).

To ensure food security, it is important to breed varieties that are adapted to drought conditions. The tolerance of plants to stress is a complex, genetically fixed trait that manifests itself under stress action. Identifying traits that are associated with increasing the potential productivity of wheat and the adaptive potential under conditions of soil moisture deficit is important for speeding up the breeding process.

Drought stress negatively impacts on the various morphological, physiological, biochemical and molecular plant characteristics, which can lead to impaired plant functioning (Sallam et al, 2019; Kapoor et al, 2020). One of the drought-sensitive links in wheat is the photosynthetic apparatus. In particular, it was established that the net photosynthetic rate, stomatal conductance, and transpiration decrease in drought-sensitive wheat varieties under moisture deficit (Saeidi and Abdoli, 2015). Such genotypes also show suppression of ribulose-1,5-bisphosphate regeneration process (Yang et al, 2021), and a reduce in the expression of the small subunit of the main photosynthetic enzyme – ribulose-1,5-bisphosphate carboxylase (Dwivedi et al, 2018). A decrease in the maximum quantum yield of photosystem II, the electron transport from $Q_A$ to $Q_B$, and carboxylation rate are characteristic of the drought-sensitive genotypes (Yang et al, 2021; Ghaffar et al, 2023). A decrease in the photosynthetic pigments content is observed under the influence of this stress factor, also (Saeidi and Abdoli, 2015; Dwivedi et al, 2018). At the same time, it is noted that under a lack of water, drought-tolerant wheat genotypes were reduce less the flag leaf chlorophyll content, than sensitive ones.

In addition, under the drought influence, the assimilation surface decrease, in particular – the leaf dry weight and area (Amoah et al, 2019) due to the fact that water stress inhibits cell growth, accelerates the aging of leaves and reduces the amount of formed photoassimilates.

So, the effect of drought is evident at different levels of the photosynthetic apparatus organization. Changes that contribute to the acquisition of tolerance to drought at the lower levels of the organization of the plant organism (for example, molecular) can be apparent at higher levels (organ and organism). Therefore, the search for drought tolerance markers is conducted at different levels of plant organization. Usually, a close correlation relationships between traits related to drought tolerance and yield are found for contrasting genotypes - due to a significant difference between them under the controlled drought conditions (more or less severe). At the same time, although a significant part of modern wheat varieties are drought-tolerance, their yield under lack of water in natural conditions can also be different.

An important plant organ is a leaf, in which absorbed solar radiation is transformed into chemical energy for the synthesis of organic substance. Photoassimilates, witch formed in the process of photosynthesis are the basis for further metabolic and growth processes, including grain filling. In this regard, we conducted a comparative analysis of the leaves assimilation surface traits in varieties with similar drought resistance, in years with different weather conditions.

The aim of this study was to analyze the leaves assimilation surface traits of soft winter wheat in order to identify physiological markers associated with tolerance to drought.

## MATERIALS AND METHODS

Research was conducted during three seasons of (2019–2020, 2020–2021, 2021–2022) at the winter wheat variety testing sites in the experimental field of the Institute of Plant Physiology and Genetics of the NAS of Ukraine (Kyiv region, 50º 16’ S, 30º 19’ E) under conditions of natural moisture supply.

Wheat varieties were sown, providing the recommended sowing density for wheat production, which was 550–600 grains per $m^2$ in plots 6.67 m long and 1.5 m wide (10 $m^2$) with 10 rows per plot. Before sowing and during the growing season, 145 kg of nitrogen (N) and 90 kg of phosphorus ($P_2O_5$) and potassium ($K_2O$) were applied per 1 ha. Agrotechnical measures and canopy management were generally accepted for this culture in the forest-steppe agroclimatic zone of Ukraine. Three replicates were applied for each variety.

The research was carried out on six varieties of bread winter wheat (*Triticum aestivum* L.), breeding at the Institute of Plant Physiology and Genetics: Kyivska 17, Horodnytsia, Pochayna, Krasnopilka, Poradnytsia, and Smuhlianka. The first five of them are modern varieties entered into the State Register of plant varieties suitable for distribution in Ukraine in 2017–2018, Smuhlianka variety – in 2003, but still a popular. The drought resistance of the first five varieties varies from 8 to 9 points, the last one – from 7 to 9. All varieties are recommended for growing in the Steppe and Forest Steppe. Phenological observations of the growth stages were carried out according to the external morphological changes of the formed organs every 3–4 days (Zadoks et al, 1974).

Morphometric measurements were carried out on 10 main shoots at anthesis and milk-wax ripeness, and biochemical ones – in average samples formed from these shoots. The average sample for determining the chlorophyll content was formed from the leaves of 5 plants, for the determination of % dry matter – from the fresh 5 plants. To determine dry weight of flag and all green leaves of the main shoot, the samples were fixed in an oven at a temperature of 105 ºC for 1 hour and after that dried to a constant weight at 65 ºC. The specific leaf weight was calculated as the ratio of leaf dry weight to leaf area. The inclination angle was defined as the inclination between the midvein of the leaf blade and the vertical stem of the plant.

The chlorophyll content (*a* and *b*) determination was carried out by the maceration-free method by extracting pigments with dimethylsulfoxide (DMSO) according to A.P. Wellburn method (1994). 100 mg of the sample (averaged from the leaves of 5 plants) was poured with 10 ml of DMSO. Subsequently, the tubes were placed in a water bath (water temperature of 67 ºC) for 4 hours. One ml of the obtained solution was made up to 4 mL by adding DMSO, and the optical density of this solution was determined on a Specord 200 spectrophotometer (AnalyticJena, Germany) at wavelengths of 480, 649, and 665 nm. Recalculation of the content of pigments per gram of dry weight was carried out taking into account all dilutions and leaf mass. Three analytical replicates were taken.

Yield was determined by direct harvesting method in 3 replications of each variety.

Temperature conditions during the spring-summer periods of winter wheat were characterized by values both higher and lower than the climatic norm (**Table 1**).

The temperature in May (the period of reproductive organs formation) in all three years was lower than normal. However, at the periods of anthesis and of grain filling (June-July), it exceeded the norm by 1.8–3.5 ºC, with the exception of July 2022 (Table 1). The effect of elevated temperatures during these two months was enhanced by the amount of precipitation that was less than the climatic norm. 2022 was the longest period with a lack of precipitation: the amount of precipitation from May to July was less than the norm by almost 2 times (Table 1).

**Table 1**. The deviation monthly values of air temperature and monthly amount of precipitation during period of spring-summer vegetation of winter wheat in 2020–2022 from long-term average mean

| Year | Month | | | |
|---|---|---|---|---|
| | April | May | June | July |
| *The deviation average monthly air temperature from climatic norm, ºC* | | | | |
| 2020 | +0.6 | –3.1 | +3.1 | +1.4 |
| 2021 | –0.2 | –1.4 | +1.8 | +3.3 |
| 2022 | –1.9 | –1.2 | +2.2 | –0.8 |
| *The deviation monthly amount of precipitation from climatic norm, mm* | | | | |
| 2020 | –10 | +69 | –24 | –41 |
| 2021 | +3 | +9 | –50 | –5 |
| 2022 | +1 | –31 | –32 | –30 |

Note: The difference with the average long-term value for each year are indicated as + (upper values) and – (lower ones).

Statistical processing of the results was carried out using one-way ANOVA in MS Excel 2010. Figures and tables show means and standard errors (m ± SE). The difference between the data was considered significant at $P \leq 0.05$.

## RESULTS AND DISCUSSION

As indices characterizing the size of the assimilation surface, we analyzed the changes in the morphological and pigment traits of the flag leaves, as well as all green leaves of the main shoots of winter wheat varieties under drought conditions during anthesis period and/or grain filling.

The dry weight of the flag leaf at anthesis in 2020 and 2022 in varieties was varied from 118 to 181 mg, while in 2021 its values for all varieties were higher: 137–240 mg of dry weight (**Fig. 1, *a***). This probably was due to more favorable meteorological conditions in the period before anthesis (Table 1). On average for 3 years, the flag leaf dry weight at this stage was higher in the Kyivska 17 and Horodnytsia varieties, and lower in the Smuhlianka and Poradnytsia.

In 2020, Kyivska 17 variety was distinguished by the highest flag leaf dry weight at milk ripeness, and Krasnopilka and Poradnytsia – by the lowest (**Fig. 1, *b***). In 2021, this index value in Kyivska 17, Horodnytsia, Pochayna and Poradnytsia varieties (183–207 mg) was higher than in Smuhlianka and Krasnopilka (134–140). In 2022, the Krasnopilka variety had the maximum flag leaf dry weight (189 ± 11 mg), while it ranged from 141 to 153 mg in the rest of the varieties.

Kyivska 17, Horodnytsia, and Pochayna varieties had the higher green leaves dry weight on the main shoot at anthesis in all three years (**Fig. 2, *a***) and at milk ripeness in 2020 (**Fig. 2, *b***). In 2021, at milk ripeness stage, Kyivska 17, Pochayna, and Poradnytsia varieties were characterized by a higher green leaves dry weight, and in 2022, it was near to all varieties.

On average, over 3 years, 2 varieties – Kyivska 17 and Horodnytsia – were distinguished by a greater dry weight of both flag and all green leaves of the main shoot.

In 2020 and 2021, Kyivska 17 and Pochayna varieties were distinguished by a higher chlorophyll content in the flag leaves at anthesis stage (11.5–12.6 mg $g^{-1}$ dry weight), in 2022 – also Horodnytsia and Krasnopilka varieties (11.8–12.3) (**Fig. 3, *a***). At milk ripeness stage,

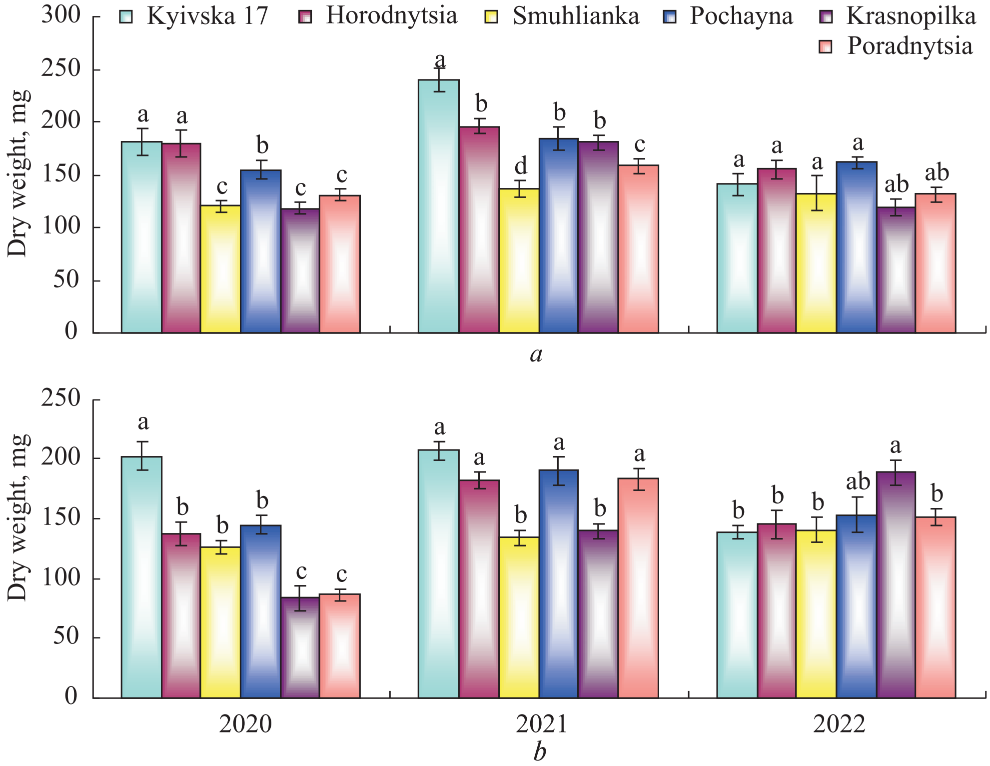

**Fig 1.** Flag leaf dry weight of main shoot, mg, at anthesis (*a*) and milk ripeness (*b*) stages in six varieties of bread winter wheat. Note. Values in the columns, labelled with different Latin letters, differ significantly at P ≤ 0.05 between varieties in each individual year. Vertical bars indicates SE (n = 10)

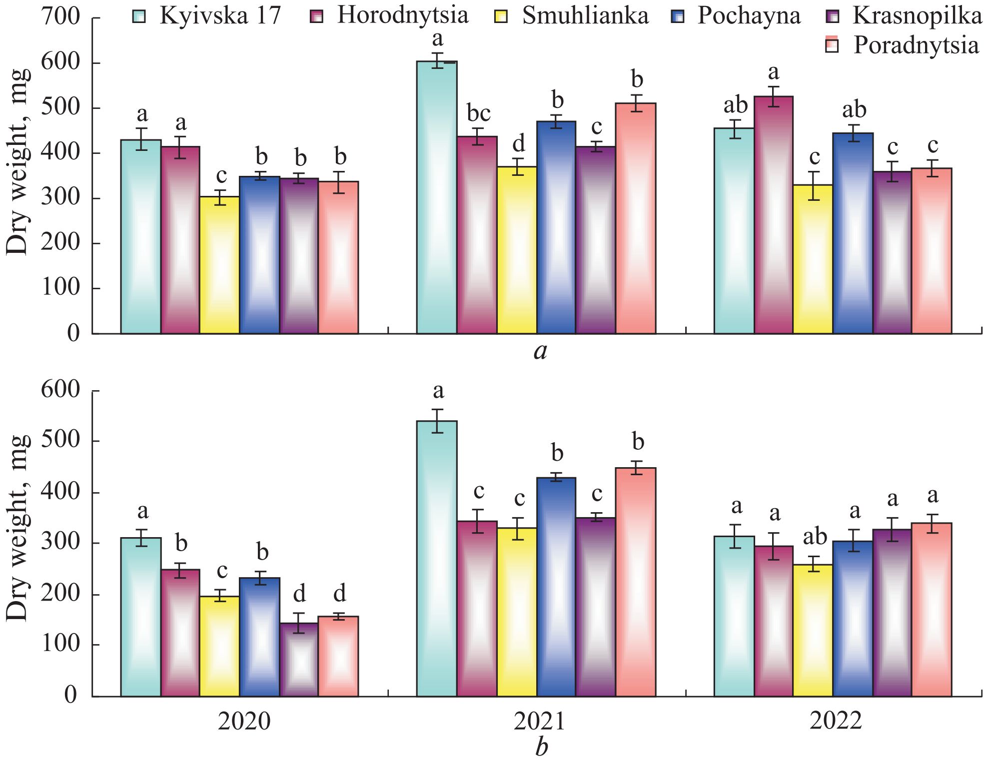

**Fig. 2.** Dry weight of green leaves of main shoot, mg, at anthesis (*a*) and milk ripeness (*b*) stages in six varieties of bread winter wheat. Explanation under Fig. 1

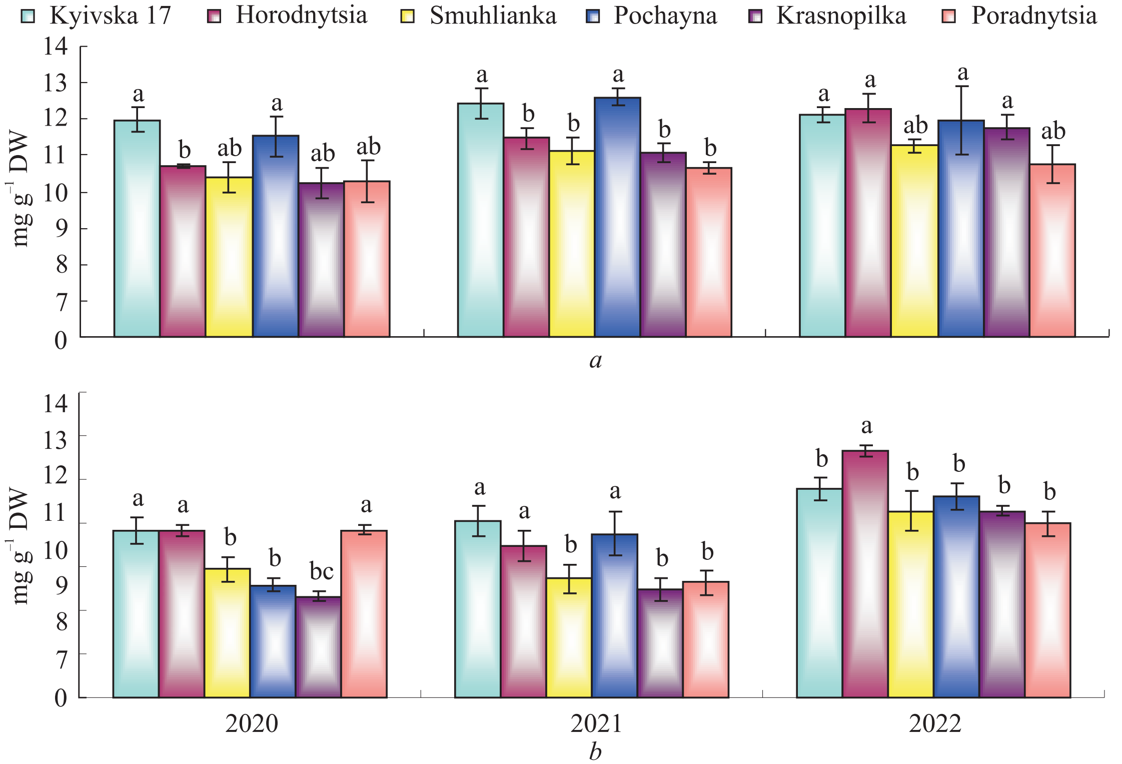

**Fig. 3.** Total chlorophyll content (*a* + *b*), mg g$^{-1}$ dry weight, in main shoots flag leaves of six bread winter wheat varieties at anthesis (*a*) and milk ripeness (*b*) stages. Explanation under Fig. 1

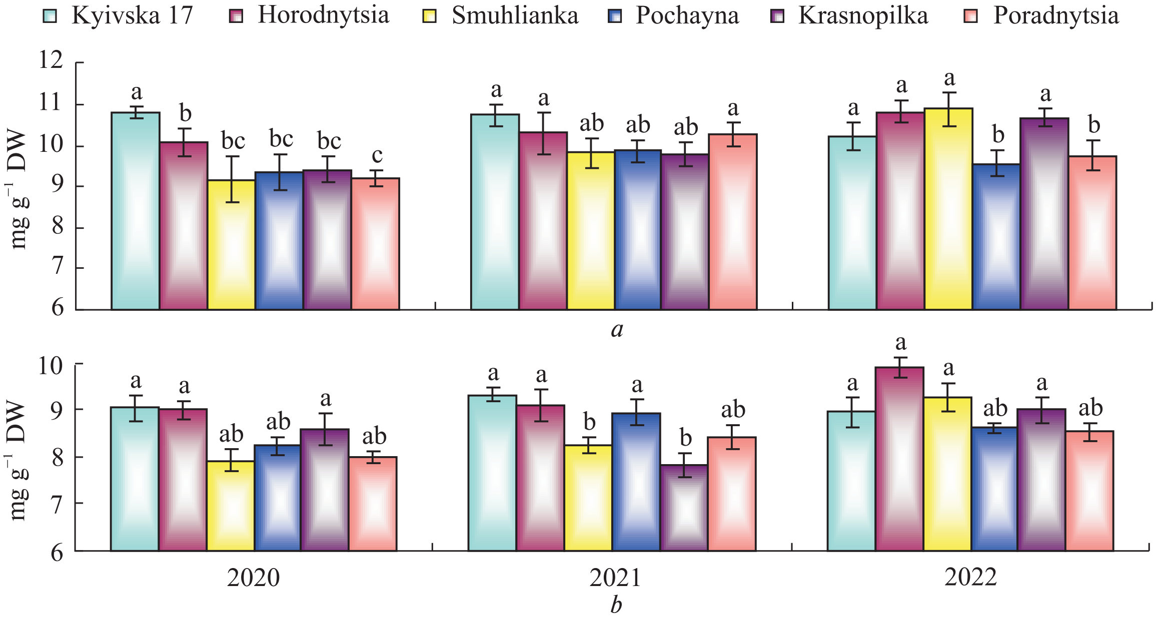

**Fig. 4.** Chlorophyll total content (*a* + *b*), mg g$^{-1}$ dry weight, in main shoots green leaves of six bread winter wheat varieties at anthesis (*a*) and milk ripeness (*b*) stages. Explanation under Fig. 1

Horodnytsia variety was distinguished by a high total chlorophyll content in all 3 years (10.7–12.3) (**Fig. 3, *b***).

The higher chlorophyll content in green leaves of the main shoot in all 3 years was characterized in the varieties Kyivska 17 and Horodnytsia at anthesis (10.2–10.8 mg g$^{-1}$ dry weight) (**Fig. 4, *a***) and milk ripeness (8.9–9.3) stages (**Fig. 4, *b***). Although the difference with other varieties was mostly small.

The analysis of wheat grain productivity showed that Kyivska 17 and Horodnytsia varieties had higher yields in 2020, Kyivska 17, Horodnytsia and Krasnopilka in 2021, and Horodnytsia and Krasnopilka in 2022 (**Table 2**). The highest yields of all varieties were in 2021.

The analysis of the main shoot assimilation surface traits revealed that the dry weight of both the flag leaf and all green leaves at both stages in 2021 was also higher, compared to 2020 and 2022 (Fig. 1 and 2), at that time as the chlorophyll content changed a little depending on the conditions of the year (Fig. 3 and 4).

A greater influence of the leaves dry weight than the chlorophyll content in them on grain productivity is also confirmed by higher or with a greater degree of probability correlation coefficients of these traits relationships with the yield (**Table 3**).

Less close correlation between the chlorophyll content and the yield may be caused by less variability of photosynthetic pigments in the studied genotypes, than the leaves dry weight (Fig. 1–4). Indeed, the variability of the chlorophyll content in both the flag leaf and all green leaves of the main shoot at each of the studied stages was insignificant, while the leaves dry weight was medium and significant (**Table 4**).

Literature data suggests that under drought conditions, the decrease in chlorophyll content in the upper fully developed leaves, compared to the irrigated control, depended little on drought tolerance both at pre-anthesis and at anthesis periods (Dwivedi et al, 2018). In addition, high chlorophyll content is not always a marker of high-yielding varieties, especially in the period when the leaf apparatus is maximally developed. This is due to the peculiarities of the distribution and use of light energy in the upper layers and inside the crop. Therefore, a high content of this pigment in the upper/flag leaves can lead to an increase in energy dissipation in non-photochemical processes and a decrease in the radiation use efficiency, while in the lower leaves, on the contrary, it can contribute to a higher photosynthetic activity (Slafer et al, 2021; Moustakas et al, 2022). Thus, it was shown that diploid species of *Triticum* and *Aegilops* with lower chlorophyll content and lower specific leaf weight had the maximum rate of photosynthesis (Kaminski et al, 1990).

Therefore, taking into account the low variability of chlorophyll content in the green leaves, it can be assumed that the amount of absorbed solar energy by the pigment apparatus in the studied wheat varieties was approximately the same. In addition, the leaves of upper tiers in all varieties were erectoid. Hence, the radiation regime inside the crops and the availability of carbon dioxide differed little.

**Table 2.** Yield, t ha$^{-1}$, of 6 bread winter wheat varieties, obtained in 2020–2022, (m ± SE, n = 3)

| Variety | Year | | |
|---|---|---|---|
| | 2020 | 2021 | 2022 |
| Kyivska 17 | 8.16 ± 0.39 $^{a, B}$ | 8.16 ± 0.39 $^{a, B}$ | 8.16 ± 0.39 $^{a, B}$ |
| Horodnytsia | 6.87 ± 0.28 $^{b, C}$ | 6.87 ± 0.28 $^{b, C}$ | 6.87 ± 0.28 $^{b, C}$ |
| Smuhlianka | 5.30 ± 0.19 d$^{, C}$ | 5.30 ± 0.19 $^{d, C}$ | 5.30 ± 0.19 $^{d, C}$ |
| Pochayna | 5.94 ± 0.29 $^{c, C}$ | 5.94 ± 0.29 $^{c, C}$ | 5.94 ± 0.29 $^{c, C}$ |
| Krasnopilka | 5.71 ± 0.25 $^{c, C}$ | 5.71 ± 0.25 $^{c, C}$ | 5.71 ± 0.25 $^{c, C}$ |
| Poradnytsia | 6.06 ± 0,30 $^{c, C}$ | 6.06 ± 0,30 $^{c, C}$ | 6.06 ± 0,30 $^{c, C}$ |

Note. Values denoted by different Latin letters differ significantly: small ones – between varieties in each individual year, large ones – for each of the varieties in some years.

**Table 3.** Correlation coefficients between some main shoot assimilation surface traits at anthesis and milk ripeness and the yield (n–2 = 16)

| Trait | Organ | Stage | |
|---|---|---|---|
| | | Anthesis | Milk ripeness |
| Dry weight | Flag leaf | 0.658 ± 0.188 ** | 0.660 ± 0.188 ** |
| | Green leaves | 0.714 ± 0.175 *** | 0.837 ± 0.137 *** |
| Chlorophyll content | Flag leaf | 0.542 ± 0.210 * | 0.243 ± 0.243 |
| | Green leaves | 0.595 ± 0.200 ** | 0.375 ± 0.232 |

Note. * – $P \leq 0.05$, ** – $P \leq 0.01$, *** – $P \leq 0.001$.

**Table 4.** Variability of winter wheat main shoot assimilation surface traits

| Stage | Minimum mean | Maximum mean | Average mean | Coefficient of variability |
|---|---|---|---|---|
| *Dry weight of flag leaf, mg DW* | | | | |
| Anthesis | 0.118 | 0.118 | 0.156 ± 0.032 | 20.67 |
| Milk ripeness | 0.084 | 0.084 | 0.152 ± 0.035 | 23.18 |
| *Chlorophyll content of flag leaf, mg/g DW* | | | | |
| Anthesis | 10.23 | 12.61 | 11.37 ± 0.76 | 6.73 |
| Milk ripeness | 8.31 | 11.64 | 9.66 ± 0.91 | 9.40 |
| *Dry weight of all green leaves mg DW* | | | | |
| Anthesis | 0.302 | 0.605 | 0.415 ± 0.079 | 19.08 |
| Milk ripeness | 0.145 | 0.449 | 0.310 ± 0.099 | 31.99 |
| *Chlorophyll content of all green leaves mg/g DW* | | | | |
| Anthesis | 8.45 | 11.21 | 10.00 ± 0.73 | 7.30 |
| Milk ripeness | 7.82 | 9.89 | 8.71 ± 0.55 | 6.31 |

**Table 5.** Specific weight of main shoot flag leaves, mg cm$^{-2}$, in winter wheat varieties, (m ± SE, n = 10)

| Stage | Variety | Year | | |
|---|---|---|---|---|
| | | 2020 | 2021 | 2022 |
| Anthesis | Kyivska 17 | $5.37 \pm 0.16^{aA}$ | $5.56 \pm 0.21^{aA}$ | $5.11 \pm 0.21^{bA}$ |
| | Horodnytsia | $5.79 \pm 0.17^{aA}$ | $5.36 \pm 0.15^{abAB}$ | $6.11 \pm 0.14^{aA}$ |
| | Smuhlianka | $4.95 \pm 0.08^{bA}$ | $5.32 \pm 0.13^{abA}$ | $5.01 \pm 0.20^{bA}$ |
| | Pochayna | $5.75 \pm 0.21^{aA}$ | $5.63 \pm 0.17^{aA}$ | $5.71 \pm 0.18^{aA}$ |
| | Krasnopilka | $4.78 \pm 0.31^{bB}$ | $5.92 \pm 0.32^{aA}$ | $5.20 \pm 0.19^{bA}$ |
| | Poradnytsia | $5.16 \pm 0.08^{b}$B | $6.11 \pm 0.39^{aA}$ | $5.02 \pm 0.12^{bA}$ |
| Milk ripeness | Kyivska 17 | $5.70 \pm 0.14^{aA}$ | $5.56 \pm 0.09^{bA}$ | $5.29 \pm 0.10^{bB}$ |
| | Horodnytsia | $5.57 \pm 0.22^{aB}$ | $6.19 \pm 0.14^{aA}$ | $5.64 \pm 0.23^{bA}$ |
| | Smuhlianka | $4.86 \pm 0.06^{bA}$ | $4.86 \pm 0.13^{cA}$ | $5.15 \pm 0.18^{bA}$ |
| | Pochayna | $5.56 \pm 0.19^{aA}$ | $5.93 \pm 0.16^{aA}$ | $5.31 \pm 0.13^{bA}$ |
| | Krasnopilka | $4.47 \pm 0.60^{bA}$ | $5.30 \pm 0.11^{bA}$ | $5.53 \pm 0.14^{aA}$ |
| | Poradnytsia | $5.12 \pm 0.18^{bA}$ | $5.18 \pm 0.08^{bcA}$ | $5.24 \pm 0.12^{bA}$ |

Note. Values denoted by different Latin letters differ significantly: small ones – between varieties in each individual year, large ones – for each of the varieties in some years.

The thickness of the leaf plate is considered an important feature of leaves that is related to the light interception and light use efficiency (Amanullah, 2015). The analysis of the flag leaves specific weight value, which indirectly characterizes the thickness of the leaf plate, showed that the difference between the varieties was also not large (**Table 5**). Hence, the difference in grain productivity of the studied varieties is not related to the increase in the leaf plate thickness.

## DISCUSSION

Therefore, the research found that, the varieties with higher grain productivity differed by a greater flag leaf dry weight at anthesis and milk ripeness stages than the less productive varieties. This may be related to the fact that bigger leaves can synthesize more photoassimilates. These assimilates, first of all, can be used for root growth, namely, to help the plant avoid water shortage due to deep rooting. And since drought stress tended to decrease in uptake and use of nitrogen, potassium, magnesium, calcium, etc. by plants (Sallam et al, 2019), the growth of roots will contribute to better absorption and translocation of micro- and macroelements to the stem. In particular, the reduction of nitrogen absorption affects the chlorophyll content and photosynthetic processes (Mobasser et al, 2014). It has also been shown that the change in the ionic homeostasis of plants during drought due to a decrease in their availability, uptake, and translocation besides violation the nutrients metabolic pathways in plants, leads to a limitation of plants growth rate, early aging of the photosynthetic apparatus, a reduction in the duration of the grain filling period and a decrease in productivity (Sallam et al, 2019).

Photoassimilates are an important source for grain filling. The higher yield of winter wheat genotypes with a bigger dry weight at anthesis may be related to the fact that such varieties have a higher photosynthetic rate. In particular, 20% increase in flag leaf photosynthetic rate during the grain filling period in spring wheat lines (due to the foreign translocation 7DL.7Ag), compared to control plants, was accompanied by a 12% increase in their grain productivity (Reynolds et al, 2005). Similarly, under combined heat and drought stress, near-isogenic lines with higher photosynthetic activity (photosynthetic rate, amount of chlorophyll and leaf area duration) showed 49.52–50.08 % decrease in yield, compared to the control, when the lines with lower photosynthetic activity showed 61.05–62.17% reduce (Kumar et al, 2022). The increased photoassimilates formation at anthesis will also contribute to the down regulation of photosynthetic rate by increasing the size of the sink (stem), and their transport to the stem will also create reserves for further grain filling (Morgun et al, 2019).

The higher yield of winter wheat varieties with a higher dry weight at milk ripeness can be due to the formation of a larger amount of photoassimilates due to the prolongation of the photosynthetic apparatus functioning in the reproductive period. The stay-green is considered as crucial trait for genetic improvement of five major grain crops, including wheat (Kamal et al, 2019). Thus, among 184 wheat lines obtained from parental lines contrast for yield and stay-green, genotypes with higher, more stable yield kept green leaf area longer (Christopher et al, 2016). The hexaploid wheat stay-green cultivar Chuannong17 had, on average, twice photosynthetic rate and a third higher plant grain yield than the cultivar Mianyang11 without such a trait (Luo et al, 2009). It is assumed that the increase in the photoassimilates production after anthesis by optimizing their distribution between the source and sink, together with the increased demand for assimilates from the sink, determines the higher yield of such genotypes (Luo et al, 2009; Li et al, 2022). It has also been shown that in order to realize the yield potential due to the delay in leaf senescence, this trait must be accompanied by an increased ability to grain filling (Borrill et al, 2015). An analysis of recent literature data evidences that the maintenance of photosynthetic capacity for a long time after anthesis, in combination with other useful traits, is associated with increased yield, especially under conditions of drought and heat stress (Kamal et al, 2019).

The mechanisms that contribute to the increase in yield under a stress can be different. Including those caused by the genetic nature of changes in the photosynthetic apparatus. Thus, the analysis of genes expression related to photosynthesis showed maximum relative expression of Rubisco-activase (2.38 fold) under temperature stress (36 °C), as compared to the control (26 °C) in more adaptable to the heat stress variety HD2967, and minimum in less tolerant variety WR544 (0.75 fold) at milk ripeness (Kumar et al, 2017).

Although more than 90 % of crop biomass is generated from photosynthetic products, improvement of this process has not yet been achieved by breeding (Yamori, 2021). Therefore, search of better photosynthetic capacity traits, can be a promising approach for breeding to increase the wheat yield.

## CONCLUSIONS

It was shown that under conditions of drought in the period of grain filling, the variability of the flag leaf and all green leaves dry weight in winter wheat varieties with similar tolerance to drought, both at anthesis and at milk ripeness stages, was greater than the variation in the chlorophyll content in them. The higher yield of winter wheat varieties with a greater leaves dry weight under drought conditions can be associated with both the possibility of photoassimilates using for root growth and, thus, reducing the water deficit, and with the prolongation of the photosynthetic apparatus functioning at the grain filling period. A close positive correlation was established between the flag leaf and all green leaves dry weight at anthesis, as well as milk ripeness stages and yield. This shows that traits of the plants assimilation surface can serve as indirect markers of drought resistance. Taking into account the correlation closeness, and the simplicity and convenience of determinations at selections in the field, which do not require the use of complex equipment, it is proposed to use the dry weight of the flag leaves at anthesis stage as a physiological marker of drought resistance. Improving the photosynthetic capacity of leaves is one of the ways to increase the yield of cereal crops.

***Adherence to ethical principles.*** All the experimental results, presented in this article, were obtained without the use of any animals.

***Conflicts of interests***. The authors declare no conflict of interest.

***Finansing.*** The research was partially financed by the Cabinet of Ministers of Ukraine project "Supporting the development of priority directions in scientific studies" within the project "Development of modern methods of marker-assisted breeding and technologies of short interfering RNAs for the creation of high-yielding varieties-innovations of winter wheat with improved grain quality, resistant to environmental stresses".

### Урожай та показники асиміляційної поверхні листків озимої пшениці

Г. О. Прядкіна *, Н. М. Махаринська, Д. В. Коновалов

Інститут фізіології рослин і генетики Національної академії наук України,
вул. Васильківська, 31/17, м. Київ, Україна, 03022

e-mail: galpryadk@gmail.com*, nadjavasko@ukr.net, davidkonovalov@ukr.net

orcid: https://orcid.org/0000-0002-4548-1747, https://orcid.org/0000-0002-9987-6437, https://orcid.org/0000-0003-1254-2926

**Мета.** Визначити маркери посухостійкості на основі аналізу ознак асиміляційної поверхні листків у 6 сортів озимої пшениці, що характеризуються близькою посухостійкістю, в умовах польової посухи в Лісостепу України. **Методи.** Ознаки асиміляційної поверхні листків визначали польовими, морфометричними, фенологічними та спектрофотометричними методами. **Результати.** За умов польової посухи в період наливу зерна суха маса прапорцевого листка та всіх зелених листків головного пагона 2 високоврожайних сортів (Київська 17 та Городниця) у період цвітіння та молочної стиглості була вищою, ніж у 4 інших у середньому за 3 роки. Питома маса прапорцевих листків головного пагона та вміст хлорофілу у досліджуваних сортів мало відрізнялися. Виявлено, що варіабельність сухої маси прапорцевого листка та всіх зелених листків головного пагона сортів озимої пшениці в період цвітіння та молочної стиглості була більшою, ніж варіабельність вмісту в них хлорофілу. Встановлено тісний зв'язок між сухою масою прапорцевого листка в період цвітіння та молочної стиглості, як і всіх зелених листків, з урожайністю (r = 0,658–0,837). **Висновки.** Вища врожайність сортів озимої пшениці з більшою сухою масою листя в умовах посухи може бути пов'язана з утворенням більшої кількості фотоасимілятів, які можуть бути використаними як для росту коренів (стратегія уникнення дефіциту води), так і для накопичення резервних асимілятів у стеблі (стратегія створення резервів для подальшого наливу зерна). Суху масу прапорцевого листка головного пагона у фазу цвітіння можна використовувати як морфометричний маркер посухостійкості, враховуючи тісноту кореляції з врожаєм та простоту і зручність визначення в польових умовах.

**Ключові слова**: *Triticum aestivum* L., польова посуха, маса сухої речовини листків, хлорофіл.

## REFERENCES

Amanullah (2015) Specific leaf area and specific leaf weight in small grain crops wheat, rye, barley, and oats differ at various growth stages and NPK source. J Plant Nutr 38(11):1694–1708. https://doi.org/10.1080/01904167.2015.1017051

Amoah JN, Ko CS, Yoon JS, Weon SY (2019) Effect of drought acclimation on oxidative stress and transcript expression in wheat (*Triticum aestivum* L.). J Plant Interact 14(1):492–505. https://doi.org/10.1080/17429145.2019.1662098

Balabukh VO (2023) Yield shortfall of cereals in Ukraine caused by the changes in air temperature and precipitation amount. Agric Sci Pract 10(1):31–53. https://doi.org/10.15407/agrisp10.01.031

Borrill P, Fahy B, Smith AM, Uauy C (2015) Wheat grain filling is limited by grain filling capacity rather than the duration of flag leaf photosynthesis: a case study using *NAM* RNAi plants. PLoS One 10(8):e0134947. https://doi.org/10.1371/journal.pone.0134947

Braun HJ, Atlin G, Payne T (2010) Multi-location testing as a tool to identify plant response to global climate change. In: Reynolds MP (ed) Climate change and crop production. Wallingford, Centre for Agriculture and Biosciences International, p 115–138.

Christopher JT, Christopher MJ, Borrell AK, Fletcher S, Chenu K (2016) Stay-green traits to improve wheat adaptation in well-watered and water-limited environments. J Exp Bot 67(17):5159–5172. https://doi.org/https://doi.org/10.1093/jxb/erw276

Dowla M, Edwards I, O'Hara G, Islam S, Ma W (2018) Developing wheat for improved yield and adaptation under a changing climate: optimization of a few key genes. Engineering 4(4):514–522. https://doi.org/10.1016/j.eng.2018.06.005

Dwivedi SK, Arora A, Singh VP, Singh GP (2018) Induction of water deficit tolerance in wheat due to exogenous application of plant growth regulators: membrane stability, water relations and photosynthesis. Photosynthetica 56(2):478–486. https://doi.org/10.1007/s11099-017-0695-2

Ghaffar A, Hussain N, Ajaj R, Shahin S, Bano H, Javed M, Khalid A, Yasmin M, Shah KH, Zaheer M, Iqbal M, Zafar Z, Athar H (2023) Photosynthetic activity and metabolic profiling of bread wheat cultivars contrasting in drought tolerance. Front Plant Sci 14. https://doi.org/10.3389/fpls.2023.1123080

Kamal NM, Alnor Gorafi YS, Abdelrahman M, Abdellatef E, Tsujimoto H (2019) Stay-Green Trait: A prospective approach for yield potential, and drought and heat stress adaptation in globally important cereals. Int J Mol Sci 20(23):5837. https://doi.org/10.3390/ijms20235837

Kaminski A, Austin RB, Ford MA, Morgan CL (1990) Flag leaf anatomy of *Triticum* and *Aegilops* species in relation to photosynthetic rate. Ann Bot 66(3):359–365. Available at: http://www.jstor.org/stable/42758321 [Accessed 24 June 2023]

Kapoor D, Bhardwaj S, Landi M, Sharma A, Ramakrishnan M, Sharma A (2020) The impact of drought in plant metabolism: how to exploit tolerance mechanisms to increase crop production. *Appl Sci* 10(16):5692. https://doi.org/https://doi.org/10.3390/app10165692

Kumar RR, Goswami S, Shamim M (2017) Biochemical defence response: Characterizing the plasticity of source and sink in spring wheat under terminal heat stress. Front Plant Sci 8:1603. https://doi.org/https://doi.org/10.3389/fpls.2017.01603

Kumar R, Krishna H, Barman D, Ghimire O, Shekharappa G, Singh P, Chinnusamy V, Padaria J, Arora A (2022) Stay-green trait serves as yield stability attribute under combined heat and drought stress in wheat (*Triticum aestivum* L.). Plant Growth Regul 96:67–78. https://doi.org/10.1007/s10725-021-00758-w

Li Q, Yang H, Guo J, Huang Q, Zhong S, Tan F, Ren T, Li Z, Chen C, Luo P (2022) Comparative transcriptome analysis revealed differential gene expression involved in wheat leaf senescence between stay-green and non-stay-green cultivars. Front Plant Sci 13:971927. https://doi.org/10.3389/fpls.2022.971927

Luo PG, Zang HY, Zhu K, Wu XH, Zhang HQ, Ren ZL (2009) The physiological genetic effects of 1BL/1RS translocated chromosome in "stay green" wheat cultivar CN17. Can J Plant Sci 89(1):1–10. https://doi.org/10.4141/cjps07072

Mobasser HR, Mohammadi GN, Heidari H, Abad S, Rigi K (2014) Effect of application elements, water stress and variety on nutrients of grain wheat in Zahak region, Iran-net. JBES 5:105–110. Available from: https://innspub.net/effect-of-application-elements-water-stress-and-variety-on-nutrients-of-grain-wheat-in-zahak-region-iran/

Morgun VV, Priadkina GA, Zborivska OV (2019). Depositing ability of stem of winter wheat varieties of different period of selection. Regul Mech Biosyst 10(2):239–244. https://doi.org/10.15421/021936

Moustakas M, Sperdouli I, Adamakis IS, Moustaka J, İşgören S, Şaş B (2022) Harnessing the role of foliar applied salicylic acid in decreasing chlorophyll content to reassess photosystem II photoprotection in crop plants. Int J Mol Sci 23(13):7038. https://doi.org/10.3390/ijms23137038

Nemati M, Zare N, Hedayat-Evrigh N, Asghary R (2022) Meta-analysis of common wheat physiological response to biotic stresses. Zemdirbyste 109(3):245–250. https://doi.org/10.13080/z-a.2022.109.031

Reynolds MP, Pellegrineschi A, Skovmand B (2005) Sink-limitation to yield and biomass: a summary of some investigations in spring wheat. Ann Appl Biol 146(1):39–49. https://doi.org/10.1111/j.1744-7348.2005.03100.x

Saeidi M, Abdoli M (2015) Effect of drought stress during grain filling on yield and its components, gas exchange variables, and some physiological traits of wheat cultivars. J Agric Sci Technol 17(4):885–898. URL: http://jast.modares.ac.ir/article-23-6741-en.html

Sallam A, Alqudah AM, Dawood MFA, Baenziger PS, Börner AJ (2019) Drought stress tolerance in wheat and barley: advances in physiology, breeding and genetics research. Int J *Mol Sci 20(13):*3137. https://doi.org/10.3390/ijms20133137

Slafer GA, Savin R, Pinochet D, Calderini D (2021) Wheat. In: Sadras VO, Calderini DF (eds) Crop physiology case histories for major crops. Academic Press, 98–163 p. https://doi.org/10.1016/B978-0-12-819194-1.00003-7

Wellburn AR (1994) The spectral determination of chlorophyll a and b, as well as carotenoids using various solvents with spectrophotometers of different resolution. J Plant Physiol 144(3):307–313. https://doi.org/http://dx.doi.org/10.1016/S0176-1617(11)81192-2

Yamori W (2021) Strategies for engineering photosynthesis for enhanced plant biomass production. In: Ali J, Wani SH (eds) Rice improvement. Springer, 31–58 p. https://doi.org/10.1007/978-3-030-66530-2_2

Yang C, Zhang D, Li X, Shi Y, Shao Y, Fang B, Yue J, Wang H, Qin F, Cheng H (2021) Drought effects on photosynthetic performance of two wheat cultivars contrasting in drought. N Z J Crop Hortic Sci 49:1–13. https://doi.org/10.1080/01140671.2020.1851264

Zadoks JC, Chang TT, Konzak CF (1974) A decimal code for the growth stages of cereals. Weed Res 14:415–421. https://doi.org/10.1111/j.1365-3180.1974.tb01084.x

Zandalinas SI, Fritschi FB, Mittler R (2021) Global warming, climate change, and environmental pollution: recipe for a multifactorial stress combination disaster. Trends Plant Sci 26(6):588–599. https://doi.org/10.1016/j.tplants.2021.02.011

Zulkiffal M, Ahsan A, Ahmad J, Musa M, Kanwal A, Saleem MF, Anwar J, Rehman AU, Ajmal S, Gulnaz S, Javaid MM (2021) Heat and drought stresses in wheat (*Triticum aestivum* L.): Substantial yield losses, practical achievements, improvement approaches, and adaptive mechanisms. In: Hossain A (ed) Plant Stress Physiology. https://doi.org/10.5772/intechopen.92378