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Influence of agronomic practices on the photosynthetic activity of grain sorghum hybrids in the Northern Steppe of Ukraine

Denys Sukhina*

Postgraduate Student

National University of Life and Environmental Sciences of Ukraine

03041, 15 Heroiv Oborony Str., Kyiv, Ukraine

<https://orcid.org/0009-0008-4352-1777>**Nataliia Novytska**

Doctor of Agricultural Sciences, Professor

National University of Life and Environmental Sciences of Ukraine

03041, 15 Heroiv Oborony Str., Kyiv, Ukraine

<https://orcid.org/0000-0002-7645-4151>

Abstract. The study of the photosynthetic activity of grain sorghum is crucial for enhancing its productivity under the conditions of the Northern Steppe of Ukraine, characterised by unstable moisture levels and significant temperature fluctuations. This research aimed to determine the influence of hybrids, plant density, and the application of the plant growth regulator Appetaizer on the indicators of photosynthetic activity in grain sorghum. The research was conducted over the period 2022-2024 on experimental plots in the Dnipropetrovsk Region. Winter wheat served as the preceding crop, and cultivation practices followed the standard techniques for the region (except for the investigated elements and a row spacing of 45 cm). The methods employed included: field observations of the phenological phases of growth and development of the crop, as well as the impact of the studied factors on the photosynthetic activity of grain sorghum; tabular methods for the systematisation, arrangement, and presentation of the data obtained; and graphical methods for data visualisation. The study established that, in terms of photosynthetic potential, the optimal combinations were found to be: the hybrid ES Alize at a density of 170 thousand plants/ha with the application of the plant growth regulator (PGR) (392.7 thousand $m^2/ha \cdot days$); hybrids ES Alize and ES Foehn at a density of 200 thousand plants/ha under control conditions (407.2 and 398.4 thousand $m^2/ha \cdot days$ respectively); the ES Foehn hybrid at the same density with the application of the PGR (404.0 thousand $m^2/ha \cdot days$); and hybrids ES Alize and ES Foehn at a density of 230 thousand plants/ha under control conditions

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*Corresponding author



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(400.0 and 415.7 thousand $\text{m}^2/\text{ha}\cdot\text{days}$ respectively), as well as ES Alize with the application of the PGR (403.2 thousand $\text{m}^2/\text{ha}\cdot\text{days}$), demonstrated optimal results. In terms of net photosynthetic productivity, the best results were recorded for the Albanus hybrid at a density of 170 thousand plants/ha – both without PGR (4.67 g/m^2 per day) and with PGR (4.70 g/m^2 per day); for the Albanus (4.77) and ES Monsoon (5.07) hybrids at 200 thousand plants/ha under control conditions, as well as with PGR (4.89 and 5.12 g/m^2 per day, respectively); and at 230 thousand plants/ha – for the Albanus (4.78) and ES Monsoon (4.69) hybrids under control conditions, and with PGR (4.78 and 4.82 g/m^2 per day, respectively). Thus, the photosynthetic activity of sorghum was influenced by plant density, hybrid, and the effect of the studied growth regulator. The results obtained will enable agricultural producers to select optimal combinations of plant density, sorghum hybrids, and the appropriateness of using growth regulators to enhance the photosynthetic activity and yield of crops

Keywords: photosynthetic potential; net photosynthetic productivity; phenological phases; plant nutrition; biostimulant; grain sorghum

Introduction

Rational cultivation of grain sorghum necessitates considering the specifics of regional soil and climatic conditions, as these factors determine the efficiency of the plants' photosynthetic apparatus, upon which yield formation directly depends. In the context of climate change and increasing moisture deficit, research into sorghum photosynthetic productivity in the Northern Steppe of Ukraine – a zone characterised by unstable moisture, high temperatures, and frequent occurrences of abiotic stress – becomes particularly relevant. Given sorghum's ability to adapt to arid conditions, identifying the most productive hybrids in combination with optimal agricultural practices, namely plant density and the application of growth regulators, offers the potential to significantly enhance the efficiency of the crop's photosynthetic potential utilisation. Therefore, studying these aspects is of considerable importance for developing adaptive grain sorghum cultivation technologies aimed at ensuring stable high productivity even under climatic constraints (Polevoy *et al.*, 2020; Prysiazhniuk *et al.*, 2022).

According to Y.Al-Salman *et al.* (2024), global climate change trends over recent decades have expanded the potential growing region for grain sorghum, which is attracting attention from the

scientific community due to its low requirements for soil and climatic conditions and its plasticity towards abiotic factors. Researchers D. Wang *et al.* (2022) investigated that grain sorghum belongs to plants with C4-type photosynthesis, which are characterised by lower water losses through transpiration due to CO_2 fixation in mesophyll cells and subsequent transfer to bundle sheath cells where photosynthesis occurs. This type of photosynthesis is more productive compared to C3 photosynthesis under high light intensity and temperature conditions.

The drought tolerance of this crop using different concentrations of PEG 6000 (polyethylene glycol) was confirmed in studies by M. Stefanov *et al.* (2023), who noted better plant recovery at PEG concentrations of 20% and 25%. Concurrently, R.G. Ávila *et al.* (2023) found that water deficit negatively impacts the photosynthetic parameters of grain sorghum plants, although the application of plant growth regulators increases plant resilience. S.Y. Davidenko (2023) argued that the insufficient realisation of the genetic potential of grain sorghum plants is linked to violations of cultivation technological protocols, including those that determine the plant's feeding area and its shape, and consequently regulate competition between plants in agrophytoecosystems.

According to R.E. Grishchenko *et al.* (2020), one of the most dynamic indicators of plant photosynthetic activity is leaf area. The capacity of the assimilatory apparatus and the duration of its function are crucial factors for photosynthetic productivity, influencing yield and grain quality indices. Research by L.A. Pravdyva *et al.* (2023) highlighted the positive impact of applying a growth regulator on the leaf area of grain sorghum, its photosynthetic potential, and net photosynthetic productivity, as well as the important role of crop nutrition in enhancing photosynthetic productivity. The authors established that the use of a regulator promotes increased leaf area development, activates photosynthetic processes, and improves the overall physiological state of plants, enabling more effective utilisation of the crop's potential under stress conditions. L. Pravdyva & V. Doronin (2020) analysed the influence of mineral nutrition on grain sorghum photosynthetic productivity. It was determined that the application of mineral fertilisers contributes to an increase in leaf area, a rise in photosynthetic potential, and an increase in net photosynthetic productivity, which collectively improve the crop's yield.

According to O.S. Tytarenko & L.M. Karpuk (2022), the photosynthetic parameters of crops are an exceptionally important component for determining the effectiveness of grain sorghum cultivation technology elements, as in cultivated plants, yield formation efficiency directly depends on the speed and quality of photosynthetic processes. They also noted a significant influence of applying micronutrients and growth regulators on the course of photosynthetic processes.

Therefore, studying the photosynthetic activity of crops depending on hybrid composition, plant density, and the application of growth regulators is a necessary condition for further improvement of grain sorghum cultivation agricultural practices to realise its biological potential. This study aimed to determine the photosynthetic efficiency of grain sorghum hybrids of different maturity groups depending on plant density and

growth regulator application under the conditions of the Northern Steppe of Ukraine.

Materials and Methods

Field research was conducted between 2022 and 2024 on the fields of Zoria LLC in the village of Havrylivka, Synelnykove District, Dnipropetrovsk Region. According to the zonal distribution, the district belongs to the northern part of the steppe zone of Ukraine, characterised by insufficient and unstable moisture and arid weather conditions. The soils at the research site are ordinary chernozems with a high humus content. Soil nutrient reserves were 260-270 kg/ha of mineral nitrogen, 240-260 kg/ha of phosphorus, and 860-880 kg/ha of potassium. The humus content during the research years fluctuated between 4.48% and 4.55%. The agricultural practices in the experiment were generally accepted for the Steppe zone of Ukraine, except for the sowing method (row spacing was 45 cm) and the experimental factors. The preceding crop was winter wheat. The experimental design involved the study of three factors. The research was conducted following the Convention on Biological Diversity (1992).

The first factor comprised grain sorghum hybrids of French breeding from the company Lidea, belonging to different maturity groups: early-maturity – Albanus; mid-early – Kalatur, ES Foehn, and ES Monsoon; and late-maturity – ES Alize. The early-maturity hybrid Albanus (FAO maize equivalent 300-350) has a vegetation period of 92-100 days. Plant height is 115-116 cm. The grain is white, with a 1,000-grain weight of 25.9-29.0 g. Grain protein content is 12.6%-13.0%, and starch content is 74.3%-74.8%. The mid-early hybrid Kalatur (FAO maize equivalent 400-450) has a vegetation period of 108-109 days. Plant height is 114-120 cm. The grain is white, with a 1,000 grain weight of 25.4-29.5 g. Grain protein content is 12.4%-12.8%, and starch content is 74.0%-74.8%. The mid-early hybrid ES Foehn (FAO maize equivalent 380-450) has a vegetation period of 108-111 days. Plant height ranges from 107 to 120 cm. The grain is red, with a 1,000 grain

weight of 24.7-30.0 g. Grain protein content is 12.0%-12.8%, and starch content is 73.8%-74.3%. The mid-early hybrid ES Monsoon (FAO maize equivalent 320-400) has a vegetation period of 103-108 days. Plant height is 105-114 cm. The grain is white, with a 1,000-grain weight of 26.2-26.5 g. Grain protein content is 11.4%-12.8%, and starch content is 71.8%-73.9%. The late-maturity hybrid ES Alize (FAO maize equivalent 400-480) has a vegetation period of 117-120 days. Plant height is 107-120 cm. The grain is red, with a 1,000-grain weight of 26.9-28.4 g. Grain protein content is 10.2%-11.6%, and starch content is 74.6%-76.4%.

The second factor investigated was plant density, which was set at 170, 200, and 230 thousand plants per hectare. The third factor investigated was the double application of the plant growth regulator Appetaizer, which stimulates physiological processes and improves plant nutrition under stress conditions. The formulation of the Appetaizer growth regulator is an aqueous solution (AS). The active ingredients are sea algae extract (GA-142) – 952 g/L, zinc salts (1%), and manganese salts (1%). The first application was carried out at the 4-5 leaf stage on the experimental variants at a rate of 0.5 L/ha with a working solution volume of 150 L/ha. To ensure high-quality application of the product per the manufacturer's recommendations, an air injection double fan nozzle IDKT 04 with a droplet size of 350-480 VMD μm was used.

The second application of the growth regulator was conducted at the 7-8 leaf stage with a product application rate of 0.5 L/ha and a working solution volume of 150 L/ha. Applications were performed in the evening at air temperatures ranging from +15°C to +20°C, relative air humidity of 20%-30%, and wind speed of 3-4 m/s. The total area of the experimental plot was 8 ha. The accounting area of a variant plot was 600 m² (6×100 linear metres), and the total area was 673.2 m² (6.6×102 linear metres). The variants were arranged systematically in three tiers (30 variants). The experiment had four replications.

Photosynthetic activity of plants was determined by the following indicators: leaf area – using the “cutting” method; photosynthetic potential of the crop (PP) and net photosynthetic productivity (NPP) – according to the methodology of A.O. Nichiporovich. Statistical analysis of the research results was performed using the analysis of variance method for multifactorial experiments with the aid of Microsoft Excel software.

Results and Discussion

During the field research conducted between 2022 and 2024, the dates of the onset of phenological growth and development stages of grain sorghum hybrids were recorded, the leaf areas of the variants were determined depending on the studied factors, and the photosynthetic potential of the crops (PP) and net photosynthetic productivity (NPP) were calculated. From the obtained data, average values over the 3 years were determined to reflect the effectiveness of the agricultural practices.

During the plant stages of stem elongation to panicle emergence, in the control variants at a plant density of 170 thousand plants/ha, the highest photosynthetic potential was observed in the late-maturity hybrid ES Alize (217.8 thousand m²/ha*days) and the early-maturity hybrid Kalatur (212.6 thousand m²/ha*days), while the lowest value was recorded for the mid-early hybrid ES Monsoon (320.3 thousand m²/ha*days) (Fig. 1). An increase in photosynthetic potential occurred in all variants with the application of the growth regulator; the minimum difference was +2.52% for the Albanus hybrid, and the maximum was +13.12% for the ES Monsoon hybrid. A significant difference was also recorded for the ES Alize (+10.59%) and ES Foehn (+10.38%) hybrids. During the panicle emergence to flowering stages of grain sorghum development, the highest photosynthetic potential was observed in the ES Alize (265 thousand m²/ha*days) and ES Foehn (262.4 thousand m²/ha*days) hybrids. The minimum value during this period was for the Albanus hybrid – 205.7 thousand m²/ha*days.

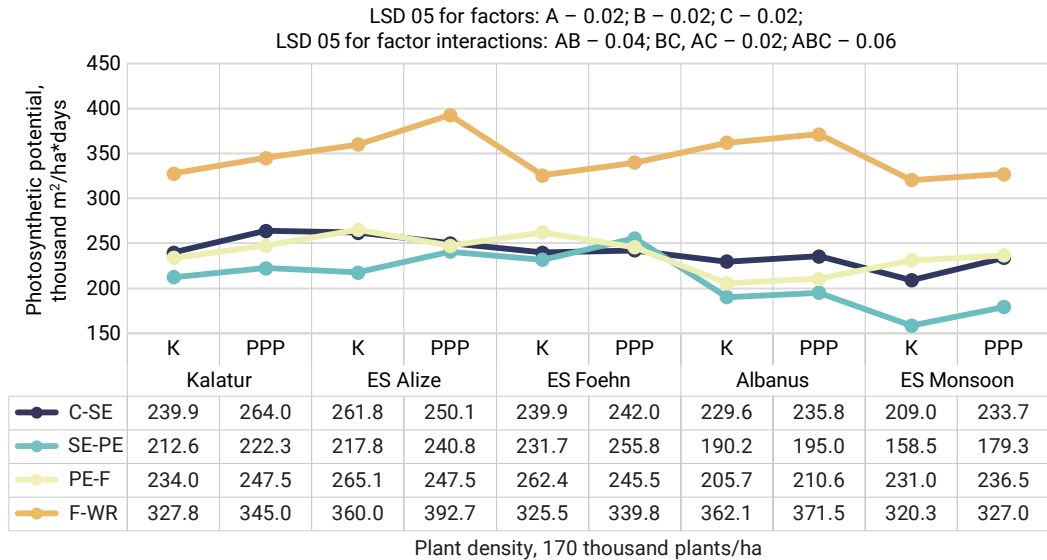


Figure 1. Photosynthetic potential of crops at a density of 170 thousand plants/ha during the main phenological growth and development stages of the plants

Note: C – control; PGR – plant growth regulator; SE – seedling; SE – stem elongation; PE – panicle emergence; F – flowering; WR – waxy ripeness

Source: developed by the authors

The application of the growth regulator at this stage had a somewhat differentiated effect – on the ES Alize and ES Foehn hybrids, the photosynthetic potential decreased by 6.42%-6.64% compared to the control, but increased by 5.77% for the Kalatur hybrid and by 2.38%-2.41% for the ES Monsoon and Albanus hybrids. This phenomenon was likely due to the genetic characteristics of the hybrids, particularly their maturity group, which in turn characterises the process of ontogenesis with specific features of biometric parameter development (formation of leaf area and senescence of lower-tier leaves). That is, the stimulating effect of the PGR led to an acceleration of the plants' passage through phenological stages, resulting in the earlier senescence of lower-tier leaves compared to the control variants.

During the flowering to waxy ripeness period, in the control variants at a plant density of 170 thousand plants/ha, the photosynthetic potential of the crop reached its maximum value in

the early maturity hybrid Albanus (362.1 thousand $m^2/ha \cdot days$) and the late-maturity hybrid ES Alize (360.0 thousand $m^2/ha \cdot days$), while the lowest value was for the mid-early hybrid ES Monsoon (320.3 thousand $m^2/ha \cdot days$). At this stage, an increase in photosynthetic potential of 2.11%-9.08% was recorded in all variants with the application of PGR. During the grain sorghum development phases from stem elongation to panicle emergence, with an increase in plant density to 200 thousand plants/ha, an increase in the PP index of 9.1%-19.4% was noted in all control variants (Fig. 2). Thus, the highest PP was observed in the ES Alize (266.0 thousand $m^2/ha \cdot days$) and ES Foehn (261.8 thousand $m^2/ha \cdot days$) hybrids, and the lowest in the ES Monsoon hybrid (189.2 thousand $m^2/ha \cdot days$). The influence of growth regulator application at this stage also proved to be differentiated: +2.31% in the Albanus hybrid; +3.00% in Kalatur; +10.29% in ES Foehn; -4.94% in ES Alize and -6.45% in ES Monsoon, for the reasons mentioned previously.

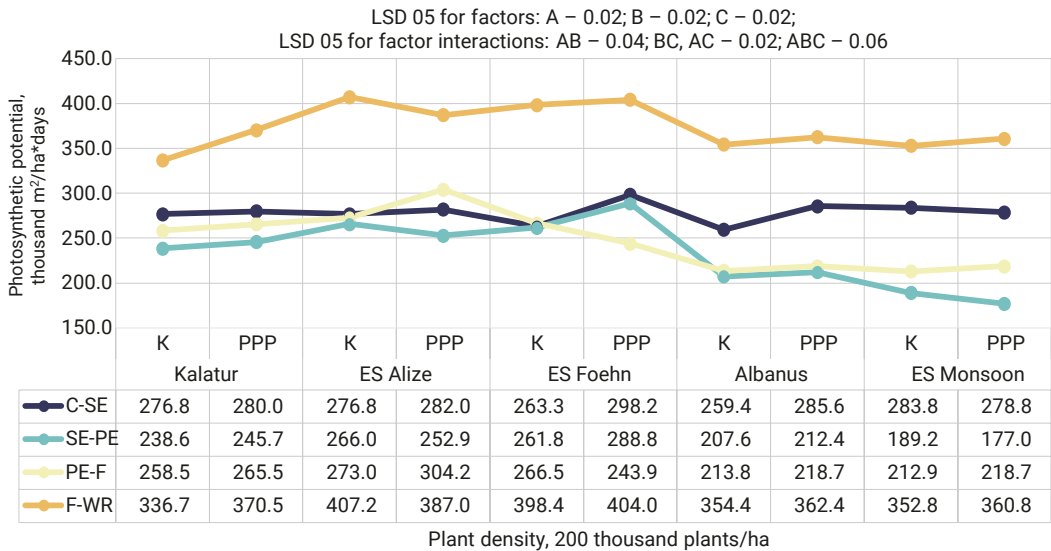


Figure 2. Photosynthetic potential of crops at a density of 200 thousand plants/ha during the main phenological growth and development stages of the plants

Note: C – control; PGR – plant growth regulator; SE – seedling; SE – stem elongation; PE – panicle emergence; F – flowering; WR – waxy ripeness

Source: developed by the authors

During the panicle emergence to flowering period, the control variants of ES Alize (273.0 thousand $m^2/ha \cdot days$), ES Foehn (266.5 thousand $m^2/ha \cdot days$), and Kalatur (258.5 thousand $m^2/ha \cdot days$) exhibited the highest photosynthetic potential. A significant positive effect of the growth regulator on PP was observed in the ES Alize hybrid (+11.41%), while others showed increases within the range of +2.35%–2.75% (except for the ES Foehn hybrid, which saw a decrease of 8.48%). During the flowering to waxy ripeness development stages of grain sorghum at a plant density of 200 thousand plants/ha, the variants with the ES Alize (407.2 thousand $m^2/ha \cdot days$) and ES Foehn (398.4 thousand $m^2/ha \cdot days$) hybrids reached maximum values in the control. Furthermore, in the variants with PGR application, the highest value was recorded for the ES Foehn hybrid – 404.0 thousand $m^2/ha \cdot days$. During the grain sorghum stages from stem elongation to panicle emergence, increasing the plant density to 230 thousand plants/ha resulted in a differentiated effect. In the control variants, an increase in the

PP index was noted for the Kalatur hybrid by 1.1%, for the ES Foehn hybrid by 8.0%, and for the Albanus hybrid by 1.4% (Fig. 3). The index decreased in other hybrids, indicating excessive density.

During the panicle emergence to flowering period, the control variants showed an increase in the PP index of 2.3% for the Kalatur hybrid, 10.6% for the ES Alize hybrid, and 3.2% for the ES Monsoon hybrid. The increase in density had almost no effect on the Albanus hybrid, while the ES Foehn hybrid showed a decrease in the index of 9.1%. PGR application was effective for all hybrids (+1.08%–11.25%), except for the ES Foehn hybrid (–5.43%). During the flowering to waxy ripeness development stages of grain sorghum at a plant density of 230 thousand plants/ha, the variants with the ES Foehn (415.7 thousand $m^2/ha \cdot days$) and ES Alize (403.0 thousand $m^2/ha \cdot days$) hybrids reached maximum values in the control. Furthermore, in the variants with PGR application, the highest value was observed in the ES Alize hybrid – 403.0 thousand $m^2/ha \cdot days$, which was slightly lower than the ES Foehn variant at a

density of 200 thousand plants/ha. Other variants with PGR application demonstrated a PP increase

of 0.8%–1.38%, except for the Kalatur (–6.09%) and ES Foehn (–5.11%) hybrids.

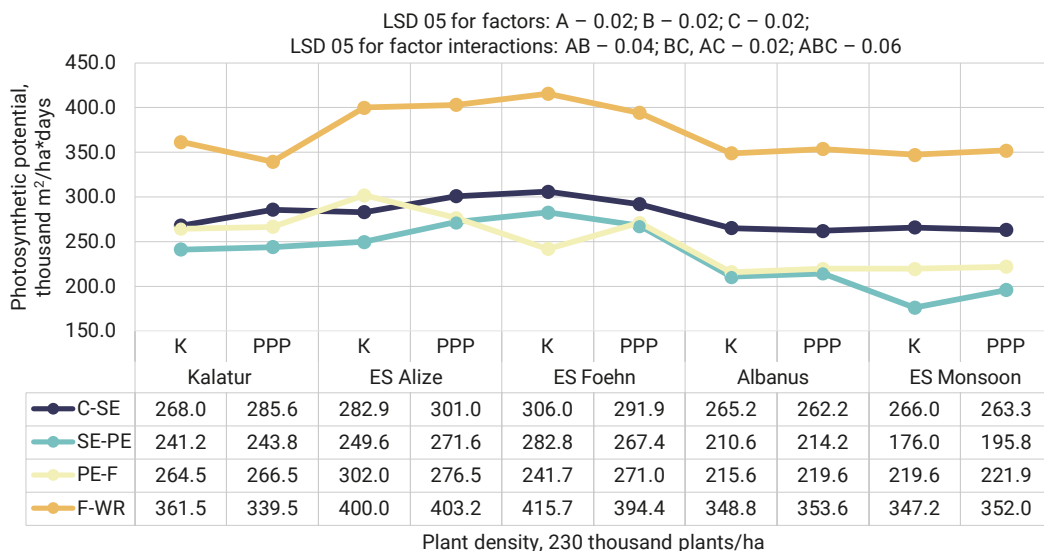


Figure 3. Photosynthetic potential of crops at a density of 230 thousand plants/ha during the main phenological growth and development stages of the plants

Note: C – control; PGR – plant growth regulator; SE – seedling; SE – stem elongation; PE – panicle emergence; F – flowering; WR – waxy ripeness

Source: developed by the authors

L.A. Herasymenko (2014) argued that a crucial condition for ensuring yield is the duration of functioning of the formed leaf area of crops, which is expressed by the photosynthetic potential (PP) index. This index can vary widely depending on the soil and climatic zone and the growing conditions of the given crop. According to their observations, with a row spacing of 45 cm and a plant density of 200 thousand plants/ha, the PP was 4.11 million $\text{m}^2/\text{ha}^*\text{days}$ for the variety Sylosne 42 and 4.41 million $\text{m}^2/\text{ha}^*\text{days}$ for the hybrid Medovyi. With an increase in plant density to 300 thousand plants/ha, this index was 4.52 and 4.78 million $\text{m}^2/\text{ha}^*\text{days}$, respectively. In the current research, the photosynthetic potential index was calculated at each stage of ontogenesis for a more precise understanding of the dynamics of changes in the grain sorghum hybrid variants depending on the studied factors. However, a comparison of the

research results indicates that grain sorghum and sweet sorghum differ significantly in terms of photosynthetic potential even at the same plant density of 200 thousand plants/ha.

In comparison with the indices from the research by L. Pravdyva & V. Doronin (2020), the current study's indices at the same plant density of 200 thousand plants/ha showed lower values, specifically: compared to the varieties Dniprovskiy 39 (1.24 million $\text{m}^2/\text{ha}^*\text{days}$) and Vinets (1.18 million $\text{m}^2/\text{ha}^*\text{days}$), the photosynthetic potential of the control variants over the vegetation period was: Kalatur hybrid – 1.11 million $\text{m}^2/\text{ha}^*\text{days}$; ES Alize – 1.22 million $\text{m}^2/\text{ha}^*\text{days}$; ES Foehn – 1.19 million $\text{m}^2/\text{ha}^*\text{days}$; Albanus – 1.04 million $\text{m}^2/\text{ha}^*\text{days}$; ES Monsoon – 1.04 million $\text{m}^2/\text{ha}^*\text{days}$. Furthermore, the variants with the application of the PGR Apettaizer were characterised by significantly higher indices: Kalatur hybrid – 1.16 million $\text{m}^2/\text{ha}^*\text{days}$;

ES Alize – 1.23 million m²/ha*days; ES Foehn – 1.23 million m²/ha*days; Albanus – 1.08 million m²/ha*days; ES Monsoon – 1.04 million m²/ha*days. In contrast, the net photosynthetic productivity of the investigated hybrids was significantly higher compared to the varieties Dniprovskiy 39 (3.91 g/m² per day) and Vinets (3.72 g/m² per day): for the Kalatur hybrid – 4.22 g/m² per day; ES Alize – 3.77 g/m² per day; ES Foehn – 4.09 g/m² per day; Albanus – 4.77 g/m² per day; ES Monsoon – 5.07 g/m² per day. These indices, considering the different agro-meteorological conditions of the areas where the comparative studies were conducted, indicate the adaptability of the investigated hybrids to the arid conditions of the Northern Steppe of Ukraine.

R.M. Vasylenko (2018) investigated the photosynthetic productivity of grain sorghum (Pivdennyi variety with 70 cm row spacing) under different sowing dates, reporting a photosynthetic

potential of 1.13 million m²/ha*days without irrigation and 1.19 million m²/ha*days under irrigation; and a net photosynthetic productivity of 3.7 g/m² per day without irrigation and 3.6 g/m² per day under irrigation. These data are significantly lower compared to the Kalatur, ES Alize, ES Foehn, Albanus, and ES Monsoon hybrids, and indicate the effectiveness of the grain sorghum hybrids investigated in non-irrigated conditions, as well as the expediency of using plant growth regulators. Furthermore, R.M. Vasylenko (2018) in their research paid attention to the plant protection system and highlighted its important role in the formation of grain sorghum photosynthetic productivity.

Based on the photosynthetic potential and data on the duration of phenological phase periods, dry biomass yield increments were calculated, after which the net photosynthetic productivity of each variant was determined (Fig. 4).

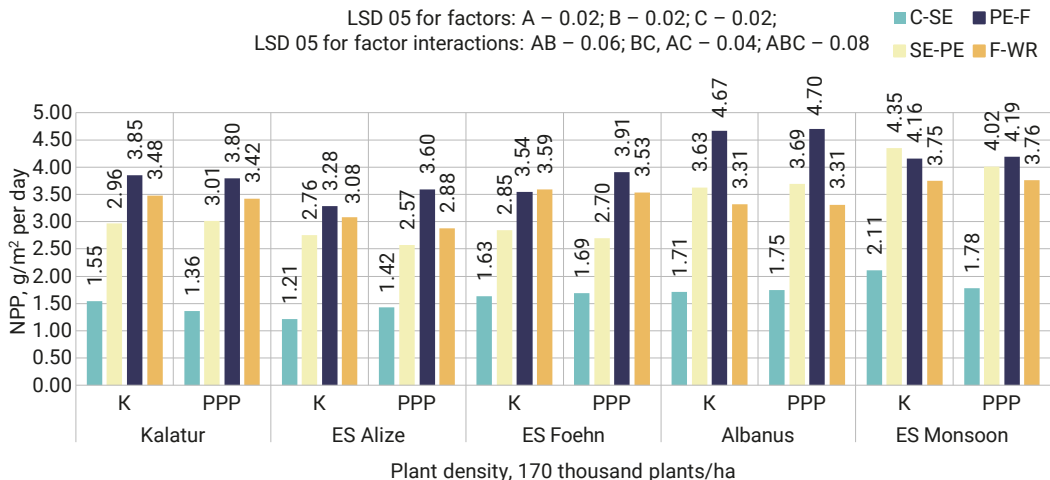


Figure 4. Net photosynthetic productivity at a density of 170 thousand plants/ha during the main phenological growth and development stages of the plants

Note: C – control; PGR – plant growth regulator; SE – seedling; SE – stem elongation; PE – panicle emergence; F – flowering; WR – waxy ripeness

Source: developed by the authors

These results indicate that at a plant density of 170 thousand plants/ha, the early-maturity Albanus hybrid exhibited the highest NPP among the hybrids during the stem elongation

to panicle emergence (3.63 g/m² per day) and flowering to waxy ripeness (4.67 g/m² per day) periods. Furthermore, the ES Monsoon hybrid consistently showed high NPP throughout all

phases (3.754.35 g/m² per day), despite low photosynthetic potential indices. The Kalatur hybrid was also stable throughout the entire period, with NPP within the range of 2.96-3.85 g/m² per day. At a plant density of 200 thousand plants/ha, the highest net photosynthetic productivity across all variants was recorded (Fig. 5). Among the hybrids, ES Monsoon (3.74-5.07 g/m²

per day), Albanus (3.564.77 g/m² per day), and Kalatur (3.95-4.22 g/m² per day) distinguished themselves with high values in the control plots. In the variants with PGR application, the highest NPP values were observed in the ES Monsoon (3.77-5.12 g/m² per day), Albanus (3.61-4.89 g/m² per day), and ES Foehn (2.98-4.63 g/m² per day) hybrids.

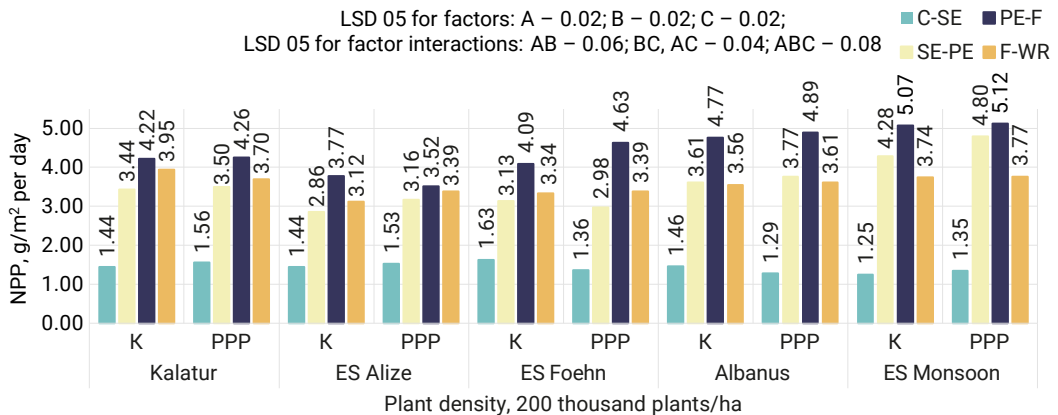


Figure 5. Net photosynthetic productivity at a density of 200 thousand plants/ha during the main phenological growth and development stages of the plants

Note: C – control; PGR – plant growth regulator; SE – seedling; SE – stem elongation; PE – panicle emergence; F – flowering; WR – waxy ripeness

Source: developed by the authors

Increasing plant density to 230 thousand plants/ha led to a decrease in NPP in the control variants during the stem elongation-panicle emergence stages by 12% for the Kalatur hybrid, 2% for the ES Alize hybrid, and 16% for ES Foehn, while remaining unchanged for the Albanus and ES Monsoon hybrids (Fig. 6). During the panicle emergence-flowering period, the NPP index decreased by 15% for the ES Alize hybrid and 8% for ES Monsoon; for other hybrids, the change was insignificant. The flowering-waxy ripeness period was characterised by a decrease in NPP for the Kalatur and ES Foehn hybrids by 13% and 10%, respectively. The indices for other hybrids remained almost at the same level. The application of the growth regulator to the variants had a differentiated effect on the hybrids at various development stages: for the Kalatur hybrid, a reduction in the effect of increased density of 1%-14% was

observed; for the ES Alize hybrid – a reduction in the negative impact of increased density of 6%-18%; for the ES Foehn hybrid – 5%-7%; a decrease in NPP occurred for the Albanus hybrid by 1%-3% at all development stages, and for the ES Monsoon hybrid there was a decrease of 16% during the stem elongation-panicle emergence period, and an increase of 1%-2% in other periods.

According to O.S. Tytarenko & L.M. Karpuk (2022), research results for grain sorghum hybrids Brigga and Yutami in the Right-bank Forest-Steppe of Ukraine, a region with unstable moisture, showed that without plant growth regulators, NPP during the stem elongation-panicle emergence period ranged from 3.29 to 3.87 g/m² per day. With the application of the PGRs Rego-plant or Stimpo, it ranged from 3.30 to 3.88 g/m² per day. In comparison, the hybrid Kalatur had an NPP of 4.22 g/m² per day; ES Alize – 3.77 g/m²

per day; ES Foehn – 4.09 g/m² per day; Albanus – 4.77 g/m² per day; and ES Monsoon – 5.07 g/m² per day on the control variants. With the application of the PGR Appetaizer, the NPP values increased to 4.26 g/m² per day for the Kalatur hybrid; 3.52 g/m² per day for ES Alize; 4.63 g/m² per day for ES Foehn; 4.89 g/m² per day for Albanus; and 5.12 g/m² per day for ES Monsoon. A similar dynamic is also observed during the panicle

emergence-flowering and flowering-waxy ripeness periods. This indicates the greater effectiveness of the PGR Appetaizer compared to the other growth regulators. However, the aforementioned research also included the application of micro-nutrients, which, in combination with the use of PGRs, resulted in photosynthetic productivity indices that exceeded those of the grain sorghum hybrids investigated in the present study.

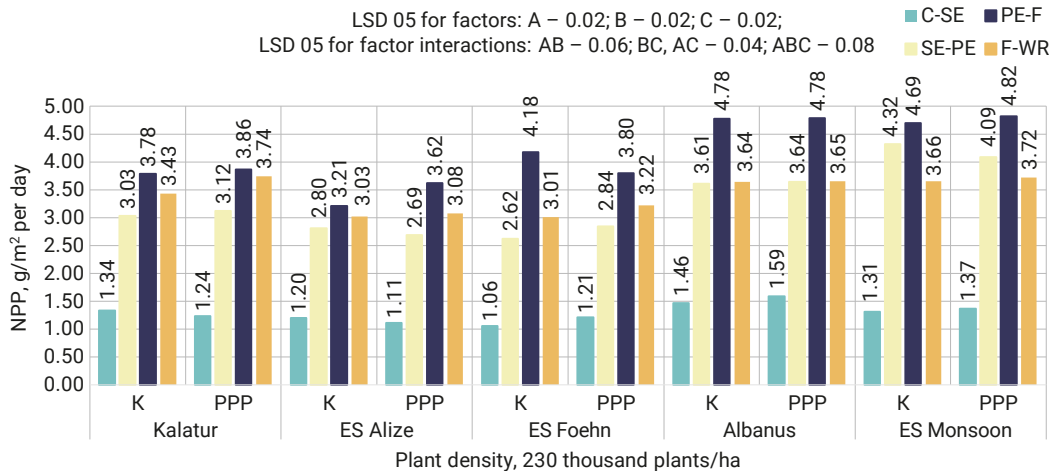


Figure 6. Net photosynthetic productivity at a density of 230 thousand plants/ha during the main phenological growth and development stages of the plants

Note: C – control; PGR – plant growth regulator; SE – seedling; SE – stem elongation; PE – panicle emergence; F – flowering; WR – waxy ripeness

Source: developed by the authors

A. Shrestha *et al.* (2016) investigated the tolerance of grain sorghum to high salt concentrations under laboratory conditions, which allowed the assertion that grain sorghum is a strategic crop for cultivation on saline soils. However, according to research by I.G. Daniells *et al.* (2001) under field conditions, the productivity of grain sorghum on saline soils is rather limited and can be up to 50% of the potential yield. The peculiarities of grain sorghum's physiological responses during drought stress involve an increase in photosynthetic rate through reduced stomatal conductance and transpiration rate (Zhang *et al.*, 2019), increased leaf temperature (Kapani-gowda *et al.*, 2014), decreased chlorophyll content, and increased oxygen evolution (Bao *et*

al., 2017). Consequently, an enhanced photosynthetic rate, which provides the nutrients and energy required for plant growth and development, is the main mechanism by which tolerant genotypes maintain grain yield in sorghum during stress (Getnet, 2015). Thus, under conditions of insufficient moisture, the photosynthetic apparatus is fundamental to plant growth and development, as well as yield formation.

According to L.A. Herasymenko (2014), sowing dates and seed burial depth significantly influence sorghum photosynthetic productivity, with optimal conditions being sowing in the second ten-day period of May and a seed burial depth of 4-6 cm. Field research by L.A. Herasymenko (2014) also established that key factors

influencing crop photosynthetic productivity are row spacing (30 cm is optimal for sweet sorghum) and plant density (300 thousand plants/ha is optimal for sweet sorghum). M.B. Grabovskiy *et al.* (2017) hold a similar view, focusing specifically on the optimal temperature for grain sorghum sowing (+10°C-12°C), and their research results indicate a close interrelationship between photosynthetic potential, net photosynthetic productivity, and increased yield.

In the research conducted by R.E. Grishchenko *et al.* (2020) on the photosynthetic productivity of the Artemida variety at a plant density of 180 thousand plants/ha with 45 cm row spacing, it was found that the highest indices of sorghum crop photosynthetic potential (2.96 million m²/ha*days) and net photosynthetic productivity (5.4-5.76 g/m² per day) were achieved with the main application of N₆₀P₆₀K₆₀ and additional nitrogen feeding (N₁₅) alongside seed treatment with the BTU preparation. Considering the somewhat lower indices in current research, it can be concluded that the agricultural practices investigated, namely the grain sorghum hybrids, plant density of 200 thousand plants/ha, and the application of the studied additive, are expedient under the unfavourable and arid conditions of the Northern Steppe of Ukraine. Thus, the obtained results demonstrate significant variability in photosynthetic potential and net photosynthetic productivity depending on the hybrid composition, plant density, and the application of the growth regulator. The optimal conditions for realising the biological potential of the hybrids were found to be a density of 200 thousand plants/ha and the use of the Appetaizer preparation, which ensured an increase in photosynthetic activity indices and productivity stability during the phases of active growth. The hybrids Kalatur, ES Foehn, and ES Monsoon proved particularly effective under the conditions of the Northern Steppe of Ukraine.

Conclusions

The presented results allow for the conclusion that, in terms of photosynthetic potential, the

optimal variants were the combinations of: the ES Alize hybrid at a plant density of 170 thousand plants/ha with PGR application; the ES Alize and ES Foehn hybrids at a plant density of 200 thousand plants/ha in the control; the ES Foehn hybrid at a plant density of 200 thousand plants/ha with PGR application; the ES Alize and ES Foehn hybrids at a plant density of 230 thousand plants/ha in the control, as well as ES Alize with PGR application.

Conversely, regarding net photosynthetic productivity, the best variant at a plant density of 170 thousand plants/ha proved to be the early-maturity Albanus hybrid, both without (4.67 g/m² per day) and with the application of the PGR Appetaizer (4.70 g/m² per day). At a density of 200 thousand plants/ha, the best control variants were the Albanus (4.77 g/m² per day) and ES Monsoon (5.07 g/m² per day) hybrids, as well as the variants with PGR application on these hybrids (4.89 and 5.12 g/m² per day, respectively). The Albanus and ES Monsoon hybrids also performed well at a density of 230 thousand plants/ha: in the control variants with values of 4.78 and 4.69 g/m² per day, respectively; and in the variants with PGR application with maximum values of 4.78 and 4.82 g/m² per day. Furthermore, the aforementioned indicates that grain sorghum photosynthetic activity is significantly dependent on plant density and the genetic characteristics of the hybrids (individual sensitivity to high density), and the application of the investigated preparation increases the indices of photosynthetic potential and net photosynthetic productivity of crops or improves plant plasticity in cases of stem stand crowding.

Prospects for further research include expanding experiments to other agro-climatic zones of Ukraine to establish the regional stability of photosynthetic indicators for different grain sorghum hybrids. It is also advisable to investigate the dynamics of photosynthetic activity in conjunction with the biochemical characteristics of leaves and the level of water resource utilisation for a comprehensive assessment of the crop's

adaptive potential under varying moisture conditions and soil tillage technologies. None.

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Conflict of Interest

None.

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Вплив агротехнічних заходів на особливості фотосинтетичної активності гібридів сорго зернового в умовах Північного Степу України

Денис Сухіна

Аспірант

Національний університет біоресурсів і природокористування України

03041, вул. Героїв Оборони, 15, м. Київ, Україна

<https://orcid.org/0009-0008-4352-1777>

Наталія Новицька

Доктор сільськогосподарських наук, професор

Національний університет біоресурсів і природокористування України

03041, вул. Героїв Оборони, 15, м. Київ, Україна

<https://orcid.org/0000-0002-7645-4151>

Анотація. Вивчення фотосинтетичної активності сорго зернового є важливим для підвищення його продуктивності в умовах Північного Степу України, що характеризується нестабільним зволоженням і високими температурними коливаннями. Метою досліджень було визначити вплив гібридів, густоти стояння рослин і застосування регулятора росту рослин «Аппетайзер» на показники фотосинтетичної активності сорго зернового. Дослідження проводили протягом періоду 2022-2024 рр. на дослідних ділянках Дніпропетровської області. Попередником була пшениця озима, агротехніка вирощування – загальноприйнята для зони вирощування (окрім досліджуваних елементів та ширини міжряддя, яке становило 45 см). Серед методів, що використовувалися, були: польовий – спостереження за фенологічними фазами росту та розвитку культури, вплив досліджуваних елементів на фотосинтетичну активність сорго зернового; табличний – для систематизації, впорядкування та відображення отриманих даних; графічний – для відображення отриманих даних. У ході дослідження встановлено, що за фотосинтетичним потенціалом оптимальними були комбінації: гібриду ЕС Алізе за густоти 170 тис. рослин/га із застосуванням регулятора (далі – PPP) росту рослин (392,7 тис.м²/га*діб); гібридів ЕС Алізе та ЕС Фоен за густоти 200 тис. рослин/га на контролі (407,2 та 398,4 тис.м²/га*діб); гібриду ЕС Фоен за тієї ж густоти з PPP (404,0 тис.м²/га*діб); гібридів ЕС Алізе та ЕС Фоен за густоти 230 тис. рослин/га на контролі (400,0 та 415,7 тис.м²/га*діб), а також ЕС Алізе із застосуванням PPP (403,2 тис.м²/га*діб). За чистою продуктивністю фотосинтезу найкращими були: гібрид Албанус при густоті 170 тис. рослин/га – без PPP (4,67 г/м²/добу) та з PPP (4,70 г/м²/добу); гібриди Албанус (4,77) та ЕС Муссон (5,07) при 200 тис. рослин/га на контролі, а також з PPP (4,89 та 5,12 г/м²/добу відповідно); при 230 тис. рослин/га – гібриди Албанус (4,78) та ЕС Муссон (4,69) на контролі та з PPP (4,78 та 4,82 г/м²/добу). Отже, фотосинтетична активність сорго залежала від густоти, гібриду та дії регулятора росту досліджуваної добавки. Отримані результати дозволять агровиrobникам обґрунтовано добирати оптимальні комбінації густоти стояння, гібридів сорго та доцільність застосування регулятора росту для підвищення фотосинтетичної активності та урожайності посівів

Ключові слова: фотосинтетичний потенціал; чиста продуктивність фотосинтезу; фенологічні фази; живлення рослин; біостимулятор; сорго зернове