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Current Trends in Sorghum Use, Grain Yield and Water Consumption Depending on the Hybrid Composition

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ABSTRACT

The success of the crop production industry in the southern region of Ukraine always depended on weather and climatic factors. Among the factors of crop formation, the availability of moisture in plants occupied the first place. This dependence has been increasing in recent decades due to changes in the climatic conditions occurring not only in Ukraine, but also around the world. In this situation, it is necessary to improve the known elements of field crop cultivation technology and develop new measures to ensure the stability of the industry as well as reduce its dependence on climatic factors. This should help to obtain stable yield levels in all years, regardless of the significant deviations in temperature, precipitation and other weather factors. The solution of this issue is also becoming relevant in connection with the conditions of martial law in Ukraine, when the area of cultivation of agricultural products partially decreased. Adjustments to the development of measures also arise in connection with a significant reduction in the area of irrigated land. At the same time, it is necessary to select not only more drought-resistant crops for cultivation, but even their varieties or hybrids with a high level of productivity. After all, regardless of the specified state and a certain weakening of the economic capacity of agricultural enterprises, it is still necessary to receive the planned amount of crop production. This will determine not only the state of the agricultural sector, but also the stability of Ukraine as a whole.

Keywords: directions of use of sorghum plants, sorghum hybrids, climatic conditions, total water consumption, efficiency of moisture use by plants, grain yield, leaf surface area.

INTRODUCTION

In the last decade, the climatic conditions in the world and Ukraine in particular have been gradually changing. This is manifested in an increase in the temperature regime, mainly in summer, a certain decrease in the amount of precipitation and their uneven distribution during the growing season of agricultural crops. With this manifestation of conditions, the yield of plants is unstable: in dry years, as a rule, it decreases significantly compared to its levels in favorable years for moisture [Gamayunova et al., 2020]. Moreover, climatic factors change not only in summer, but also in winter, which affects the conditions of overwintering and the further formation of grain productivity of winter crops. The yield of the latter is also significantly determined by the reserves of soil moisture for the sowing period and the amount of precipitation during the growing season. Changes in climatic and growing factors, in addition to the yield level, significantly affect water consumption and, first of all, the use of moisture by plants for the formation of a unit of production [Gamayunova and Litovchenko, 2017].

Studies of scientists, including those conducted by the authors of this paper with many agricultural crops, established that more moisture accumulates and it was retained by soils enriched with organic matter, which had favorable water-physical properties and optimal supply of nutrients [Gamayunova, 1983; Gamajunova et al., 2021]. At the same time, in recent decades, organic fertilizers were almost not applied, or they were used in insufficient quantities relative to the recommended standards. This leads to compaction of soils, deterioration of water permeability and water retention capacity. In addition, in modern farming, there was practically no scientifically based alternation of agricultural crops. Crop rotations were oversaturated with sunflower, which was grown in some farms for 5 or even more consecutive years. This situation led to drying of soils, a significant deterioration in their properties and fertility in general [Gamayunova et al., 2019].

This state of modern management makes it necessary to search for new approaches to improving the efficiency of the industry, in particular, to improve the main elements of technology and measures that allow, obtaining sustainable crop productivity regardless of weatherfactors. Simultaneously, in addition to adapting agrotechnical measures to climate change, it is necessary to select the most drought-resistant plants, as well as determine the best varieties (hybrids) that can ensure the formation of stable yield levels.

Drought-resistant crops primarily include sorghum, millet, maize, safflower dye and others. It is advisable to adapt these plants to changing climatic conditions, introduce the most important elements of technology in their cultivation, which can significantly increase not only the level of yield and product quality, but also ensure high efficiency of using the available moisture in the soil and precipitation. After all, this factor is in the first minimum among all factors of crop formation. The second place after moisture is occupied by plant nutrition; both of these factors in interaction provide the highest yield gains.

These factors increase the productivity of agricultural plants especially significantly in recent years, when the alternation of crops in crop rotations has been disrupted and soil fertility decreased. If plants are sufficiently provided with nutrients, they form a more powerful root system, aboveground biomass, and more fully shade the soil, which prevents clogging and evaporation of moisture from its surface. The latter remains more in the soil for agricultural crops, and the efficiency of water consumption increases significantly. This is extremely important for the arid steppe zone of Ukraine and can significantly increase the productivity of cultivated crops by providing them with moisture that is more complete.

Thus, optimization of nutrition of all agricultural crops is aimed, in turn, at more efficient and economical water consumption. This also applies to the most drought-resistant plants, including millet, soriza and sorghum. After all, increasing their productivity is an important economic factor. This will contribute to obtaining significantly more products of these valuable crops, including biomass. In recent decades, bioethanol has been successfully produced from the biomass of sorghum plants. The high potential of sorghum crops is an important energy resource in the production of biofuels. Many researchers consider sugar cane, sugar beet, sorghum (grain and silage), and Miscanthus to be the most suitable for the production of various types of biofuels (bioethanol, biogas, etc.) [Mathur et al., 2017; Gavrish and Nosenko, 2016; Lopushniak et al., 2021]. Maize is recognized as a common crop used to produce biofuels (bioethanol and biodiesel). It is able to form a high yield of aboveground biomass [Meyer-Aurich et al., 2016; Mayer et al., 2014].

According to many characteristics, sorghum is a fairly close crop to maize, which, unlike it, has a higher drought resistance and uses less nutrients (fossil energy – fertilizers) to form stable productivity [Guo et al. 2017, Assefa et al. 2010]. Therefore, under the conditions of increasing temperature and aridity, sorghum varieties will become increasingly important. In many European countries, crop biomass was used for the production of biofuels for several decades. These plants serve as a major energy resource as a substitute for fossil fuels, in addition to reducing greenhouse gas emissions. Agricultural plants, as well as their by-products, can serve as a valuable source of energy and meet energy needs in the modern period and in the future in clean and ecological fuels [Bórawski et al., 2019; Nitsenko et al., 2018].

It is known that sorghum biomass is used as a raw material for the production of lignocellulose bioethanol. In addition, the average yield of bioethanol from sorghum significantly exceeds the yield level of other plants from which lignocellulose raw materials are obtained [Roozeboom et al., 2019].

Sorghum can be used as the main crop for the production of bioethanol it is characterized by a high specific methane yield. According to this yield, sorghum approaches the silage biomass of maize [Wannasek et al., 2017].

Sugar sorghum effectively produces biogas and bioethanol, which the researchers suggest, especially after pretreatment of biomass [Dar et al., 2018; Cattani et al., 2016; Ostovareh et al., 2015]. It is advisable to grow sorghum due to changes in climatic conditions, since this crop has a number of advantages over other energy plants. Sorghum is able to form a stable yield at high air temperatures, droughts, and can withstand cultivation on saline soils.

This crop consumes less moisture per unit of biomass, which reduces the cost of growing it, also when compared to maize [Amaducci et al., 2016]. In addition, it is known that by optimizing nutrition, sorghum provides significant yield increases for both grain and biomass. This is extremely important for energy crops, which must have a positive energy balance [Gamayunova et al., 2021; Kovalenko and Chernova, 2018; Gamayunova et al., 2021]. The above-mentioned properties and characteristics of sorghum are confirmed by other researchers [Batog et al., 2020; Barcelos et al., 2016]. They point out the appropriateness of attracting sorghum for cultivation in crop rotations, due to its advantages over other agricultural crops, as well as minimal competition of sorghum in comparison with them for the production of bioethanol and biogas.

Researchers recognized that the improvement of agrotechnical measures in the technology of sorghum cultivation, in particular the selection of varietal composition, optimization of nutrition can significantly increase the level of yield and, accordingly, raw materials for the production of bioethanol [Bonin et al., 2016; Gamayunova et al., 2021; Mishra et al., 2016; Meyer-Aurich et al., 2016]. This indicates a fairly high energy balance of the sorghum crop, because the energy efficiency of cultivation is determined by the ratio of energy input to the crop and its costs. The latter are low in the production process, because sorghum plants are undemanding in terms of growing conditions [Larnaudie et al., 2016; Mishra et al., 2016].

The above-mentioned review of literature sources, authors' previous research and the importance and wide possibilities of using sorghum plants indicate the feasibility of growing them in the Southern steppe of Ukraine. At the same time, despite changes in climatic conditions, the area under sorghum crops is still insignificant [State Statistics Service of Ukraine, 2019; Boiko, 2016; Gamayunova et al., 2022; Bazaluk et al., 2021].

In authors' opinion, due to the gradual decrease in the volume of fossil fuels, climate changes and the value of versatile use, the area of sorghum cultivation should be significantly increased. For this purpose, it is necessary to improve well-known elements of technology in all regions, directing them to adapt to climate change and increase productivity.

Such studies have been conducted under the conditions of the Southern steppe of Ukraine in

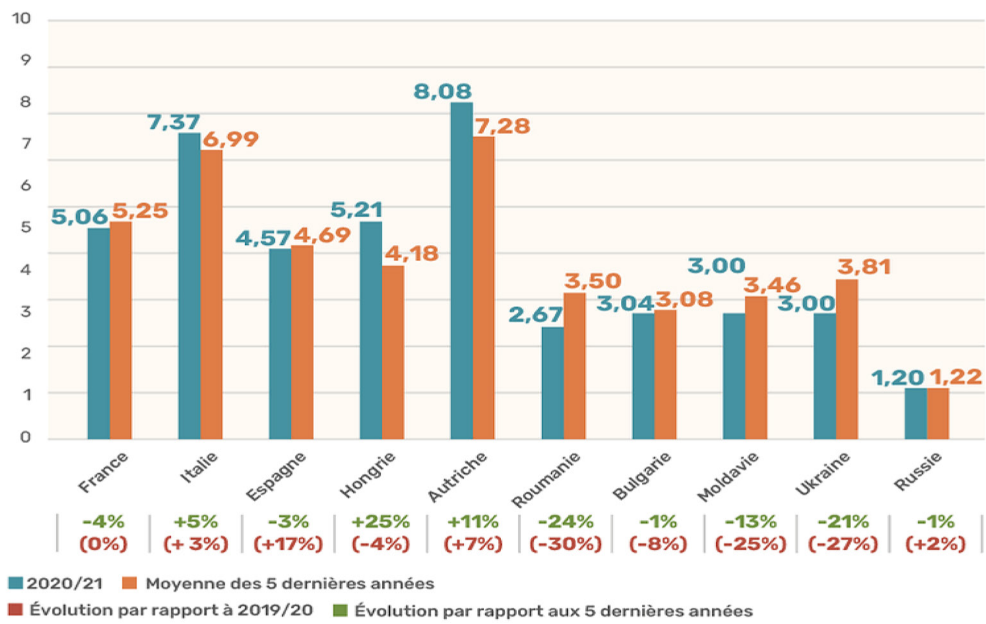

Figure 1. Average yield of grain sorghum in 2019/20 mg and 2020/21 mg. Source: electronic resource https://landlord.ua/news/posivni-ploshchi-pid-sorho-u-ievropi-u-2020-rotsi-zrosly-na-18/

recent years. In addition, the yield of grain sorghum in Ukraine was not the lowest among world producers (Fig. 1).

However, Figure 1 shows the data on the yield of sorghum grain in Europe and the USA. Thus, the highest productivity on average for 2019/2020 and 2020/2021 was obtained in Austria, then in Italy, the next positions were occupied by France and Hungary, then Spain. Ukraine occupies an intermediate position in this indicator. After it, Romania, Moldova, Bulgaria and Russia are placed in terms of yield.

For 2020 95 varieties and hybrids of grain sorghum, 19 – soriza, 27 sugar sorghum, 16 – sorghum-Sudan hybrids, 7 – broom sorghum were entered in the state register of plant varieties in Ukraine. Therefore, in addition to clarifying and refining the main elements of the technology, researchers need to determine the best, most productive and adapted to the conditions of the zone varieties and hybrids. They also have to effectively use moisture to form a crop unit.

The previously conducted studies in different zones of Ukraine substantiate the influence of fertilizer on the level of yield of sorghum grain and other energy plants and the main indicators [Kalenskaya and Naidenko, 2018; Lopushniak and Hrytsulyak, 2016; Rakhmetova et al., 2020]. After all, the productivity of the quality of grown raw materials of sorghum plants, including the application of mineral fertilizers, largely depends on the yield of bioethanol, established by both Ukrainian and foreign researchers [Kobernyuk and Mulyarchuk, 2017; Krzystek et al., 2018; Garofalo et al., 2016; Lopushniak et al., 2022].

However, in the literature sources there is practically no information about the peculiarities of the use of moisture by sorghum plants. In the southern steppe zone of Ukraine, such studies were conducted with many agricultural crops in the fields of the Mykolaiv National Agrarian University, also depending on the varietal composition without irrigation [Gamayunova et al., 2017; Gamayunova and Kudrina, 2018; Panfilova and Gamayunova, 2018; Gamajunova et al., 2020; Panfilova et al., 2020].

Of course, the highest productivity of all crops, regardless of the weather and climatic conditions of the year in the southern region of Ukraine, can be guaranteed to be obtained for growing on irrigated land. The yield significantly depends on the dose of fertilizers applied, the method and mode of irrigation [Gamayunova and Zadorozhny, 2015]. Unfortunately, the area of irrigated land was significantly decreased in recent years and in the post-war period increasing it would be problematic, also taking into account the economic viability of farms. Therefore, it was necessary to use preliminary scientific results to increase the productivity of plants, save their moisture consumption directly for crop formation, as well as significantly reduce and prevent unproductive costs.

Taking into account the importance and relevance of these issues, as elements in the cultivation of sorghum varieties in particular, they were taken for study.

The aim of the research was to determine the ability of eight sorghum hybrids to use moisture (soil and precipitation) sparingly to form a crop unit in different growing years in terms of moisture content. This issue is extremely important for the southern steppe zone of Ukraine, where moisture is at the first minimum and among the factors that take part in the formation of yield levels and limit productivity in exceptionally dry years. This issue is insufficiently studied in the cultivation of crops and especially in recent years due to changes in climatic conditions.

RESEARCH METHODOLOGY

The field experiments to determine the adaptation of a number of sorghum hybrids regarding their ability to form a grain crop and effectively use moisture were conducted at the Educational, Scientific and practical center of the Mykolaiv National Agrarian University. The study was conducted in the southern steppe zone of Ukraine during 2020–2022. The soil diversity is southern chernozem. The supply of soil with mobile forms of nutrients in the years of cultivation for nitrogen was average, and for phosphorus and potassium, it had an increased content. Humus in the arable soil layer contained 2.9–3.1%, pH – 6.8–7.2.

The weather conditions during the growing years of sorghum hybrids varied, especially in terms of precipitation and its distribution during the growing season, but were typical for the research area.

The grain yield at the onset of its humidity of 18% was determined from the entire area of the accounting plot. Soil moisture was determined by using the thermostatic-weight method, total water consumption was determined by means of the water balance method, and leaf surface area was determined by die-cutting.

When conducting observations, accounting, definitions and calculations, the guidelines recommended for the zone and DSTU were used.

Agricultural techniques for growing sorghum hybrids taken for study were generally accepted for the southern steppe zone of Ukraine.

RESEARCH RESULTS AND THEIR JUSTIFICATION

Total water consumption plays an extremely important role in climate aridity. The level of water consumption in different agricultural crops depends on biological characteristics, even the variety (hybrid). It can vary significantly and it varies depending on the fertility of the field (soil structure), the level of mineral nutrition, plant density, agrotechnical measures, initial moisture reserves for the sowing period, precipitation and temperature during the growing season of the crop, even individual interphase periods, etc. The conducted studies determined that the total water consumption and components of its balance in the years of growing sorghum hybrids differed (Table. 1).

Therefore, if in 2020 and 2022 the total amount of water used by plants was quite close: 2962 and 2937 m^3/ha, respectively, then in 2021, which was significantly more favorable in terms of moisture, it amounted up to 4038 m^3/ha. In all the years of research, the greater need for moisture of the plants of sorghum hybrids taken for research was met by precipitation that fell during the growing season. This element of the balance in the years of cultivation ranged from 68.4 up to 74.9%, and on average for 2020-2022 amounted to 71.9%. The share of water that plants used from the soil accounted for between 25.1 and 31.6% of the total balance of research years, and on average for 2020–2022, this figure was 28.1%.

The supply of moisture to plants during their growing season – from sowing and germination to full grain maturation, significantly affected the levels of grain productivity of the studied sorghum hybrids (Table 2).

The lowest grain productivity was determined in 2020 which was the least favorable in terms of precipitation. On average, for all hybrids taken for study, the grain yield this year was 4.64 t/ha. Grain yield levels ranged from 2.2 t/ha (MR Bazley hybrid) up to 6.9 (U 60116 IG hybrid). Despite the close values of total water consumption in this year and in 2022, the distribution of

Table 1. Total water consumption of grain sorghum hybrids and its balance during the growing years

Growing season	General water consumption, m^3/ha	Balance sheet components			
		Water consumption from the soil		Precipitation of the growing season	
		m^3/ha	%	m^3/ha	%
2020	2962	854	28.8	2114	71.2
2021	4038	1014	25.1	3024	74.9
2022	2937	927	31.6	2010	68.4
Average for 2020–2022 years	3312	932	28.1	2383	71.9

Table 2. Influence of weather conditions on the grain yield of sorghum hybrids, t/ha

Hybrid	Growing years			Average for 2020–2022 years
	2020	2021	2022	
ADV G 1329	3.2	7.3	5.0	5.2
Yankee	5.8	9.6	7.1	7.5
Sentinel	2.4	7.8	4.9	4.7
Bianca	6.1	13.3	9.7	9.7
MR Eclipse	4.3	8.5	6.9	6.6
MR Bazley	2.1	6.9	4.4	4.5
U 60116 IG	6.9	14.5	9.8	10.4
U 60117 IG	6.3	13.8	9.6	9.9
HIP_{05}	0.45	0.74	0.63	

precipitation during the critical growing season in the latter was significantly more favorable. The average grain yield for all hybrids in 2022 was 7.09 t/ha, or it was by 34.6% higher than in 2020. In the context of hybrids, their tendency to form a grain crop remained.

The maximum yield of sorghum grain was determined in 2021, in which it averaged 10.21 t/ha for the studied hybrids.

The conducted research allowed identifying both the most potentially productive and zone-adapted hybrids of grain sorghum, as well as the least productive ones, which were impractical to recommend to production.

The value of grain yields that formed the most and least productive sorghum hybrids during the growing years were provided (Fig. 2).

After all, it is well known that the higher productivity a variety or hybrid can provide under the same growing conditions, the more efficiently (economically) it spends moisture on obtaining a unit of yield. It should be noted that the water consumption coefficient changed significantly both in the context of the studied hybrids and the years of cultivation (Table 3).

Sorghum hybrid plants used the most economical moisture (soil and precipitation) in 2021. On average, for all hybrids, water consumption per 1 ton of grain with the corresponding amount of aboveground biomass was 428.3 m^3.

In the context of hybrids taken for research, this indicator in 2021 ranged from 208.5 up to 585.2 m^3/t. The maximum amount of moisture for the formation of a crop unit was spent by grain sorghum hybrids in the unfavorable moisture content of 2020 studies. The above values this year were: 770.9, 430.1 and 1413.3 m^3/t, respectively. This indicated that the sorghum hybrid, which was able to use moisture most economically, or vice versa was completely unproductive compared to

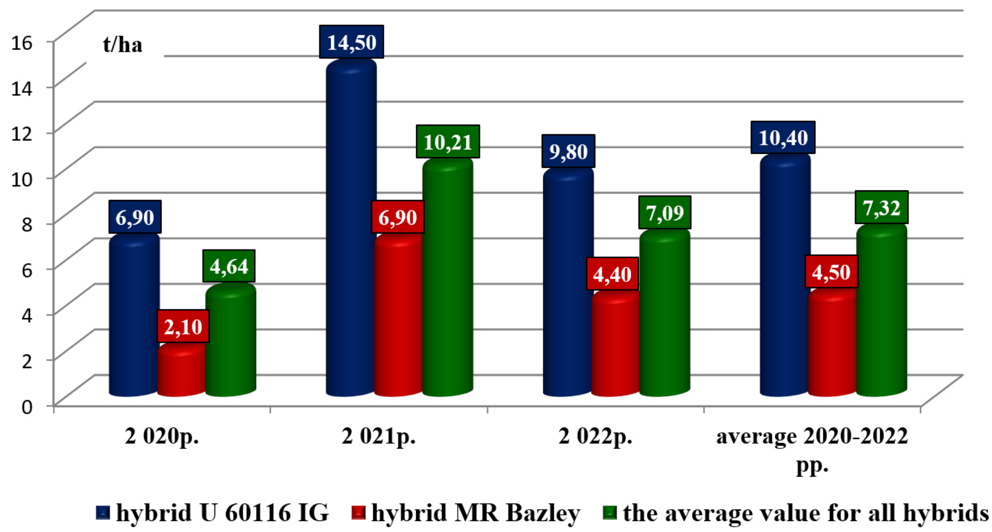

Figure 2. The most contrasting grain yield levels of sorghum hybrids in the years of cultivation, t/ha

Table 3. Moisture consumption by plants of sorghum hybrids for the formation of grain with the corresponding amount of aboveground biomass, m^3/t

Hybrid	Coefficient of water consumption in years of cultivation			Average for 2020–2022 yrs
	2020 yr	2021yr	2022 yr	
ADV G 1329	927.5	553.2	662.4	714.4
Yankee	511.7	420.6	466.5	466.3
Sentinel	1236.7	517.7	675.9	810.1
Bianca	486.6	309.6	341.4	377.2
MR Eclipse	690.2	475.1	480.0	548.4
MR Bazley	1413.3	585.2	752.7	916.1
U 60116 IG	430.1	278.5	338.0	348.9
U 60117 IG	471.1	292.7	345.0	369.6
Average value for Hybridax	770.9	428.3	507.7	568.8

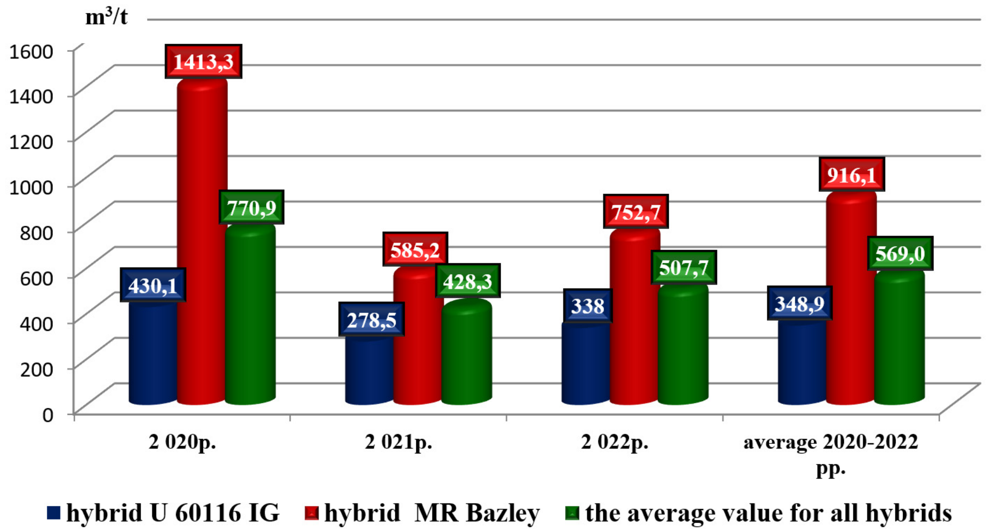

Figure 3. Fluctuations in the water consumption coefficient of grain sorghum hybrids depending on the climatic conditions of the year of cultivation, m^3/t

the average indicators of the water consumption coefficient. This is clearly illustrated in Figure 3.

Thus, the higher the grain sorghum hybrid is able to generate grain yield, the more productively it uses moisture per unit of grown production, and vice versa: with a low yield level, water consumption increases significantly. At the same time, much more moisture is spent not by plants directly on the crop, but on evaporation from the field surface, use by weeds, etc., that is, these are unproductive losses.

To a large extent, this phenomenon is caused by the peculiarities of both the agricultural crop and the variety or hybrid in the context of the crop, and precisely by their ability to accumulate aboveground biomass and the corresponding area of the assimilation apparatus. The more it is formed, the more efficiently plants are able to use solar energy and moisture to form the crop itself, because they tightly shade the field surface, which prevents unproductive moisture loss due to evaporation. This is also typical for the cultivation of other agricultural crops, especially for optimizing their nutrition [Gamayunova et al., 2017].

Taking into account the above, the leaf surface area of grain sorghum hybrids taken for research during the main growing seasons was determined (Table. 4).

Studies established that the area of assimilation surface of sorghum plants in the context of hybrids, already from the initial phases of growth and development, differed. A more significant difference in this indicator was manifested during the period of plant entry into the tube and subsequent periods of determination.

The maximum values of the leaf surface area of plants of all the studied sorghum hybrids reached during the flowering period, and by the full ripeness of the grain, it significantly decreased. This was due to the biological characteristics of the culture. From flowering to full ripeness of grain, a fairly long period passes, during which the processes of grain

Table 4. Dynamics of leaf surface area of sorghum hybrids, (average for 2020–2022 yrs), thousand m^2/ha

Hybrid	Growth and development phase					
	Full seedlings	Tillering	Stooling	Throwing out the panicle	Flowering	Full ripeness of grains
ADV G 1329	1.43	10.92	34.27	46.32	53.12	22.84
Yankee	1.61	11.24	38.41	49.57	59.37	23.41
Sentinel	1.48	10.31	37.35	49.12	59.13	23.64
Bianca	1.92	11.45	37.94	50.36	59.93	24.35
MR Eclipse	1.59	11.16	33.32	43.64	51.72	21.67
MR Bazley	1.31	10.37	29.12	39.72	48.31	19.72
U 60116 IG	1.93	11.84	38.39	50.29	59.45	23.96
U 60117 IG	1.95	11.88	38.47	50.18	59.87	25.01

formation and the passage of various phases – milk ripeness, waxy and full ripeness-directly occurred. During this period, assimilants entered the grain from the leaves, which were directly involved in the formation of grain mass and affected its quality. The leaves began to turn yellow, lose moisture, mass and dry out. That is, by the end of the growing season and full maturation of the grain, the assimilation surface of the plants of the studied sorghum hybrids was significantly reduced. At the same time, as determined by studies, the leaf surface area of plants of all hybrids that were taken for study varied significantly. Both its increase in the initial periods and its decrease by the end of the growing season occurred with a certain regularity.

It was established that this indicator was quite closely correlated with the level of grain yield. The maximum values of the assimilation area of plants were reached in the most productive hybrids and vice versa, it was formed the smallest in hybrids with a low level of grain yield. This dependence was traced in all the main phases of plant growth and development of the studied sorghum hybrids, which can be traced according to the data given in Table 4. A close correlation relationship R^2 = 0.887–0.901 was determined between the leaf surface area of sorghum plants during the periods of panicle ejection and flowering and the level of grain yield.

It was determined that the area of the assimilation apparatus in sorghum plants depended and it was formed due to the number of shoots formed. Thus, the tillering coefficient of the MR Bazley hybrid on average for 2020–2022 studies was only 1.6, and in the most highly productive sorghum hybrids it grew up to values in the range of 2.8–3.5. Of course, this affected the foliage of hybrids in subsequent growing periods, as well as the mass of panicles, which during the period of full grain ripeness in the MR Bazley hybrid was determined to average 116.6 g, and in the U 60117 IG hybrid – 303.3 g.

CONCLUSIONS

This article highlighted the importance of sorghum culture, the possibility of its widespread use, including for processing into ecological fuels. The advantages of sorghum plants as drought-resistant and unpretentious in cultivation were justified. The most productive and adapted to arid conditions sorghum hybrids were identified, which could significantly affect the balance of grain production in Ukraine.

At the same time, the ability of sorghum hybrids to effectively use moisture under different climatic conditions of growing years was determined. This was extremely important for arid conditions and climate change.

According to the results of studies conducted during 2020–2022 on Southern chernozem in the steppe zone of Ukraine with a number of grain sorghum hybrids, it was found that the higher they were able to form grain yields, the more efficiently plants use moisture (soil and precipitation during the growing season). The increase in grain productivity and economical water consumption was due to a more developed assimilation apparatus in plants due to an increase in the tillering coefficient. A close correlation was determined between the grain yield levels and the leaf surface area during the most important growing seasons.

According to the ability of hybrids to provide high grain yield under the conditions of the Southern steppe of Ukraine, including in unfavorable years with significant aridity due to the most efficient use of moisture, the following sorghum hybrids can be recommended for cultivation: U 60116 IG, U 60117 IG, Bianca and Yankee.

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