Received: 20.06.2024 Revised: 08.10.2024 Accepted: 27.11.2024

BIOLOGICAL SYSTEMS: Theory and Innovation

Journal homepage: https://bioscience.com.ua/en
Vol. 15, No. 4, 2024, 73-85

UDC 635.65:631.5 DOI: 10.31548/biologiya/4.2024.73

Influence of meteorological conditions on the yield and seed quality of differently ripened soybean varieties in the central Forest-Steppe

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Abstract. The relationship between meteorological conditions and crop yields is mainly aimed at explaining the impact of climate change on the environment. Fluctuations in air temperature and humidity affect the water balance and are the main factors for increasing or decreasing crop yields. Such hydrothermal variations can affect any region. Despite this, the purpose of the study was to establish the influence of meteorological conditions such as temperature, precipitation, the sum of active temperatures, and the Selyaninov hydrothermal coefficient (HTC) on the yield and quality of seeds of different varieties of differently ripened soybeans Glycine max (L.) Merril of foreign selection in the conditions of the central Forest-Steppe. The study used general scientific and special research methods, in particular, field, laboratory, and statistical. The highest yield on average over the years of research was observed in the standard Mentor variety (2.45 t/ha), which was slightly higher than the Cordoba variety (< 1%). The deviation of the target for the Moravia variety from the standard variety was 7.4%. According to the results, the lowest yield variability was found in the standard Mentor variety (2.57%), the Cordoba variety was also characterised by low variability (5.99%), while in the Moravia variety, this indicator was with an average variability of 17.62%. During the three-year research period, the protein content

Suggested Citation:
Chabaniuk, Ya., Brovko, I., Kovtun, A., & Milova, M. (2024). Influence of meteorological conditions on the yield and seed quality of differently ripened soybean varieties in the central Forest-Steppe. *Biological Systems: Theory and Innovation*, 15(4), 73-85. doi: 10.31548/biologiya/4.2024.73.

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in soybean seeds ranged from 38.75% to 40.31%. All soybean varieties had low trait variability (< 3%). The analysis of the relationship between the yield and quality of seeds of soybean varieties of foreign selection and the main factors of climatic conditions formed in the central Forest-Steppe region was carried out. Correlation analysis showed the degree of influence of various meteorological conditions on the productivity of the soybean varieties under study, which facilitates a more purposeful and balanced approach to the choice of varieties in specific climatic conditions. The results of the conducted studies can be applied in the implementation of measures for a reasonable choice of soybean varieties to ensure consistently high yields during periods of possible adverse meteorological conditions

Keywords: *Glycine max* (L.) Merril; productivity; sum of active temperatures; sum of precipitation; hydrothermal coefficient; correlation

INTRODUCTION

At the current stage of development of the agricultural industry, one of the main challenges for Ukraine's agricultural sector remains a significant increase and stabilisation of production of legumes, in particular soybeans. Ukraine is a key producer of soybeans in Europe and is one of the world's leading suppliers of this crop, occupying a significant share in the global market. The acreage under soybeans in Ukraine is constantly increasing, which indicates the importance of this crop. Ensuring stable yields of this crop in the context of global and local climate changes is an urgent scientific task.

Soybeans are highly sensitive to the presence of moisture, so its main growing areas in Ukraine are located in the zone with sufficient moisture supply – in the "soybean belt", which includes the Forest-Steppe zone, Steppe areas with "forest-steppe" conditions and Southern Polissia regions with "forest-steppe" conditions. V.G. Didora *et al.* (2017) noted that the forest-steppe is the main area of soybean production, it is a significant area with suitable soils for growing soybeans, light, heat and water resources, and the duration of the growing season. Given this, the area under this crop should increase in these regions of the country. Despite the fact that most of the territory of Ukraine has favourable agroclimatic conditions for growing soybeans, even in relatively favourable areas, there is a periodic negative impact of extreme weather conditions on this crop.

Weather conditions make significant adjustments to the soybean yield. Drought in the leading regions of intensive soybean production worsens the prospects for its harvest. Temperature is a key climatic factor for growing soybeans. According to M.Y. Shevnikov (2010), due to the wide diversity of varieties, soy demonstrates high adaptability to different growing conditions, and its distribution area covers territories from the equator to 52-54˚N. During the growing season, most varieties require the sum of active air temperatures (above 10˚C) from 1,600-2,000˚C to 3,200˚C. The requirements for active temperatures for different groups of varieties are as follows: for the earliest – maturing varieties – 1,600-1,900˚C, for early-maturing varieties – 2,000-2,200˚C, medium-maturing – 2,300-2,700˚C, medium-late-maturing – 2,800-2,950˚C and late-maturing – 3,000-3,200˚C.

However, the impact of climate change on soybean quality is a serious problem. Researchers W. Zhu *et al.* (2024) found that factors such as temperature and precipitation caused by climate change have a direct and indirect impact on the growth, development, and quality of soybean. In addition, extreme weather events cause various types of damage to soybean plants, which further affects the quality indicators of seeds – the protein and oil content. Among extreme weather events, drought is the most common and strongly affects the development and yield of soybeans. According to F.A. Alsajri *et al.* (2020), S. Poudel *et al*. (2023), a drought at the beginning of the season can reduce the protein content, but at later stages of crop growth, on the contrary, it increases its content, in contrast to the oil content, which is negatively affected by a late seasonal drought.

An important measure to increase the yield and improve the quality of soybean products is the scientifically based selection of varieties for cultivation. O. Sydiakina & M. Ivaniv (2023) state that the variety is one of the resource-saving elements of cultivation technology, it accounts for up to

30-35% of crop growth, and in extreme weather years it is the variety that plays a crucial role in shaping crop productivity.

According to O.Y. Revtio & O.O. Zolin (2023), Ukraine has a fairly large assortment of soybeans of different ripeness groups: ultra-precocious, early-maturing, medium-early-maturing, medium-maturing, and medium-late-maturing. The State Register of Plant Varieties of Ukraine for 2022 includes 300 different varieties of soybeans, which are represented by breeding in more than 10 countries of the world. The largest share is made up of domestic varieties – 42.3% of the total number of soybean varieties, Canada – 24.7%, France – 16.5%, Austria – 5.1%, Serbia – 2.5%, and Poland – 1.8%. The share of varieties of foreign selection from other countries: Germany, USA, Romania, and Croatia as a whole are 7.1%.

In general, as stated by O.P. Tkachuk *et al.* (2022), for the conditions of the Ukrainian Steppe, mainly medium-ripened and late-ripened varieties are suitable, for the forest-steppe – early-ripened and medium-ripened, and in Polissia – ultra-early- and early-season varieties. In addition, H.M. Zabolotnyi *et al.* (2020) emphasised that when choosing a variety, it is necessary to consider nutritional properties – protein content, which, in turn, affects the cost of grown products. In conditions of intensive farming with extreme weather conditions, it is important to grow several varieties of different ripeness groups on farms.

Among environmental factors, the determining and most influential factors of agricultural productivity are weather and climate. According to conclusions of A.A. Zymaroyeva (2020), trends in climate change can significantly affect crop productivity, despite advances in cultivation technologies. Climate change is projected to be accompanied by an increase in global average temperatures, changes in precipitation patterns, and an increase in the frequency and intensity of extreme weather events, which will undoubtedly have an impact on crop yields.

Thus, obtaining stable yields of this crop in the context of global and local climate changes in Ukraine, in particular due to increased aridisation, is an urgent task. Its implementation is impossible without studying heterogeneous material, sampling the most adapted to arid conditions. Fluctuations in temperature and humidity affect the water balance and are the main factors for increasing or decreasing the yield of agricultural crops, in particular soybeans. Such hydrothermal variations can affect any region of the country.

The purpose of the study was to identify the influence of agrometeorological conditions on the development of yields of various varieties of cultivated soybean *Glycine max* (L.) Merril and the main indicators of the quality of seeds of this crop in the south-western part of the Forest-Steppe zone of Ukraine (on the example of the Vinnytsia Oblast).

MATERIALS AND METHODS

The research was conducted in the Forest-Steppe during 2019-2021 on the experimental field of the Institute of Agribiology LLC in Velykyi Mytnyk village, Khmilnyk district, Vinnytsia Oblast (Fig. 1).

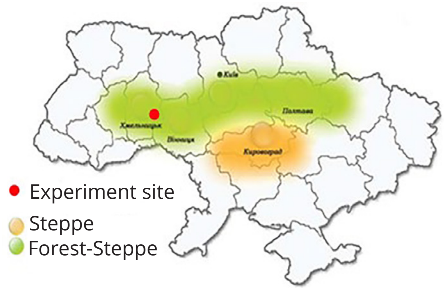

Figure 1. Schematic map of the main cultivated areas of soybeans ("soybean belt") in Ukraine and the experiment site

Source: developed by the authors based on V. Petrychenko (2012)

Three soybean varieties *G. max* (L.) Merril of foreign selection of different maturity groups were grown in experimental crops: Mentor (standard variety, st), Cordoba, and Moravia. Mentor variety: country of creation – France (Euralis Semans); year of registration – 2013; recommended growing area: Forest-Steppe, Polissia, Steppe; direction of use – grain; quality – medium oil; protein content, % – 39.6-40.7; oil content, % – 19.7-20.5; ripeness group – early ripening; yield: Steppe – 19.7 hwt/ha; Forest-Steppe – 22.5 hwt/ha; Polissia – 24.9 hwt/ha; drought resistance: 7.8-9.0 points; lodging resistance: 8.6-9.0 points; shedding resistance: 8.6-9.0 points; resistance to certain types of pests (diseases): peronosporosis – 9.0 points; ascochitosis – 9.0 points; bacteriosis – 9.0 points;

septoria – 9.0 points; fusarium – 9.0 points; growing season duration – 105-115 days.

Cordoba Variety: country of creation – Canada (Agreliant Genetix Inc.); year of registration – 2014; recommended area for cultivation: Forest-Steppe, Polissia, Steppe; direction of use – grain; quality – medium oil; protein content, % – 38.6-39.2; oil content, % – 20.9-22.3; ripeness group – medium early; yield: Steppe – 17.6 hwt/ha; Forest-Steppe – 23.7 hwt/ha; Polissia – 20.7 hwt/ha; drought resistance: 8.1 – resistance to shedding: 8.8-9.0 points; resistance to shedding: 8.5-9.0 points; resistance to certain types of pests (diseases): peronosporosis – 9.0 points; ascochitosis – 9.0 points; bacteriosis – 9.0 points; septoria – 9.0 points; fusarium – 9.0 points; growing season duration – 114-138 days.

Moravia variety: country of creation – Canada (Semenses Prograin Inc.); year of registration – 2011; recommended area for cultivation: Forest-Steppe, Polissia, Steppe (irrigation); direction of use – grain; quality – medium oil; protein content, % – 38-41; oil content, % – 20.5-22.0; ripeness group – medium-ripened; yield: Steppe – 17.6 hwt/ha; Forest-Steppe – 23.7 hwt/ha; Polissia – 20.7 hwt/ha; drought resistance – 8.1-9.0 points; resistance to lodging – 5.0 points; growing season duration – 122-135 days.

The total area of the experiment site was 150 m^2, accounting – 100 m^2. The repetition of the experiment was four-fold, the predecessor – fallow, and the method of placing variants in repetition was used by the method of randomised split plots. Agricultural techniques for conducting experiments were generally accepted for the growing area. Type of land – tilled soil. The soil is a typical low-humus, medium-loamy chernozem. When conducting the research, the authors were guided by the methodology of scientific research in agronomy regarding the specific features of research on leguminous crops according to V.G. Didora (2013). Regular phenological observations and biometric surveys were carried out throughout the growing season. The average yield was determined by the ratio of the weight of the harvested crop to the total area of the fields on which it was grown. The content of “crude protein” (protein) was determined by infrared spectroscopy according to DSTU 4117:2007 (2007).

To assess the impact of weather conditions on the yield and quality of soybean seeds, the following indicators were used: air temperature, precipitation, and Selyaninov hydrothermal coefficient (HTC) during the soybean growing season. The meteorological data were obtained from the Khmilnyk hydrometeorological station in Vinnytsia Oblast and recorded using a Bresser weather centre 5-in-1 weather station. HTC was defined as the ratio of the sum of precipitation ($\sum R$) in mm for a period with average daily air temperatures > 10°C (active growing period) to the sum of temperatures ($\sum t > 10°C$) during the same time, reduced by 10 times using the following scale: HTC < 0.4 – very severe drought; HTC from 0.4 to 0.5 – severe drought; HTC from 0.6 to 0.7 – average drought; HTC from 0.8 to 0.9 – weak drought; HTC from 1.0 to 1.5 – sufficient moisture; HTC > 1.5 – excessive moisture. Mathematical and statistical processing of the obtained data was carried out using descriptive and variational statistics methods, using the data processing programmes “IBM SPSS Statistics (v. 23.0)” and “Microsoft Excel 2016”. The variability of a feature was considered insignificant if the coefficient of variation (V,%) did not exceed 10%. If the value of this indicator was more than 10%, but less than 20%, the volatility was considered average. If $V > 20\%$, then the volatility was considered significant. The Pearson pair correlation coefficients were calculated (a certain number from - 1 to + 1, which characterises the tightness of the linear correlation between the dependent and independent random variables).

Experimental plant research, including the collection of plant material, complied with institutional, national or international guidelines and adhered to the standards of the Convention on Biological Diversity (1992).

RESULTS AND DISCUSSION

Weather conditions in the years of research differed in the temperature regime, the amount of precipitation, and the indicator of moisture content of the territory during the growing season (Table 1). The growing season of soybeans in 2019 was characterised by insufficient moisture supply (average drought) against the background of unseasonably high air temperature levels throughout the entire growing season. The hydrothermal coefficient (HTC) was 0.7; the sum of active temperatures above 10°C – 3,548°C (Table 1).

Table 1. Weather conditions during the growing seasons of soybeans over the years of research (Velykyi Mytnyk, Khmilnyk district, Vinnytsia Oblast, 2019-2021)

Years of observations	Indicator of the growing season			
	Sum of active temperatures, °C (*∑t > 10°C*)	Amount of precipitation, mm (*∑R*)	Average air temperature, °C (t_{avg})	HTC
2019	3,548	279.0	18.7	0.7
2020	2,525	252.6	19.0	1.0
2021	2,909	280.8	19.1	0.9

Note: HTC – Selyaninov hydrothermal coefficient
Source: compiled by the authors

In 2020, soybean growth and development took place under abnormal conditions, with a drought, a shortage of precipitation, and an increase in the duration of drought periods. The hydrothermal coefficient has reached 1.0, which indicates sufficient moisture content. The sum of active temperatures (∑*t* > 10°C) from germination to harvesting in the wax ripeness phase was 2,525°C, which is 1.4 times less compared to 2019 (Table 1).

In the third year of testing (2021), weather conditions in the first half of the growing season developed similarly to 2019. However, the presence of productive precipitation in April-May, high air temperature contributed to the development of a good vegetative mass. Flowering and bean development took place in conditions of mild drought. The hydrothermal coefficient (HTC) was 0.9. For the entire growing season from germination to soybean harvesting, the sum of active temperatures above 10°C was 2,909°C, which is 1.2 times less compared to 2019 and 1.1 times more than in 2020 (Table 1).

O.V. Shovkova (2022) noted that the yield indicator is a key element of the economic value of an agricultural crop. It reflects the combined influence of all the factors that affect the plant during its growing season. Crop yield is always a consequence of the interaction between productivity and the ability to withstand adverse environmental conditions.

Considering the current meteorological conditions during the years of research, the average soybean yield in 2019 was 2.33 t/ha, in 2020 – 2.21, and in 2021 – 2.52 t/ha. The highest yield for all years of research was formed by Mentor st and Cordoba varieties, which were characterised by similar indicators – 2.45 and 2.43 t/ha, respectively (Table 2; Fig. 2). This indicator was lowest in the early-maturing Moravia variety – 2.28 t/ha. That is, the deviation of the yield of the Cordoba and Moravia varieties from the Mentor St standard variety is < 1% and 7.4%, respectively. The results showed the lowest yield variability in the Mentor St standard variety (2.57%) and Cordoba variety (5.99%), while in the Moravia variety this indicator was with an average variability of 17.62% (Table 2).

Table 2. Yield of soybean varieties (t/ha) over the years of research (2019-2021)

No.	Varieties	Yield, *t/ha*				Deviation, +/-		*V*, %
		2019	2020	2021	average	*t/ha*	%	
1	Mentor, st	2.49	2.39	2.47	2.45	–	–	2.57
2	Cordoba	2.43	2.28	2.58	2.43	-0.02	-0.8	5.99
3	Moravia	2.07	1.97	2.81	2.28	-0.17	-7.4	17.62

Note: *V*, % – coefficient of variation
Source: compiled by the authors

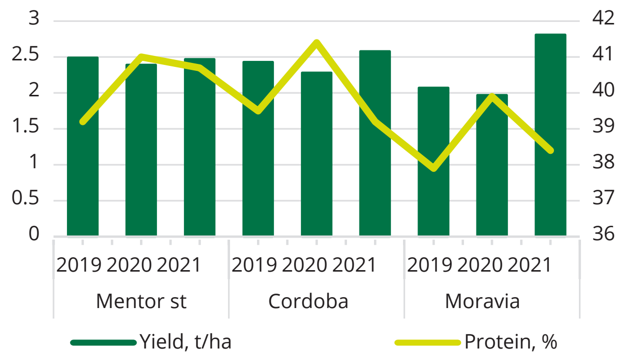

Figure 2. Yield (t/ha) and protein content (%) of soybean varieties depending on the year of research (Velykyi Mytnyk, Khmilnyk district, Vinnytsia Oblast, 2019-2021)
Source: compiled by the authors

According to L.V. Gubenko *et al.* (2019), the quality of products obtained in the process of growing agricultural crops is no less significant than the yield indicator. The main criterion that determines quality of soy seeds have a crude protein content. It is known that the commercial characteristics of soybean seeds are formed based on the combination of biological characteristics of the variety, agrotechnical practices, and soil and climatic conditions.

According to the results of biochemical analysis, it was found that the protein content in seeds of all soybean varieties averaged: in 2019 – 38.8%, in 2020 – 40.7%, and in 2021 – 39.4%. The protein content in the seeds of soy varieties Mentor st, Cordoba, and Moravia in general over the years of research was on average in the range from 38.75% to 40.31% (Table 3; Fig. 2). The results showed a deviation of this indicator among all the varieties under study, compared with the Mentor st standard variety, the deviation in protein content ranged from -0.28% (Cordoba) to -1.56% (Moravia). Analysis of statistical parameters shows that during the study period, the coefficient of variation was not characterised by high variability of the trait, but was at a low level in all soybean varieties ($V < 3\%$) (Table 3).

Table 3. Protein content in soybean seeds (%) over the years of research (2019-2021)

No.	Varieties	Protein content, %				Deviation, +/-		*V*, %
		2019	2020	2021	average	% of protein content	%	
1	Mentor, st	39.2	41.0	40.7	40.31	–	–	2.40
2	Cordoba	39.5	41.4	39.2	40.03	-0.28	-0.69	2.97
3	Moravia	37.9	39.9	38.4	38.75	-1.56	-4.02	2.72

Note: Protein content in soybean seeds (%) over the years of research (2019-2021)
Source: compiled by the authors

The main indicators used in agrometeorology to assess weather conditions are air temperature, precipitation, the sum of active temperatures, and an integral indicator that simultaneously considers both of these indicators can be considered the Selyaninov hydrothermal coefficient (HTC) for displaying humidification conditions. It is well known that the limiting environmental factor in Ukraine is, first of all, the hydrological conditions of existence of any living organisms, as a result of which special importance is attached to the assessment of moisture conditions. The correlation of yields and protein content in seeds of the studied soybean varieties of foreign selection with meteorological indicators for three years is presented in Table 4.

Table 4. Influence of meteorological conditions on yield and protein content in soybean seeds (correlation coefficients, *r*)

No.	Varieties	Indicator of the growing season			
		Sum of active temperatures, °C ($\sum t$ > 10°C)	Amount of precipitation, mm ($\sum R$)	Average air temperature, °C (t_{avg})	*HTC*
1	Mentor, st	+0.8 / -0.9#	+0.9 / -0.5	-0.5 / +0.9	-0.8 / +0.9
2	Cordoba	+0.3 / -0.7	+0.8 / -0.9	+0.2 / +0.2	-0.3 / +0.7
3	Moravia	-0.03 / -0.9	+0.6 / -0.9	+0.6 / +0.5	+0.08 / +0.8

Note: # – parameter value separated by fractions is specified for yields / protein content; HTC – Selyaninov hydrothermal coefficient
Source: compiled by the authors

When evaluating the correlation coefficient between yield and weather conditions of the growing season for 2019-2021, a high correlation density was established in the Mentor st standard variety (r = 0.9 ± 0.8), which showed a strong dependence of the obtained products on meteorological conditions (Table 4). There was also a strong direct relationship between the yield of the Cordoba variety and moisture availability (r = 0.8) during the growing season and a low degree of correlation with heat availability and moisture content. Correlation analysis between the yield and weather conditions of the growing season in the Moravia variety showed that the productivity of this variety did not correlate with the sum of active temperatures ($\sum t$ > 10°C) and HTC, but the average direct relationship between the yield from precipitation and temperature was established (Table 4).

According to the results of the analysis of the correlation coefficient between the seed quality (protein content) of soybean varieties and the weather conditions of the growing season of the three-year period (2019-2021), a high relationship was established in the Mentor st standard variety in terms of heat supply and moisture content (r = 0.9 ± 0.9), and an average inverse correlation with precipitation (r = -0.5). A strong negative dependence of protein content on precipitation was recorded in the Cordoba variety (r = -0.9), and the correlation with other weather indicators was characterised by medium and low binding density. A qualitative assessment of the tightness of the correlation analysis between the protein content and the main weather indicators of the growing season in the Moravia variety showed a strong relationship between all the studied indicators and a direct average sum of active temperatures ($\sum t$ > 10°C) (Table 4).

According to A.A. Korobko (2021), in Ukraine, the average soybean yield in 2019 was 2.40 t/ha, in 2020 it reached a lower level – 1.77 t/ha, and in 2021 – 2.23 t/ha. Analysis of available data in the State Register of Plant Varieties Suitable for Distribution in Ukraine (State Register ..., n.d.) and official descriptions of plant varieties and indicators of economic suitability, presented in the bulletins "Protection of rights to plant varieties", placed in the information and reference system "Variety" (Information and reference system ..., 2024) showed that the yield of early-maturing soybean variety Mentor in various soil and climatic conditions of Ukraine is: Polissia – 2.49 t/ha, Forest-Steppe – 2.25 t/ha, and Steppe – 1.97 t/ha, and the protein content in seeds ranged from 39.6% to 40.7%. As for the mid-early soybean varieties – Cordoba and Moravia, the yield level of the Cordoba variety was on average: in Polissia – 2.07 t/ha, Forest-Steppe – 2.37 t/ha, and Steppe (irrigation) – 1.76 t/ha, and the protein content varied from 38.0% to 39.2%; in Moravia, these indicators on average reach 2.00 t/ha in terms of yield, and 41% in terms of protein content. With this in mind, for the Forest-Steppe zone, these varieties can be arranged in the following descending order relative to the yield level (t/ha): Cordoba > Mentor > Moravia; by protein content (%): Moravia > Mentor > Cordoba.

The results of three years of research in this paper are somewhat consistent, and in some ways differ from the above-mentioned data on the yield and quality (protein content) of seeds of these soybean varieties in the Forest-Steppe of Ukraine. It was found that in terms of yield, these varieties are arranged in a similar way (Cordoba > Mentor > Moravia), but a radically different picture is observed regarding the protein content in seeds, their order of arrangement (descending) differs from above mentioned and has the following form: Mentor > Cordoba > Moravia.

Both Ukrainian and foreign researchers have conducted studies analysing the impact of climate change separately from other factors affecting soybean yields. However, it is worth noting that Ukrainian researchers paid less attention to the study of the impact of climatic conditions and weather data directly on the yield and, especially, the quality of soybeans compared to other priority crops, despite the fact that soybeans occupy a leading position in export and processing for food and feed needs (along with grain crops), and are also strategically important for ensuring food and economic security of the state.

In particular, the analysis of weather conditions of the Left-Bank Forest-Steppe (on the example of Poltava Oblast), L.G. Bilyavska (2010) showed that over the past 17 years, there has been a deterioration in humidification conditions, an increase in the average annual air temperature by 0.8-0.9˚C, and there is also a pronounced downward trend in HTC indicators. As a result, the above-mentioned phenomena have a significant impact on the duration of seasons, there is a gradual increase in the heat supply of the growing season, and an increase in the number and intensity of stress factors. Under such conditions, fluctuations in the soybean yield occur in the range of 10-20%, and the impact of extreme weather conditions reaches the level of 30-60%. Therefore, the researcher notes that varieties intended for growing in the Forest-Steppe of Ukraine should be photoperiodically neutral, precocious, cold-resistant at different stages of organogenesis, and quickly release moisture during seed maturation. Ultimately, the researcher concluded that given the influence of environmental factors occurring in soybean production, it is necessary to introduce soybean varieties of regional selection adapted for certain soil and climatic zones.

V.S. Zuza *et al.* (2015) presented the results of studies on the yield of soybeans of the early-ripening Romantika variety of Ukrainian selection (growing season 90-100 days) in years with different levels of moisture supply (2009-2012) in the conditions of the Left-Bank Forest-Steppe. It is shown that the level of soybean yield in some years of research was significantly influenced by the humidification regime during the critical period for yield development (from the third ten days of June to the third ten days of August inclusive). Research by A.A. Zymaroyeva (2020), which focused on establishing the contribution of agroecological factors, namely bioclimatic variables, soil indicators, and landscape diversity factors, to the variation of soybean yields in Polissia and Forest-Steppe of Ukraine (Vinnytsia, Volyn, Zhytomyr, Kyiv, Lviv, Rivne, Ternopil, Khmelnytskyi, Cherkasy, and Chernihiv oblasts) during 1991-2017, proved that the variation of the soybean yield growth rate by 9% depends on climatic conditions and soil variables. In addition, soil and climatic factors determined 51% variation in the minimum and 69% variation in the maximum yield of this crop.

According to the studies by Ukrainian researchers V. Polovyy *et al.* (2021), which were conducted during 1985-2018 at the stationary field of the Institute of Agriculture of Western Polissia of the National Academy of Sciences (Ukraine), clarified the trends of changes in temperature and humidity of the climate, which led to the restructuring of crops and the yield of some crops, in particular soybeans, in the north-western Forest-Steppe of Ukraine. The researchers have found that the heat supply of landscape agroecosystems has significantly improved: a rapid increase in the sum of effective temperatures has created favourable conditions for growing heat-loving crops such as soybeans, corn, and sunflower in the north-western Forest-Steppe. As these crops are rapidly expanding, the area structure and overall agricultural landscapes of the region are very similar to the southern Right-Bank Forest-Steppe.

A study conducted by A.V. Golodna *et al.* (2024) during 2021-2023, in the stationary experiment of the National Research Centre Institute of Agriculture of the National Academy of Sciences of Ukraine, which was geographically located in the Right-Bank Forest-Steppe, on the influence of weather conditions during the growing season of soybeans of the Ukrainian variety Muza on the yield level using correlation analysis, showed that there are different strengths and areas of the relationship between the yield of soybean seeds and weather conditions, both within decades and on average for individual months of the growing season. It was found that the tightness of the connection ranged from weak to strong. When analysing the dependence of yields on individual weather factors, it was found that July had the most pronounced negative correlation with the average monthly air temperature, while May, June, and August had the highest correlation with precipitation. The greatest combined effect of average daily air temperature and precipitation was observed in the third ten days of June and August.

According to field research by M. Tsekhmeistruk *et al.* (2021), conducted in the period 2004-2020 at the V.Y. Yuriev Institute of Plant Production of the National Academy of Agrarian Sciences of Ukraine and subsequent correlation analysis between the impact of weather conditions on soybean yields, noted the negative impact of the average daily temperature in August when applying $N_{30}P_{30}K_{30}$ and 30 t/ha of manure before sowing soybeans. With a different mineral background of nutrition, the average daily temperature had little effect on the yield level. The amount of precipitation had a slightly greater impact, and the July precipitation had a positive effect on the crop on all mineral nutrition backgrounds. May precipitation had a positive effect only when growing soybeans under control (without fertilisers) and against the background of $N_{60}P_{60}K_{60}$ + 30 t/ha of manure.

Analysing foreign statistics on the dynamics of growth of acreage and soybean yields, the United States of America is in the leading positions, along with Brazil, Argentina, China, and India, which together account for 48% of the world's land area (Sedibe *et al.*, 2023). Despite this, scientific research is actively conducted in these countries to investigate the impact of climate change and meteorological conditions (together with or without various agricultural activities) on soybean cultivation.

American researchers R.K. Sharma *et al.* (2022) using a fixed-effect model based on panel data to study the effects of climate variables such as maximum daily temperature, minimum temperature, and precipitation and soybean yields in the south-eastern region of the United States (Arkansas, Alabama, Florida, Louisiana, Mississippi, Georgia, Tennessee, North Carolina, South Carolina, Texas, and Virginia) from 1980 to 2020 showed significant variability in temperature and precipitation over the past four decades. The maximum daily temperature, minimum temperature, and precipitation varied by: 0.50°C, 1.45°C, and 3.95 cm, respectively, during the soybean growing season. Moreover, the annual rate of change of the maximum daily temperature, minimum temperature and precipitation over the studied forty-year period increased by 0.012°C, 0.034°C, and 0.094 cm, respectively. Precipitation did not significantly affect soybean yields: an increase in precipitation by 1 cm reduced soybean yields by 0.40%. An increase in the minimum temperature by 1°C led to a decrease in soybean yield by 31.6%, and an increase in the maximum daily temperature by 1°C reduced soybean yield by 25.6%.

Research by American scientists F.A. Alsajri *et al.* (2020), which was aimed at studying the influence of temperature conditions (day/night temperatures: 21/13°C, 25/17°C, 29/21°C, 33/25°C, and 37/29°C) on the yield and quality of seeds of indeterminate (Asgrow AG5332, AG) and determinant (Progeny P5333RY, PR) of soybean varieties showed that the variety-temperature interaction was significant for seed yield, protein, oil and other quality parameters (palmitic, oleic, linolenic acids, raffinose and stachyose). Analysis of the quadratic functions of yield dependence on temperature showed that the optimal temperature for maximum yield was 26°C for AG and 23°C for PR. The temperature affected all indicators of seed quality in both varieties. The protein concentration in the seeds was slightly higher at two lower and higher temperatures than at 29/21°C. The oil concentration in the seeds increased with increasing temperature to 26°C for AG and 25°C for PR, and decreased at higher temperatures.

In a study by Argentine scientists E.O. Thomasz *et al.* (2024), using multiple partial regression, the correlation between soybean yields in various combinations of weather stations for the period 2001-2021 was estimated, which covered the entire soybean growing area in Argentina (an average of 17 million hectares). The results showed that there is a strong statistical relationship between precipitation and maximum temperature and overall soybean yield. However, precipitation did not have sufficient explanatory power at the local level due to the importance of other local agroclimatic variables, which explained an average of 72% of the yield variation in total production. That is, precipitation as the only variable was statistically significant at the macro scale. When temperature was introduced into the model, the explanatory capacity increased to 91.3%.

Another study by Indian scientists R.S. Gadhave *et al.* (2023) conducted in 2019 in India (Parbhani) on the correlation between weather parameters and the yield of various soybean varieties (MAUS-71; MAUS-158 and JS-335) during the summer agricultural season (the so-called "harif") showed that temperature and some thermal indices have a significant impact on seed yield. The maximum temperature was positively associated with soybean seed yield at the stages: pre-emergence after sowing; from germination to branching; from branching to flowering; from flowering to pod formation; from pod formation to pod development containing full-size grain in the MAUS-158 variety, but negatively correlated at the stages – emergence; from pod formation to grain formation; from grain formation to bean development. The maximum temperature was positively associated with soybean seed yield in the stages from germination to branching, from branching to flowering; from flowering to pod formation; from pod formation to pod development containing full-size grain in relation to the MAUS-71 variety, while it was negatively correlated in the stages of emergence, from pod formation to grain formation, and from fully formed pod to maturation. The highest temperature was positively associated with soybean seed yield at the stages – from germination to branching, from branching to flowering, from flowering to pod formation, and from the end stage of pod formation to full maturation; and negatively correlated at the stages of emergence, from pod formation to grain formation, and from the fully formed pod to the beginning of maturation in the variety JS-335.

The correlation analysis carried out in this paper by the authors showed the degree of influence of the main meteorological conditions on the formation of yield and seed quality (protein content) of the studied differently ripened soybean varieties, which ripen at the sum of active temperatures above 10°C from 2000-2200°C to 2700°C, in the conditions of the central Forest-Steppe (Vinnytsia Oblast), which allows a more purposeful approach to the choice of varieties for specific climatic conditions. Mentor st (early-maturing) and Cordoba (medium-early-maturing) varieties react approximately equally to growing conditions and climatic factors and have fairly similar patterns in yield development, but differ in its quality (protein content). However, this study has certain limitations that may be covered by future research areas. Among the most important is the inclusion of other agroclimatic variables, and various agricultural measures in the technology of growing soybeans in specific soil and climatic conditions.

CONCLUSIONS

Meteorological conditions that developed during the years of the study (2019-2021) in the south-western part of the Forest-Steppe zone of Ukraine (Vinnytsia Oblast) significantly varied in temperature conditions, indicators of moisture content of the territory, to a lesser extent – in the amount of precipitation during vegetation periods. In the soil and climatic conditions of the central Forest-Steppe, during the three-year research period, the deviation of the yield (in %) of soybean grain in experimental varieties from the standard variety (mentor) ranged from -0.8 (Cordoba) to -7.4 (Moravia). The lowest yield variability was recorded in the standard Mentor st variety (2.57%), while Cordoba and Moravia varieties were characterised by low (5.99%) and medium variability (17.62%), respectively. However, when compared with the standard Mentor st variety, the protein content deviation ranged from -0.69% (Cordoba) to -4.02% (Moravia) with low target trait variability in all varieties (< 3%).

In the conditions of the central Forest-Steppe, the yield of Mentor st and Cordoba varieties was significantly affected by the moisture availability of the growing season, the temperature regime had a strong degree of correlation only in the standard Mentor st variety, and vice versa – a low degree of correlation in terms of heat availability in the Cordoba variety. In the Moravia variety, the average indicators of moisture and heat supply during the growing season do not fully reflect their impact on yield, possibly because the direction of their influence varies greatly by the phases of crop development, which requires additional research.

A high correlation of protein content in the standard Mentor st variety was established in terms of heat supply and moisture content. A strong inverse dependence of protein content on precipitation was recorded in the Cordoba variety, in contrast to other weather indicators of the growing season. The Moravia variety has a strong relationship between the protein content and all the weather indicators under study. Prospects for further research are to investigate the influence of meteorological conditions on the productivity of soybean varieties of foreign and Ukrainian regional selection in the context of climate change using inoculation on different nutritional backgrounds.

ACKNOWLEDGEMENTS

None.

CONFLICT OF INTEREST

None.

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Вплив метеорологічних умов на формування урожайності та якості насіння різностиглих сортів сої в умовах Центрального Лісостепу

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Анотація. Залежність між метеорологічними умовами та врожайністю сільськогосподарських культур спрямована переважно на пояснення впливу змін клімату на навколишнє середовище. Коливання температури та вологості повітря впливають на водний баланс і є головними чинниками підвищення або зниження врожайності сільськогосподарських культур. Такі гідротермічні варіації здатні вплинути на будь-який регіон. Зважаючи на це, метою досліджень було встановлення впливу метеорологічних умов таких як температура, опади, суми активних температур та гідротермічний коефіцієнт Селянінова (ГТК) на урожайність та якість насіння різностиглих сортів сої культурної *Glycine max* (L.) Merril зарубіжної селекції в умовах центрального Лісостепу. Використовували загальнонаукові та спеціальні методи досліджень, зокрема польовий, лабораторний і статистичний. Найбільша врожайність у середньому за роки досліджень відзначена у стандартному сорті Ментор (2,45 т/га), що незначно перевищує сорт Кордоба (< 1 %). Відхилення цільового показника в сорті Моравія від сорту стандарту було на рівні 7,4 %. За результатами досліджень виявлено найнижчу варіабельність урожайності у сорті стандарті Ментор (2,57 %), сорт Кордоба характеризувався також низькою мінливістю (5,99 %), тоді як у сорті Моравія цей показник був із середньою мінливістю – 17,62 %. За трирічний період досліджень вміст білка в насінні сортів сої знаходився у межах від 38,75 % до 40,31 %. Усі сорти сої мали низьку варіабельність ознаки (< 3 %). Проведено аналіз взаємозв'язку врожайності та якості насіння сортів сої зарубіжної селекції з основними факторами кліматичних умов, що формуються в регіоні центрального Лісостепу. Кореляційний аналіз показав ступінь впливу різних метеорологічних умов на формування продуктивності досліджуваних сортів сої, що дозволяє більш цілеспрямовано та виважено підходити до вибору сорту в конкретних кліматичних умовах. Результати проведених досліджень можуть бути застосовані при реалізації заходів щодо обґрунтованого вибору сортів сої для забезпечення стабільно високих врожаїв у періоди можливих несприятливих метеорологічних умов

Ключові слова: *Glycine max* (L.) Merril; продуктивність; сума активних температур; сума опадів; гідротермічний коефіцієнт; кореляційний зв’язок