Received 19.12.2025 Revised 20.03.2026 Accepted 21.05.2026 Published: 27.05.2026

Vol. 22, No. 3
2026

Scientific Reports of the National University of Life and Environmental Sciences of Ukraine

Journal homepage: https://scireports.com.ua/en e-ISSN 2223-1609

UDC 633.174:631.582 DOI: 10.31548/dopovidi/3.2026.102

Morphometric indicators of grain sorghum depending on sowing dates and stage of development

Liubov Honchar*
PhD in Agricultural Sciences, Associate Professor
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
https://orcid.org/0000-0002-3628-6659

Bohdan Mazurenko
PhD, Associate Professor
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., 15, Kyiv, Ukraine
https://orcid.org/0000-0002-4177-9909

Abstract. In the context of climate change and frequent droughts, the study of optimal sowing dates for grain sorghum as a drought-resistant crop with a C4 type of photosynthesis is highly relevant for ensuring the stable progression of critical growth stages and crop formation. The aim of the study was to determine the influence of sowing dates on the formation of morphometric indicators and the yield performance of grain sorghum plants under the conditions of the Forest-Steppe zone of Ukraine. The study employed a combination of field, analytical, morphometric, visual-instrumental, recording and statistical methods. It was established that the recommended sowing date ensured the maximum values of plant height (at BBCH stages 81-82) and the largest leaf surface area, which resulted in the highest photosynthetic potential of the crops. A tendency was identified whereby early sowing led to slower growth at the initial stages, whereas late sowing was accompanied by reduced growth intensity during the second half of the growing season and more rapid leaf senescence. The following tendency was observed: between the stage of plant development (BBCH 21-22 and BBCH 81-82) and both plant height and leaf surface area, there was a positive linear relationship ($r > 0$) with high values of the coefficient of determination (R^2), indicating a consistent increase in morphometric indicators throughout the growing season and varying intensity of their accumulation depending on the sowing date. It was established that the highest yield was obtained under the recommended sowing date,

Suggested Citation:
Honchar, L., & Mazurenko, B. (2026). Morphometric indicators of grain sorghum depending on sowing dates and stage of development. *Scientific Reports of the National University of Life and Environmental Sciences of Ukraine*, 22(3), 102-116. doi: 10.31548/dopovidi/3.2026.102.

**Corresponding author (honchar@nubip.edu.ua)*

Copyright © The Author(s). This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/)

while the earliest sowing date resulted in the lowest yield, and the late sowing date produced yields at the level of the recommended one. It was also found that late sowing promoted more uniform seedling emergence and more rapid initial development and, provided sufficient moisture was available, made it possible to maintain a yield level close to that of the recommended sowing date. The obtained results may be used for the scientifically grounded selection of sowing dates for grain sorghum in order to improve the stability of productivity and the efficiency of its cultivation under the conditions of the Forest-Steppe zone of Ukraine

Keywords: productivity; leaf surface area; plant height; hybrid; grain sorghum

Introduction

Sorghum (*Sorghum bicolor* L.) is among the world's five most important cereal crops and is characterised by a strong capacity for growth under arid and semi-arid climatic conditions (Choudhary *et al.*, 2025). Sorghum is a major global crop possessing the C4 type of photosynthesis, which makes it highly resistant to abiotic stresses. Grain sorghum is cultivated for the production of high-quality feed. It is also used as a bioenergy crop, with sweet sorghum providing the highest ethanol yield per unit area among agricultural crops (Anija Hari Kumar *et al.*, 2025). Sorghum grain occupies an important place in human nutrition, which has led to growing interest in ancient cereal crops and the demand for gluten-free grain. Sorghum grain is used in food production as a nutrient-rich baking grain with a lower glycaemic index than wheat, high resistant starch content, and significantly greater antioxidant levels (McGinnis & Webster, 2024). B. Chen *et al.* (2025) note that climate change is increasingly affecting crop yields in various regions of the world due to rising temperatures, reduced precipitation, and frequent extreme weather events. Water deficiency affects plant functions ranging from transpiration, photosynthesis, and leaf and root growth to reproduction and other key physiological processes. At the same time, increasing sorghum productivity is largely determined by the improvement of cultivation technology elements (plant density, sowing methods and dates, etc.), as well as crop management systems, which has been confirmed by domestic studies (Pravdyva, 2021; Titarenko & Karpuk, 2021).

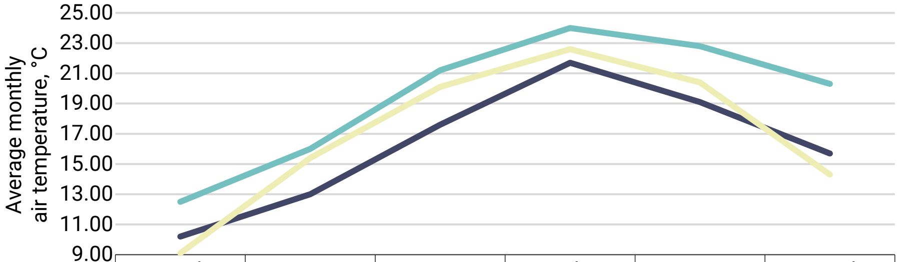
Grain sorghum may serve as a substitute for fodder maize in arid regions, as it adapts to changing conditions throughout ontogenesis. Its drought stress avoidance mechanism is based on the specific structure of the root system, which exploits the entire soil profile, and on the efficient use of moisture during photosynthesis (Otwani *et al.*, 2024). Due to the accumulation of carbon in the form of organic acids and their utilisation through the C4 photosynthetic pathway, sorghum is capable of continuing dry matter synthesis even when stomata are closed, while the stomata themselves can continue functioning without damage even under prolonged drought conditions (Fontanet-Manzaneque *et al.*, 2025). F. Fardin *et al.* (2023) emphasised that the cultivation of resilient and stress-tolerant crops is an alternative strategy for reducing crop yield losses caused by climate change. In particular, drought stress negatively affected sorghum plant height, leaf number, biomass, leaf-to-stem ratio, seed yield and yield components, as well as crude protein and hydrocyanic acid content in sorghum. However, different genotypes did not exhibit the same response to drought stress. O.P. Kibalnik *et al.* (2023) indicate that the biometric indicators of sorghum plants, including plant height, are among the principal parameters comprehensively reflecting plant responses to agronomic growing conditions, particularly sowing dates, temperature regime, and moisture availability. Numerous studies have confirmed that plant height is the most sensitive indicator to changes during cultivation, and its dynamics are associated with the progression of the main developmental stages.

L. Porčová *et al.* (2025), in their study, noted that sowing parameters, particularly sowing dates, determine the initial growth conditions of plants, which in turn define different intensities of stem growth throughout ontogenesis. Early sowing dates increase the duration of the growing season, thereby creating favourable conditions for the formation of sorghum plant height, whereas late sowing dates, conversely, lead to shorter interphase periods and reduced growth parameters. Sowing dates also influence the intensity of leaf surface formation and its values, especially during the tillering and stem elongation stages. Early sowing creates conditions for a longer period of leaf surface development, which in turn increases the photosynthetic potential of crops. Late sowing dates have the opposite effect, reducing the duration of interphase periods, which consequently decreases active leaf formation and results in a reduction of leaf surface area. Under early sowing dates, sorghum plants experience a longer period of active photosynthesis, whereas under late sowing dates accelerated leaf senescence is observed due to high temperatures and moisture deficiency during the period of active functioning. D. Otwani *et al.* (2024) stated that the selection of a sorghum hybrid is a key element of cultivation technology, since different genotypes respond differently to sowing dates, temperature regime, moisture availability, and the duration of phenological phases; the relevance of this issue is emphasised by contemporary reviews on breeding and the development of new sorghum hybrids (Lv *et al.*, 2024). The adaptive properties of hybrids to specific growing conditions determine the level of realisation of their productive potential, while sowing dates represent a critical factor that may either enhance or negate genetic advantages (Takanashi, 2023).

The aim of the study was to determine the influence of sowing dates on the formation of morphometric indicators of grain sorghum plants, particularly plant height, leaf surface area, and yield. The objectives of the study were to assess the influence of cultivation technology elements on the yield of the investigated crop and on the formation of morphometric indicators and productivity of grain sorghum plants.

Materials and Methods

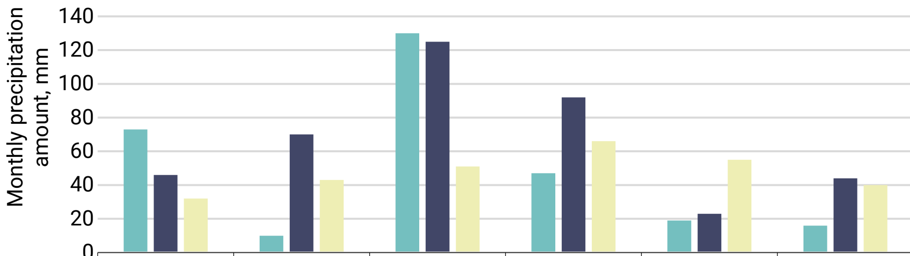
Field experiments were conducted during 2024-2025 at the farm enterprise "Promin", located in the western part of the Nizhyn district of Chernihiv region. The soil cover of the experimental site consisted of meadow-chernozem weakly solonetzic soil with a humus content of 2.84%. Soil nutrient reserves amounted to 107-110 mg/kg soil of mineral nitrogen, 135-140 mg/kg soil of available phosphorus, and 90-95 mg/kg soil of exchangeable potassium. Weather conditions in the Chernihiv region during the research period were characterised by elevated average monthly temperatures during the summer period compared with long-term averages, particularly in 2024 (Fig. 1). Air temperatures were especially higher in September, which promoted the ripening of grain sorghum – during this month temperatures were 6.0°C higher than normal, which is anomalous for this period. The 2024 growing season was characterised by a shortage of rainfall or its uneven distribution relative to long-term averages. Particularly unfavourable moisture conditions were observed during critical stages of sorghum development, which limited the intensity of growth processes and the formation of reproductive organs (Fig. 2). In contrast to 2024, in 2025 moisture conditions were more favourable for the growth and development of grain sorghum. Precipitation levels during the growing season were close to or exceeded long-term averages.



	April	May	June	July	August	September
2024 year	12.5	16	21.2	24	22.8	20.3
2025 year	10.2	13	17.6	21.7	19.1	15.7
pa – perennial	9.1	15.4	20.1	22.6	20.4	14.3

Figure 1. *Average monthly air temperature during the growing season of grain sorghum (April-September), 2024 and 2025*

Note: pa – perennial – perennial value
Source: developed by the authors



	April	May	June	July	August	September
2024 year	73	10	130	47	19	16
2025 year	46	70	125	92	23	44
pa – perennial	32	43	51	66	55	40

Figure 2. *Monthly precipitation during the growing season of grain sorghum (April-September), 2024 and 2025*

Note: pa – perennial – perennial value
Source: developed by the authors

The preceding crop in the experiment was winter wheat. Field tillage included two stubble cultivations with a disc harrow to a depth of 10-12 cm at two-week intervals. Following weed emergence, ploughing was carried out to a depth of 25-27 cm. The spring fieldwork commenced with early spring harrowing of the soil after reaching physical maturity. Subsequently, two cultivations were performed – the first to a depth of 10-12 cm and the second (pre-sowing) to 6-8 cm. Sowing was carried out according to the experimental design, with row spacing of 45 cm and a sowing rate of 170.0 thousand seeds/ha. The fertilisation system included the application of a complete mineral fertiliser at a rate of $N_{60}P_{40}K_{40}$. At BBCH stage 50-51, the crops were sprayed with the fungicide Impact T (application rate 0.8 l/ha) in a tank mixture with the insecticide Fosorgan Duo (application rate 0.3 l/ha). Grain sorghum was harvested by direct combining at full maturity.

The experiment was two-factorial: factor A – grain sorghum hybrids RGT Icebergg and Albanus (early-maturing); factor B – sowing dates: first sowing date (soil temperature 8-10°C at a depth of 10 cm); second sowing date (soil temperature

12-14°C at a depth of 10 cm); third sowing date (soil temperature 16-18°C at a depth of 10 cm). The total experimental plot area was 100 m^2, while the accounting plot area was 80.0 m^2. The experiment was conducted with three replications. Morphometric assessments were performed at BBCH stages 21-22, BBCH 36-37, and BBCH 81-82 (according to the experimental scheme), selecting representative plants from the accounting area of each plot in every replication; measurements were taken at the same time of day in order to minimise the influence of daily fluctuations in turgor and leaf position. Leaf surface area (S) was calculated using the linear method as the sum of the areas of all leaves on a single plant: for each leaf, length (L) and maximum width (B) were measured, after which leaf area was determined using the formula:

$$S = L \times B \times k, \quad (1)$$

where k – the coefficient of leaf blade shape; the leaf surface area per plant was obtained by summing the areas of all leaves; the results were expressed in cm^2/plant.

Field experiments were conducted in compliance with the national legislation of Ukraine, the principles of responsible scientific research, and the provisions of the Convention on Biological Diversity (1992) regarding the responsible use of plant resources. Grain yield was determined by the method of complete threshing of the accounting area of each plot followed by weighing of the obtained grain; the indicator was recalculated in t/ha taking into account the accounting plot area and adjusted to standard moisture content. Statistical processing was carried out using methods of statistics and comparative analysis; to assess the nature of changes in morphometric indicators throughout ontogenesis, linear regression analysis was applied with determination of the correlation coefficient (r) and coefficient of determination (R^2). The reliability of the results was evaluated taking into account the threefold replication of the experiment: primary datasets were formed separately for each replication, after which mean values of indicators and their variability were calculated. For all quantitative indicators (plant height, leaf surface area, yield, etc.), the mean value and standard error were presented, calculated using the R software environment (version 4.4.3) with the ggplot2 package. Similarity groups were calculated based on the results of Tukey's $HSD_{0.05}$ test. For linear regressions, 95% confidence intervals for model parameters were additionally calculated, ensuring correct interpretation of differences between treatments and the level of data variability.

Results

According to the results of the study conducted during 2024-2025, it was established that sorghum plant height depended significantly on both sowing date and plant developmental stage, as well as on the genetic characteristics of the hybrids. A clear dynamics of grain sorghum plant growth throughout the developmental stages was observed, and different responses of the studied hybrids to sowing dates were noted (Table 1).

Table 1. *Plant height of grain sorghum hybrids depending on sowing dates and stage of development*

Hybrid (factor A)	Sowing dates* (factor B)	Developmental stage		
		BBCH 21-22	BBCH 36-37	BBCH 81-82
Albanus	early	20.3 ± 0.1 c*	67.9 ± 0.3 c	106.9 ± 0.5 bc
	recommended	21.0 ± 0.2 abc	69.8 ± 0.2 b	108.0 ± 0.4 b
	late	20.5 ± 0.4 c	69.3 ± 0.3 bc	105.5 ± 0.5 cd
RGT Icebergg	early	20.8 ± 0.2 bc	69.6 ± 0.3 b	111.1 ± 0.1 a
	recommended	21.5 ± 0.2 ab	72.1 ± 0.4 a	112.6 ± 0.4 a
	late	21.9 ± 0.2 a	70.5 ± 0.4 b	103.8 ± 0.6 d

***Table 1.** Continued*

Hybrid (factor A)	Sowing dates* (factor B)	Developmental stage		
		BBCH 21-22	BBCH 36-37	BBCH 81-82
Mean for factor A		21.0	69.9	108.0
Mean for factor B	early	20.6	68.8	109.0
	recommended	21.3	71.0	110.3
	late	21.2	69.9	104.7

Note: *1. Early sowing date (soil temperature 8-10°C at a depth of 10 cm); 2. Recommended sowing date (soil temperature 12-14°C at a depth of 10 cm); 3. Late sowing date (soil temperature 16-18°C at a depth of 10 cm). Values are presented with the standard error of the mean (±SE); letters indicate membership of similarity groups according to Tukey's $HSD_{0.05}$ criterion for data within the column

Source: compiled by the authors

At BBCH stage 21-22 (beginning of tillering), the minimum height of sorghum plants was recorded, and only slight variability was observed. Depending on the studied hybrid and its sowing date, this indicator ranged from 20.3 to 21.9 cm. The average plant height was 21.0 cm, indicating a weak influence of the studied factors on the growth of grain sorghum plants at the early developmental stages. At BBCH stages 30-39, intensive growth of grain sorghum plants occurred. It was established that under the early sowing date, the average plant height was 68.8 cm, under the recommended sowing date – 71.0 cm, and under the late sowing date – 69.9 cm. Thus, the highest values were recorded under the recommended sowing date. At BBCH stage 81-82, growth processes were completed, and the differences between sowing dates became clearly expressed. The reduction in plant height under the late sowing date compared with the recommended sowing date amounted to 5.6 cm or 5.1%. A similar tendency was observed for the early sowing date, where plant height was 1.3 cm or 1.2% lower compared with the recommended sowing date, which was not significant. Among the studied hybrids, the tallest plants were obtained from sowing the RGT Icebergg hybrid under the recommended sowing date, where plant height reached 112.6 cm, exceeding the indicator of the Albanus hybrid by 4.6 cm. The results of the regression analysis confirmed that sowing dates influenced not only the absolute values of plant height, but also the intensity of their linear growth throughout the growing season (Fig. 3).

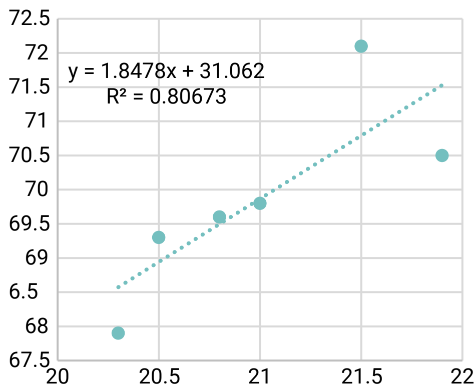


***Figure 3.** Linear relationship between the height of grain sorghum plants and the stage of development and sowing date*

Source: compiled by the authors

The linear regression models were characterised by positive regression coefficients (r > 0), confirming the natural increase in plant height during the growth process. Deviations in the values of the regression lines differed depending on the sowing dates, indicating unequal intensity of linear plant growth during the growing season. The highest values of the regression coefficient were established under the recommended sowing date, indicating higher rates of plant height increase at each developmental stage. Under the early sowing date, a slight reduction in growth processes was observed, whereas under late sowing dates the greatest decrease in the intensity of linear growth was recorded. High values of the coefficient of determination (R^2) indicate a strong linear relationship between developmental stages, plant height, and sowing dates.

Unlike the linear growth of the stem, leaf surface area responded more sensitively to changes in growing conditions. Thus, the next stage of the study involved determining the influence of sowing dates on the formation of leaf surface area in grain sorghum plants. At BBCH stage 21-22, the leaf surface area per plant varied within the range of 89.6-129.4 cm²/plant. On average, the leaf area per plant was 91.9 cm² under the early sowing date, 115.4 cm² under the recommended sowing date, and 121.3 cm² under the late sowing date (Table 2). Thus, at this developmental stage, the highest leaf area values were formed under the late sowing date, which in turn was associated with a more favourable temperature regime for leaf growth in grain sorghum plants.

Table 2. *Leaf area on grain sorghum plants depending on sowing date and stage of development*

Hybrid (factor A)	Sowing dates* (factor B)	Developmental stage		
		BBCH 21-22	BBCH 36-37	BBCH 81-82
Albanus	early	89.6 ± 1.7 d	468.3 ± 1.1 d	498.1 ± 2.6 e
	recommended	101.3 ± 1.8 c	523.2 ± 1.7 c	619.4 ± 2.9 c
	late	118.5 ± 2.9 b	518.4 ± 1.6 c	603.4 ± 2.3 d
RGT Icebergg	early	94.2 ± 1.0 cd	547.6 ± 1.3 b	684.3 ± 4.7 b
	recommended	129.4 ± 1.6 a	625.2 ± 2.7 a	769.5 ± 2.1 a
	late	124.1 ± 1.0 ab	617.1 ± 3.3 a	763.1 ± 1.2 a
Mean for factor A		109.5	550.0	656.3
Mean for factor B	early	91.9	508.0	591.2
	recommended	115.4	574.2	694.5
	late	121.3	567.8	683.3

Note: * – values are presented with the standard error of the mean (±SE); letters indicate membership of similarity groups according to Tukey's $HSD_{0.05}$ criterion for data within the column
Source: compiled by the authors

At BBCH stage 36-37, a rapid increase in leaf surface area occurred, corresponding to the period of intensive growth of grain sorghum plants. The maximum values were obtained under the recommended sowing date, where the leaf surface area reached 574.2 cm², exceeding the treatment with the early sowing date by 66.2 cm² and the late sowing date by 6.4 cm². This can be explained by the fact that optimal conditions for the formation of leaf surface area in grain sorghum plants were achieved under the recommended sowing date.

A similar tendency was maintained at BBCH stage 81-82, where the leaf surface area of sorghum plants increased to 591.2 cm² under the early sowing date, to 694.5 cm² under the recommended sowing date, and to 683.3 cm² under the late sowing date. Thus, the reduction in the assimilation surface of sorghum plants under the early sowing date was associated with delayed plant development at the beginning of the growing season, whereas under the late sowing date it was related to rapid leaf senescence caused by high temperatures and drought during the second half of the crop growing season. Among the studied hybrids, the RGT Icebergg hybrid formed a greater assimilation surface at all developmental stages and sowing dates compared with the Albanus hybrid.

A consistent pattern was established whereby all sowing dates were characterised by a positive linear tendency ($r > 0$), indicating a gradual increase in leaf surface area from BBCH stage 21-22 to BBCH stage 81-82. At the same time, the slope of the regression lines differed significantly, indicating unequal intensity of leaf apparatus formation under different sowing dates (Fig. 4). The greatest deviation of the regression line was observed under the recommended sowing date, indicating a rapid increase in leaf surface area during developmental stages. This was achieved due to the optimal combination of temperature and moisture regimes during the period of active growth of grain sorghum plants, which promoted prolonged functioning of the leaf apparatus and reduced premature leaf senescence. Under the early sowing date, the intensity of assimilation surface increase was lower, which was caused by the temperature regime at the initial stages of vegetation that slowed the formation of leaf blades. At the same time, under the late sowing date, despite the rapid initial growth of leaves, a subsequent decline in the rate of leaf surface formation was observed.

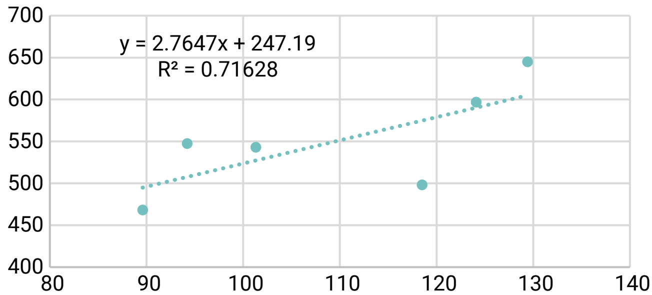


***Figure 4.** Linear relationship between the leaf area of grain sorghum plants and their stage of development and sowing date*

Source: compiled by the authors

The high values of the coefficient of determination (R^2) for all variants studied indicate a strong linear relationship between the stage of plant development and leaf area. Thus, it has been confirmed that sowing dates have a significant influence not only on the absolute values of leaf area but also on the dynamics of its formation throughout the growing season, and the highest photosynthetic potential of grain sorghum was obtained at the recommended sowing date.

Analysis of the data indicates that yield levels varied significantly under the influence of both cultivation practices (sowing date) and the genetic characteristics of the hybrids, as well as the weather conditions during the growing seasons. In 2024, sorghum grain yield was lower compared to 2025 for all variants studied, which was due to the dry conditions during the growing season. On average, the yield in 2024 was 6.16 t/ha, whereas in 2025 it increased to 6.87 t/ha (Table 3).

***Table 3.** Grain yield of grain sorghum depending on sowing dates, t/ha*

Hybrid (factor A)	Sowing dates* (factor B)	Year		
		2024	2025	Average for 2024-2025
Albanus	I	4.73 ± 0.07 c	5.20 ± 0.09 c	4.96 ± 0.12 c
	II	6.12 ± 0.08 b	6.89 ± 0.11 b	6.51 ± 0.18 b
	III	6.15 ± 0.08 b	6.84 ± 0.08 b	6.49 ± 0.16 b
RGT Icebergg	I	5.88 ± 0.04 b	6.53 ± 0.15 b	6.20 ± 0.16 b
	II	6.98 ± 0.21 a	7.91 ± 0.13 a	7.45 ± 0.24 a
	III	7.12 ± 0.09 a	7.83 ± 0.17 a	7.48 ± 0.18 a
Mean for factor A		6.16	6.87	6.51

Table 3. *Continued*

Hybrid (factor A)	Sowing dates* (factor B)	Year		
		2024	2025	Average for 2024-2025
Mean for factor B	I	5.30	5.86	5.58
	II	6.55	7.40	6.98
	III	6.64	7.34	6.99

Note: * – values are presented with the standard error of the mean (±SE); letters indicate membership of similarity groups according to Tukey's $HSD_{0.05}$ criterion for data within the column

Source: compiled by the authors

Among the sowing dates, the lowest grain sorghum yield was obtained under the early sowing date. On average for 2024-2025, it amounted to 5.58 t/ha, which was 1.40 t/ha or 20.1% lower compared with the recommended sowing date. The recommended sowing date ensured the highest grain yield level of 6.98 t/ha. Under the late sowing date, the yield was slightly lower and amounted to 6.99 t/ha; however, the difference compared with the recommended sowing date was minimal, indicating sufficient adaptability of the crop to shifts in sowing dates under favourable weather conditions. The RGT Icebergg hybrid was characterised by consistently higher grain yield compared with the Albanus hybrid across all sowing date treatments during 2024-2025. On average, the grain yield of the RGT Icebergg hybrid amounted to 7.04 t/ha, whereas the Albanus hybrid produced 5.99 t/ha, indicating a better realisation potential of the hybrid. The highest grain yield indicators were obtained when cultivating the RGT Icebergg hybrid under the recommended and late sowing dates, reaching 7.45 and 7.48 t/ha, respectively. This was achieved, in particular, due to plant height and leaf surface area, which were maximal under these treatments and ensured a high photosynthetic potential of grain sorghum crops.

It was established that the relationship exhibited a clearly expressed positive trend when transitioning from the early to the recommended sowing date, indicating an increase in grain yield. It was under the recommended sowing date that maximum yield was achieved, which in turn was associated with the most favourable conditions for the progression of critical developmental stages, particularly the formation of the leaf apparatus, reproductive organs, and grain filling (Fig. 5).

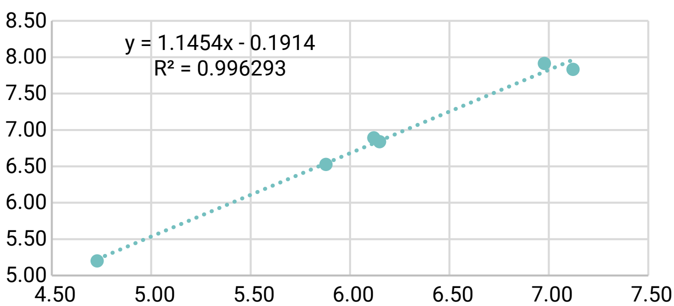


Figure 5. *Linear relationship between grain sorghum yield and sowing date*

Source: compiled by the authors

A further shift in sowing dates towards later periods is accompanied by a slight decrease in yield, as reflected in the less pronounced slope of the regression line. At the same time, the negligible difference between the recommended and late sowing dates indicates sufficient ecological plasticity of grain sorghum and its ability to adapt to climate change. Thus, optimising sowing dates is one of the key elements of grain sorghum cultivation technology, ensuring stability and increased yield. Recommended and late sowing dates create the most favourable conditions for the development of high photosynthetic potential in crops and the maximum realisation of the crop's potential.

Discussion

The results obtained confirm that sowing dates are one of the decisive factors influencing the morphometric characteristics of grain sorghum, as they determine the initial temperature conditions and the duration of the interphase periods. Thus, during 2024-2025, a consistent growth pattern was observed: at the early stages (BBCH 21-22), the difference in plant height between treatments was minimal, whereas during the period of intensive growth (BBCH 36-37) and at the end of the growing season (BBCH 81-82), the advantage of the recommended sowing date became evident. A similar pattern of crop response to sowing dates was also reported by other researchers, such as O.P. Kibalnik *et al.* (2023) and L. Porčová *et al.* (2025), who pointed to the relationship between plant height, temperature regime, moisture availability, and plant response to agronomic conditions.

The influence of sowing dates on leaf surface area was even more pronounced, which corresponds to the significant role of the assimilation apparatus in the formation of sorghum productivity. In the current experiment, the maximum leaf surface area values at the assessed developmental stages were predominantly formed under the recommended sowing date, which ensured a higher photosynthetic potential of the crops and, consequently, better conditions for grain formation and filling. Similar patterns regarding the role of assimilation surface in the formation of sorghum crop productivity were also reported by other authors (Gyrka *et al.*, 2021; Pravdyva *et al.*, 2023). Likewise, in the works of O.P. Kibalnik *et al.* (2023), devoted to the physiology and adaptation of sorghum to abiotic stresses, it is emphasised that temperature and moisture regimes significantly affect the intensity of leaf apparatus formation, the duration of leaf functioning, and the efficiency of photosynthesis (Behera *et al.*, 2022). In this context, the reduction in assimilation surface recorded under early sowing can be associated with slower initial growth at lower temperatures, while under late sowing it was related to rapid leaf senescence.

It is also important to note that the response of hybrids to sowing dates was not identical. This is confirmed by F.C. Gao *et al.* (2022) and D. Otwani *et al.* (2024), who state that morphometric indicators may be regarded as informative traits of potential productivity, particularly during stages of intensive growth when the basis of the crop photosynthetic potential is formed. The dynamics of plant height and assimilation surface in relation to yield indicate that the developmental stages from BBCH 30-31 to BBCH 82-85 are the most "sensitive" to sowing dates. P.P. Behera *et al.* (2022) and H.Y. Wu *et al.* (2025) note that it is during this period that the difference in leaf surface area between treatments is maximal; thus, treatments that ensure longer functioning of leaves create better conditions for dry matter accumulation and the realisation of hybrid potential. From a practical perspective, this means that assessment of the leaf apparatus condition at BBCH stage 36-37 may be useful for early forecasting of expected crop productivity.

The obtained results confirm that the influence of sowing date largely affects the progression of phenological phases and, accordingly, the differing probability of critical periods occurring under stress conditions. Under precipitation deficit, the early sowing date led to slower initial growth and the formation of a smaller leaf apparatus surface, which limited the compensatory capacity of the crop at later stages (Fardin *et al.*, 2023; Chen *et al.*, 2025). Under more favourable moisture conditions, the late sowing date did not cause a significant reduction in yield, as evidenced by the productivity indicators under the recommended and late sowing dates in the current experiment. The regression relationships obtained for plant height and leaf surface area demonstrate the systematic nature of changes in morphometric indicators throughout ontogenesis and confirm that sowing dates alter not only the value of the trait itself but also the rate of its increase. O. Brendel (2021) and P.P. Behera *et al.* (2022) note in their studies that higher values of the coefficients of determination for linear models indicate the predictability of growth processes within each sowing date, whereas differences in the slopes of the regression lines reflect variations in the rate of biomass accumulation and assimilation surface formation. From an applied perspective, this emphasises the expediency of selecting sowing dates as a tool for regulating crop growth rates with consideration of the typical weather risks of a particular region.

From an agronomic point of view, the early sowing date, despite the potential extension of the growing period, increases the risk of uneven emergence and slow growth under insufficient soil warming, which may subsequently affect the development of the leaf apparatus. L. Porčová *et al.* (2025) and D. Otwani *et al.* (2025) note that the late sowing date, on the contrary, shortens the duration of interphase periods and may increase the risk of grain filling occurring during periods of high temperatures and moisture deficit, thereby promoting premature leaf senescence. Thus, under the conditions of the Forest-Steppe zone of Ukraine, it is advisable to consider the recommended sowing date as the basic option, while shifting to a later sowing date may be regarded as acceptable under sufficient moisture availability and when using early-maturing and plastic hybrids.

At the same time, it should be taken into account that the results were obtained under the conditions of a specific soil cover and technological elements (preceding crop, replication, production conditions), while the range of weather conditions was limited to two years of research. In their studies, Y. Zhou *et al.* (2022), V.A. Tsygankova (2023) note that the interaction of sowing dates with plant density, mineral nutrition level, and crop protection may potentially alter the intensity of morphometric indicator formation and their relationship with yield. Thus, further studies should be aimed at expanding the temperature range, including years with more contrasting moisture conditions, and analysing complex technological combinations in order to refine optimal production decisions. F. Fardin *et al.* (2023) note that under drier conditions the yield level was lower in all treatments, which is consistent with data on the negative effect of drought on biomass, morphometry, and yield components of sorghum. At the same time, the higher average productivity indicators under the recommended and late sowing dates indicate the possibility of partially compensating for weather-related risks through optimisation of sowing dates and the selection of adaptive genotypes, as also highlighted by other authors analysing the "genotype × environment × sowing date" interaction (Gao *et al.*, 2022; Otwani *et al.*, 2024).

Overall, the comparison of the obtained data with literature sources indicates that the optimal sowing date for the conditions of the Forest-Steppe zone of Ukraine should be regarded as a compromise between ensuring a sufficient duration of vegetation and avoiding the occurrence of reproductive stages during periods of the highest stress load. The recorded yield levels under the recommended and late sowing dates may indicate the high ecological plasticity of sorghum and its potential for adaptation to changing weather conditions, which is consistent with current concepts of adaptability and yield plasticity in hybrids. Thus, further refinement of optimal sowing dates should be combined with assessment of the duration of leaf apparatus functioning and the photosynthetic productivity of specific hybrids in years differing in moisture availability.

Conclusions

Despite certain limitations of the study, particularly the lack of open access to some specialised scientific sources, the obtained results made it possible to establish that sowing dates are among the leading technological factors significantly affecting the growth, development, formation of morphometric indicators, and yield of grain sorghum under the conditions of the Forest-Steppe zone of Ukraine. It was experimentally proven that optimisation of sowing dates with consideration of the soil temperature regime contributes to a more complete realisation of the biological potential of the crop and enhances the stability of its productivity under variable agroclimatic conditions. The most favourable conditions for plant growth and development were observed under the recommended sowing date at a soil temperature of 10-14°C and the late sowing date at a temperature of 16-18°C at a depth of 10 cm.

It was established that under the recommended sowing date, the maximum indicators of plant height and leaf surface area were formed during the critical developmental stages (BBCH 81-82), which ensured the highest photosynthetic potential of the crops and created favourable conditions for the formation of high grain yield. The early sowing date negatively affected the initial stages of plant development, which was manifested in suppression and delay of growth processes and slower formation of the assimilation apparatus. The late sowing date was characterised by more uniform seedling emergence and more intensive initial growth; however, during the second half of the growing season, a decrease in growth intensity and accelerated leaf senescence were observed. At the same time, under sufficient moisture availability, grain yield under the late sowing date remained at the level of the recommended sowing date, indicating the ecological plasticity of the crop and the possibility of using this sowing period as an alternative under certain weather conditions.

Grain sorghum yield depended significantly on the combination of sowing dates and the meteorological conditions of the growing years. The highest productivity indicators were formed under the recommended sowing date, whereas the early sowing date provided the lowest yield. The identified patterns are confirmed by positive correlation-regression relationships between plant developmental stages, plant height, and leaf surface area, indicating a consistent increase in morphometric indicators throughout the growing season and differing intensities of their formation depending on the sowing date. Among the studied hybrids, RGT Icebergg formed greater morphometric indicators and grain yield under all sowing dates, indicating its higher adaptability and better capacity for realisation in the Forest-Steppe zone of Ukraine.

Further research should be directed towards a more detailed investigation of the adaptive responses of grain sorghum under variable agroclimatic growing conditions, particularly the study of sowing dates in combination with other technological elements and a deeper analysis of physiological and biochemical processes (duration of leaf apparatus functioning and photosynthetic intensity), which would make it possible to clarify the limits of the ecological plasticity of the crop and predict its productivity under climate change conditions.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

References

[1] Anija Hari Kumar, S., Chacko Thomas, U., Al-Salman, Y., Cano, F.J., Stephen, R., Pillai, P.S., & Ghannoum, O. (2025). Evaluation of yield-related morphological, physiological, agronomic, and nutrient uptake traits of grain sorghum varieties in the Kerala Region (India). *Agronomy*, 15(10), article number 2320. doi: 10.3390/agronomy15102320.

[2] Behera, P.P., Saharia, N., Borah, N., Devi, S.H., & Sarma, R.N. (2022). Sorghum physiology and adaptation to abiotic stresses. *International Journal of Environment and Climate Change*, 12(10), 1005-1022. doi: 10.9734/ijecc/2022/v12i1030891.

[3] Brendel, O. (2021). The relationship between plant growth and water consumption: A history from the classical four elements to modern stable isotopes. *Annals of Forest Science*, 78, article number 47. doi: 10.1007/s13595-021-01063-2.

[4] Chen, B., *et al.* (2025). The green revolution of Chinese grain hybrid sorghum. *Scientia Agricultura Sinica*, 58(8), 1494-1507. doi: 10.3864/j.issn.0578-1752.2025.08.003.

[5] Choudhary, K.B., Khandelwal, V., Singh, D., & Sharma, S.R. (2025). Optimizing hybrid sorghum seed production: Key challenges and future opportunities. In *Hybrid seed production for boosting crop yields: Applications, challenges and opportunities* (pp. 105-125). Singapore: Springer Nature Singapore. doi: 10.1007/978-981-96-0506-4_5.

[6] Convention on Biological Diversity. (1992, June). Retrieved from https://zakon.rada.gov.ua/laws/show/995_030#Text.

[7] Fardin, F., Sani, B., Moaveni, P., Afsharmanesh, G., & Mozafari, H. (2023). Nutritional value and agronomic traits of forage sorghum under drought stress. *Biocatalysis and Agricultural Biotechnology*, 48, article number 102624. doi: 10.1016/j.bcab.2023.102624.

[8] Gao, F.C., *et al.* (2022). Interpretation of genotype-environment-sowing date/plant density interaction in sorghum [*Sorghum bicolo*r (L.) Moench] in early mature regions of China. *Frontiers in Plant Science*, 13, article number 1008198. doi: 10.3389/fpls.2022.1008198.

[9] Gyrka, A.D., Alieksieiev, Ya.V., Sydorenko, Yu.Ya., & Bochevar, O.V. (2021). Influence density and sowing method of grain sorghum on the formation of assimilation surface and grain productivity of plants. *Grain Crops*, 5(2), 302-309. doi: 10.31867/2523-4544/0189.

[10] Kibalnik, O.P., Sazonova, I.A., Bochkareva, Y.V., Bychkova, V.V., & Semin, D.S. (2023). Influence of abiotic stresses on morphophysiological characteristics and biological value of grain *Sorghum bicolor* (L.) Moench. *International Journal of Plant Biology*, 14(1), 150-161. doi: 10.3390/ijpb14010013.

[11] Lv, X., Shi, L., Zhang, F., Zhu, Z., & Lu, H. (2024). A review of breeding strategies for new hybrid sorghum varieties. *Molecular Plant Breeding*, 15. doi: 10.5376/mpb.2024.15.0034.

[12] McGinnis, M.J., & Webster, M. (2024). Current and potential future uses of sorghum to increase nutrient density for human foods. *Journal of Food Science*, 89(S1), A42-A51. doi: 10.1111/1750-3841.17571.

[13] Otwani, D., Hunt, C., Cruickshank, A., Powell, O., Koltunow, A., Mace, E., & Jordan, D. (2024). Adaptation and plasticity of yield in hybrid and inbred sorghum. *Crop Science*, 64(2), 560-570. doi: 10.1002/csc2.21160.

[14] Otwani, D., *et al.* (2025). Extended grain filling has potential to improve yield in grain sorghum. *Journal of Experimental Botany*, 76(10), 2763-2774. doi: 10.1093/jxb/eraf117.

[15] Porčová, L., Frantová, N., Rábek, M., Jovanović, I., Smutný, V., Řiháček, M., & Mrkvicová, E. (2025). Yield potential of silage sorghum: cultivar differences in biomass production, plant height, and tillering under contrasting soil conditions in central Europe. *Agronomy*, 15(10), article number 2352. doi: 10.3390/agronomy15102352.

[16] Pravdyva, L. (2021). Influence of elements of growing technology on productivity of sorghum and biofuel output. *Bulletin of Agricultural Science*, 99(5), 25-29. doi: 10.31073/agrovisnyk202105-03.

[17] Pravdyva, L., Zatserkovna, N., Vakhniy, S., Khakhula, V., & Hornovska, S. (2023). Photosynthetic productivity of sorghum (*Sorghum bicolor* L. (Moenh) in the conditions of the Right-Bank Forest-Steppe of Ukraine. *Scientific Horizons*, 26(5), 56-64. doi: 10.48077/scihor5.2023.56.

[18] Sukhina, D. (2025) Formation of leaf surface area of sorghum (*Sorghum*) grain hybrids depending on plant quantity and application of growth regulator. *Agroecological Journal*, 2, 156-162. doi: 10.33730/2077-4893.2.2025.333841.

[19] Takanashi, H. (2023). Genetic control of morphological traits is useful for improving sorghum. *Breeding Science,* 73(1), 57-69. doi: 10.1270/jsbbs.22069.

[20] Titarenko, O.S., & Karpuk, L.M. (2021). Efficiency of grain sorghum cultivation for various crop care measures. *Advanced Agritechnologies*, 9. doi: 10.47414/na.9.2021.259698.

[21] Tsygankova, V.A., Voloshchuk, I.V., Pilyo, S.H., Klyuchko, S.V., & Brovarets, V.S. (2023). Enhancing sorghum productivity with Methyur, Kamethur, and Ivin plant growth regulators. *Biology and Life Sciences Forum*, 27(1), article number 36. doi: 10.3390/IECAG2023-15222.

[22] Wu, H.Y., Liu, Z.Q., Zhang, W.F., Pan, Q.M., & Jiang, C.D. (2025). Does leaf lifespan affect the regulation of photosynthetic function during natural senescence of leaves in various sorghum cultivars? *Journal of Experimental Botany*, 76(14), 4071-4084. doi: 10.1093/jxb/eraf195.

[23] Zhou, Y., Huang, J., Li, Z., Wu, Y., Zhang, J., & Zhang, Y. (2022). Yield and quality in main and ratoon crops of grain sorghum under different nitrogen rates and planting densities. *Frontiers in Plant Science*, 12, article number 778663. doi: 10.3389/fpls.2021.778663.

Морфометричні показники сорго зернового залежно від строків сівби та стадії розвитку

Любов Гончар
Кандидат сільськогосподарських наук, доцент
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
https://orcid.org/0000-0002-3628-6659
Богдан Мазуренко
Доктор філософії, доцент
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
https://orcid.org/0000-0002-4177-9909

Анотація. В умовах кліматичних змін і частих посух актуальним є дослідження оптимальних строків сівби зернового сорго як посухостійкої культури з С4-типом фотосинтезу для забезпечення стабільного проходження критичних фаз росту та формування врожаю. Метою дослідження було встановити вплив строків сівби на формування морфометричних показників та урожайності рослин сорго зернового в умовах Лісостепу України. У дослідженні застосовано комплекс польових, аналітичних, морфометричних, візуально-інструментальних, облікових і статистичних методів. Встановлено, що рекомендований строк сівби забезпечував максимальні значення висоти рослин (на стадіях BBCH 81-82) і найбільшу площу листкової поверхні, що формувало найвищий фотосинтетичний потенціал посівів. Виявлено тенденцію, що ранній строк сівби зумовлював уповільнення росту на початкових етапах, тоді як пізній строк супроводжувався зниженням інтенсивності росту в другій половині вегетації та швидшим відмирання листків. Виявлено таку тенденцію між стадією розвитку рослин (BBCH 21-22 і BBCH 81-82) та їх висотою, і площею листкової поверхні простежується позитивна лінійна залежність ($r > 0$) з високими значеннями коефіцієнта детермінації (R^2), що свідчить про закономірне зростання морфометричних показників упродовж вегетації та різну інтенсивність їх наростання залежно від строку сівби. Було встановлено, що найвищу врожайність отримано за рекомендованого строку сівби, за раннього строку вона була найнижчою, а за пізнього − на рівні рекомендованого. Було встановлено, що пізній строк сівби сприяв появі дружнішим сходам і швидшому стартовому розвитку та, за наявності достатнього зволоження, дає змогу зберігати рівень урожайності, близький до рекомендованого. Отримані результати можуть бути використані для науково обґрунтованого вибору строків сівби сорго зернового з метою підвищення стабільності продуктивності та ефективності його вирощування в умовах Лісостепу України

Ключові слова: продуктивність, листкова поверхня, висота рослин, гібрид, сорго зернове