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DETERMINATION OF DROUGHT TOLERANCE OF POPCORN HYBRIDS (*ZEA MAYS* L. *EVERTA STURT*.)

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***Topicality**. The subzone of the Northern Steppe of Ukraine is characterized by severe droughts, which lead to a significant decrease in the yield of popcorn (Zea mays everta Sturt.). In this regard, evaluation of hybrids for drought resistance is essential for selection of the best samples that can withstand difficult hydrothermal growing conditions. **Purpose**. To determine the drought resistance of popcorn hybrids under conditions of air and soil drought. **Materials and Methods**. The material for the research was 58 popcorn hybrids that were subjected to competitive variety testing. The mid-early hybrid Shans and the mid-ripening hybrid Hostynets were used as standards. The trials were conducted at the Laboratory of Food Maize Breeding at the Synelnykove Breeding and Research Station of the SE Institute of Grain Crops of NAAS of Ukraine in 2020–2021. An index approach based on both resistance and susceptibility of genotypes to moisture deficit was used to study the hybrids' response to drought. **Results**. The growing season of 2020 was hot and dry in contrast to 2021. In unfavourable conditions of 2020, average grain yields for mid-early hybrids were 3.1 times lower and for mid-ripening hybrids 3.2 times lower compared to 2020. Such weather conditions allowed us to evaluate the maize hybrids for drought resistance, and identified 22 hybrids (36.7 %) as drought-resistant, given their corresponding indices for 5–7 indicators. The Shans hybrid, a standard of the mid-early group, was also drought-resistant. **Conclusions.** According to the results of research, it was established that mid-early popcorn hybrids (IKR 30 × IKR 2-3), (IKR 2-3 × IKR 9-2) × IKR 4, (IKR 30 × IKR 24) × IKR 37 and mid-ripening hybrids (IKR 11-9 × IKR 16/75/24-5), (IKR 15-2 × IKR 37/17/72-5) × IKR 21, (IKR 30 × IKR 2-1) had high yield and drought resistance.*

***Key words**: popcorn, selection, tolerance, drought, drought tolerance indices, grain yield*

Introduction. Earth's warming climate is one of the crucial challenges of our time. Greenhouse gas emissions have already led to a 1.1°C rise in global average air temperature, and could reach 1.5 °C in the period from 2030 to 2052, according to the Intergovernmental Panel on Climate Change (IPCC), thus increasing the frequency of extreme droughts worldwide [1].

In Ukraine, the average air temperature in summer increased by 1.3 °C, in winter by 0.9 °C, in spring by 0.9 °C, and in autumn by 0.4 °C. If analysed on a monthly basis, the largest increase in average temperature occurred in two months: January (by 2.3 °C) and July (by 1.4 °C) compared to the long-term average [2].

The Northern Steppe of Ukraine is characterised by frequent and severe droughts. According to A. O. Babych and A. A. Babych-Poberezhna, zonal atmospheric droughts have occurred in spring and autumn in the Steppe of Ukraine about 30 times over the past 100 years. Summer atmospheric droughts in the Steppe zone are more frequent than spring and autumn droughts; there were 45 droughts in the South of the zone and about 40 ones in the North over the century [3].

At the same time, if the average annual air temperature rises by 1.5 °C in 2020–2050, every second season could be dry [2]. Therefore, evaluation of hybrids for drought resistance is required to select the best samples that can withstand severe hydrothermal conditions.

Poor drought tolerance of plants is a feature of popcorn, which is often caused by a less deve-

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loped root system compared to grain maize [4, 5].

According to S. H. Kamphorst et al, water deficit is one of the most limiting abiotic factors for the formation of productivity of this crop. Drought stress significantly affected the volume of popcorn per hectare, the 100 grain weight and the greenness index (SPAD index). The decrease in grain yield of popcorn hybrids under the influence of drought was 55.29 %, and the popping expansion of grain decreased by 29.19 % [6, 7].

Maize is most vulnerable to moisture deficit in the period from the beginning of tasseling stage to waxy ripeness. During flowering, the plant uses 8-9 mm of water daily, and 170–180 mm over the entire period of grain filling. Popcorn yields are halved in case the plants remain wilted for 4 days in the period from pollination to milky ripeness [8].

The research was aimed at determining the drought tolerance of popcorn hybrids under air and soil drought conditions and identifying the best genotypes for further research.

Materials and Methods. The material for the research was 58 popcorn hybrids that were subjected to competitive variety testing. The Shans hybrid (FAO 260) and Hostynets hybrid (FAO 320) were used as standards. The experiments were conducted at the Laboratory of Food Maize Breeding at the Synelnykove Breeding and Research Station of SE Institute of Grain Crops of NAAS of Ukraine during 2020–2021.

Agricultural practices used in the research were generally accepted for the Northern Steppe of Ukraine. The plot area was 8.4 m^2; the experiment was repeated three times. Sowing of popcorn hybrids was carried out with a plot drill, and the harvest was collected with a Wintersteiger Delta plot combine. The harvesting results were recalculated to 14 % grain moisture content [9].

To study the response of hybrids to drought, an index approach was used, which was based on both tolerance and susceptibility of genotypes to moisture deficit [10]. The following indices were calculated [11]:

– stress susceptibility index – $SSI = 1 - \frac{Y_s}{Y_p} / 1 - \frac{\bar{Y}_s}{\bar{Y}_p}$ (1)

– tolerance index – $TOL = Y_p - Y_s$ (2)

– mean productivity – $MP = \frac{Y_p + Y_s}{2}$ (3)

– yield stability index – $YSI = \frac{Y_s}{Y_p}$ (4)

– yield index – $YI = \frac{Y_s}{\bar{Y}_s} \times 100$ (5)

– stress tolerance index – $STI = \frac{Y_p \times Y_s}{\bar{Y}_p^{\,2}}$ (6)

– geometric mean productivity – $GMP = \sqrt{Y_p \times Y_s}$ (7),

where Y_p – yield under optimal conditions; Y_s – yield under stressful conditions; $\bar{Y}_p$ – average yield of all hybrids under optimal conditions; $\bar{Y}_s$ – average yield of all hybrids under stressful conditions.

For each index, the median was calculated, which characterised the mean variance of its manifestation. The lower level of the median of SSI and TOL indices and the higher level of MP, YSI, YI, STI, GMP indices were responsible for drought tolerance of genotypes [12].

Mathematical data processing was carried out by means of special software Microsoft Office Excel (Statistica) on a personal computer. The statistical reliability of the experimental data was calculated according to P. P. Litun et al. [13].

Results and Discussion. According to the Synelnykove Agrometeorological Station, the weather conditions were extremely dry in 2020 (Table 1).

Despite the cold and wet May, only 69.2 mm of precipitation fell over the summer, or 36.2 % of the long-term average, and the air temperature was 1.5–3.0 ℃ above the long-term average.

Table 1. Hydrothermal conditions during the growing season of maize hybrids, 2020–2021

Month	Precipitation, mm			Sum of effective temperatures above 10 ℃			Hydrothermal coefficient (HTC)	
	long-term average	2020	2021	long-term average	2020	2021	2020	2021
May	50.0	66.5	33.4	179.0	121.3	185.9	5.5	1.8
June	59.0	28.8	181.9	284.0	361.8	296.0	0.8	6.1
July	61.0	25.1	126.8	348.0	392.0	421.5	0.6	3.0
August	35.0	15.3	39.3	323.0	393.8	398.9	0.4	1.0
September	36.0	9.5	22.3	148.0	288.0	163.2	0.3	1.4
Total	241.0	145.5	403.7	1282.0	1556.9	1465.5	-	-

In contrast to the previous year, 2021 was very rainy. Precipitation fell to 403.7 mm from May to September (168 % of the long-term average). The highest precipitation was 181.9 mm in June and 126.8 mm in July. At the beginning of the popcorn growing season, average monthly temperatures were close to the long-term average, and in July and August they exceeded them by 2.7 ℃ and 2.8 ℃, respectively.

Soil moisture content was determined by the hydrothermal coefficient according to G. T. Selianinov [14]. The data analysis showed that soil moisture content was sufficient only in May 2020, while in June there was a mild drought, in July – medium, and in August and September – extremely severe drought. During the growing season in 2021, the soil moisture content was sufficient or excessive (Table 1).

The heat and dry conditions of 2020 had a negative impact on popcorn yields. The minimum yields for mid-early hybrids were 1.01 t/ha, and for mid-ripening hybrids – 1.00 t/ha, while the maximum yields were 1.86 t/ha and 2.26 t/ha, respectively (Table 2).

Table 2. Grain yield of popcorn hybrids, 2020–2021

Maturity group	Number of hybrids, pcs.	Indicator	Yield, t/ha	
			2020	2021
Mid-early	27	$\bar{x} \pm ts_x$	1.37 ± 0.18	4.29 ± 0.18
		min	1.01	3.25
		max	1.86	5.38
		Shans, standard	***1.86***	***5.33***
Mid-ripening	31	$\bar{x} \pm ts_{\bar{x}}$	1.43 ± 0.18	4.62 ± 0.18
		min	1.00	3.19
		max	2.26	6.53
		Hostynets, standard	***1.54***	***6.04***
LSD_{05}			0.50	0.52

Average grain yields were 3.1 times lower for mid-early hybrids and 3.2 times lower for mid-ripening hybrids in 2020, compared to favourable weather conditions in 2021.

In 2020, the best grain yields were achieved by such mid-early hybrids as Shans - 1.86 t/ha; F_1 (IKR 30 S × IKR 2-3 VS) – 1.84 t/ha; F_1 [(IKR 75-1 × IKR 37-2) × IKR 15-1] – 1.72 t/ha; F_1 [(IKR 2-3 × IKR 9-2) × IKR 4] – 1.69 t/ha, and in 2021 – F_1 [(IKR 30 × IKR 2-1) × IKR 35] – 5.38 t/ha; Shans - 5.33 t/ha; F_1 [(IKR 35 × IKR 16-1) × IKR 37/17/72-5] – 5.25 t/ha; F_1 [(IKR 35 × IKR 16-1) × IKR 2-3] – 5.08 t/ha. Over two years, the following hybrids stood out on average: Shans – 3.60 t/ha; F_1 (IKR 30 S × IKR 2-3 VS) – 3.46 t/ha and F_1 [(IKR 30 × IKR 2-1) × IKR 35] – 3.43 t/ha.

In 2020, the following combinations were distinguished among the mid-ripening hybrids: F_1 (IKR 30 × IKR 2-1) – 2.26 t/ha; F_1 (IKR 11-9 × IKR 16/75/24-5) – 2.18 t/ha; F_1 (IKR 30 S × IKR 3-6 VS) – 2.04 t/ha; F_1 (IKR 30/1 × IKR 35) – 1.90 t/ha, and in 2021 – F_1 (IKR 30/1 × IKR 35) – 6.53 t/ha; F_1 (IKR 11-9 × IKR 37/17/72-3) – 6.34 t/ha; Hostynets – 6.04 t/ha; F_1 [(IKR 2-3 × IKR 9-2) × IKR 1] – 6.02 t/ha. The highest yields on average for two years were shown by F_1 (IKR 30/1 × IKR 35) – 4.22 t/ha; F_1 (IKR 11-9 × IKR 16/75/24-5) – 4.0 t/ha and F_1 [(IKR 2-3 × IKR 9-2) × IKR 1] – 3.89 t/ha.

The following indices were calculated to determine the drought tolerance of popcorn hybrids: SSI – stress susceptibility index (1), TOL – tolerance index (2), MP – mean productivity (3), YSI – yield stability index (4), YI – yield index (5), STI – stress tolerance index (6) and GMP – geometric mean productivity (7). Table 3 shows the variation of drought tolerance indices of tested hybrids and indices of standards.

Stress susceptibility index (SSI) describes the sensitivity of a genotype to drought. The lower the value of this index, the greater the drought tolerance of plants. Among the popcorn hybrids, the lowest level of stress susceptibility index was in F_1 (IR 30 S × IR 3-6 VS) – 0.71, and the highest – in F_1 [(IR 35 × IR 16-1) × IR 37/17/72-5] – 1.19. Shans standard (0.96) had a better drought tolerance compared to Hostynets standard (1.01), according to the stress susceptibility index. Values of this index lower than the median level were also observed in 29 other hybrids.

The drought tolerance index (TOL) indicates the grain yield losses of the popcorn hybrid under the influence of drought in absolute-units, and its high value corresponds to the sus-

Table 3. Variation of drought tolerance indices in popcorn hybrids, 2020–2021

Variation parameters		Drought tolerance indices						
		SSI*	TOL, t/ha	MP, t/ha	YSI	YI, %	STI	GMP, t/ha
Limits	min	0.71	1.88	2.22	0.19	69.9	0.19	1.89
	max	1.19	4.69	4.22	0.52	158.0	0.52	3.52
Median		1.01	2.95	2.88	0.31	96.9	0.31	2.45
Shans, standard		0.96	3.47	3.60	0.35	130.1	0.35	3.15
Hostynets, st.		1.01	4.50	3.79	0.25	107.7	0.25	3.05

***Note**. * SSI - stress susceptibility index, TOL - tolerance index, MP - mean productivity, YSI - yield stability index, YI - yield index, STI - stress tolerance index, GMP - geometric mean productivity.*

ceptibility of the genotype to water stress. The minimum values of this index were observed in the F_1 hybrid (IKR 30 S × IKR 3-6 VS) – 1.88 t/ha, and the maximum values - in the F_1 hybrid (IKR 11-9 × IKR 37/17/72-3) - 4.69 t/ha. Standards Shans and Hostynets were characterised by a high level of tolerance index, 3.47 t/ha and 4.50 t/ha, respectively. High drought tolerance according to this index was observed in 30 maize hybrids.

The mean productivity (MP) of popcorn hybrids was calculated in an optimal and dry year, which determines their response to drought conditions. According to our research, this indicator ranged from 2.22 t/ha to 4.22 t/ha, and the mean productivity median was 2.88 t/ha. The mean productivity was higher than the median level in 27 hybrids, the best of which was F_1 (IKR 30/1 × IKR 35) with a yield of 4.22 t/ha. The Shans and Hostynets standards had productivity above the median value.

Yield stability index (YSI) is defined as the ratio of yield in dry conditions to yield in optimal conditions. The highest index was demonstrated by the F_1 hybrid (IKR 30 S × IKR 3-6 VS) – 0.52, and the lowest index – 0.19 – by the F_1 hybrid [(IKR 35 × IKR 16-1) × IKR 37/17/72-5]. The Shans standard had an index above the median value of 0.35, and the Hostynets hybrid had a lower index of 0.25.

The yield index (YI) is the ratio of the yield of a certain popcorn hybrid in dry conditions to the mean yield of all hybrids in the same year in percentage terms. The fluctuation range of yield index was from 69.9 % for the F_1 hybrid [(IKR 17-2 × IKR 37) × IKR 35/8-3] to 158 % for the F_1 hybrid (IKR 30 × IKR 2-1). The index was higher than the median level in 30 hybrids, including standards Shans – 130.1 % and Hostynets – 107.7 %.

Stress tolerance indices (STI) identified hybrids with high yields in both dry and optimal weather conditions, so this index describes the ability of a genotype to maintain a stable yield level regardless of environmental factors. According to the results of the studies, the highest stress tolerance index was 0.52 in the F_1 hybrid (IKR 30 S × IKR 3-6 VS), and the lowest was 0.19 in the F_1 hybrid [(IKR 35 × IKR 16-1) × IKR 37/17/72-5]. The Shans standard had a higher value of this index than the median, as well as 28 other popcorn hybrids, while the Hostynets standard had a low value (0.25) of the stress tolerance index.

The geometric mean (or proportional mean) productivity (GMP) characterises the relative yield, as drought stress can vary in its severity over the years. The highest indicator was 3.52 t/ha in the F_1 hybrid (IKR 30/1 × IKR 35), and the lowest was 1.89 t/ha in the F_1 hybrid [(IKR 2-3 × IKR 37) × IKR 4]. This indicator was higher than the median level in 31 hybrids, including Shans (3.15 t/ha) and Hostynets (3.05 t/ha).

According to the results of the research, 22 drought-tolerant hybrids (or 36.7 %), which had the corresponding indices for 5–7 indicators, were identified. Table 4 shows the best hybrid combinations that combined drought tolerance with high yields.

Conclusions. According to our research,

Table 4. Average grain yield and deviation of drought tolerance indices from the median in popcorn hybrids, 2020–2021

Hybrid combination	FAO	Average yield, t/ha	Deviation of drought tolerance indices from the median						
			SSI	TOL, t/ha	MP, t/ha	YSI	YI, %	STI	GMP t/ha
1	2	3	4	5	6	7	8	9	10
F_1 (IKR 11-9 × IKR 16/75/24-5)	320	3.81	-0.13	0.31	0.93	0.09	55.5	0.09	0.99

Table 4 continuation

1	2	3	4	5	6	7	8	9	10
Shans, standard	260	3.60	-0.05	0.52	0.72	0.04	33.2	0.04	0.70
F_1 [(IKR 15-2 × IKR 37/17/72-5) × IKR 21]	320	3.55	-0.06	0.44	0.67	0.04	32.5	0.04	0.66
F_1 (IKR 30 × IKR 2-1)	320	3.53	-0.23	-0.42	0.65	0.16	61.1	0.16	0.84
F_1 (IKR 30 S × IKR 2-3 VS)	280	3.46	-0.07	0.28	0.58	0.05	31.8	0.05	0.60
F_1 [(IKR 2-3 × IKR 9-2) × IKR 4]	280	3.34	-0.04	0.35	0.46	0.03	21.3	0.03	0.45
F_1 [(IKR 30 S × IKR 24 ZS) × IKR 37 VS]	280	3.14	-0.01	0.27	0.26	0.01	10.1	0.01	0.25
Median	-	-	1.01	2.95	2.88	0.31	96.9	0.31	2.45

***Note**. * SSI - stress susceptibility index, TOL - tolerance index, MP - mean productivity, YSI - yield stability index, YI - yield index, STI - stress tolerance index, GMP - geometric mean productivity.*

it was found that high yield and drought tolerance in the mid-early group were observed in the popcorn hybrids: Shans standard and tested hybrids F_1 (IKR 30 S × IKR 2-3 VS); F_1 [(IKR 2-3 × IKR 9-2) × IKR 4] and F_1 [(IKR 30 S × IKR 24 VS) × IKR 37 VS]; and in the mid-ripening group – F_1 hybrids (IKR 11-9 × IKR 16/75/24-5); F_1 [(IKR 15-2 × IKR 37/17/72-5) × IKR 21] and F_1 (IKR 30 × IKR 2-1). In the future, the best test combinations will be investigated in terms of a set of traits for popcorn in order to transfer them to the Ukrainian Institute for Plant Variety Examination for qualification evaluation and further acquisition of intellectual property rights.

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Актуальність. Підзона Північного Степу України характеризується сильними посухами, які призводять до значного зниження урожайності кукурудзи розлусної (Zea mays everta Sturt.). У зв'язку із цим дуже важливо робити оцінку гібридів на посухостійкість для добору найкращих зразків, здатних витримувати складні гідротермічні умови вирощування**. Мета** досліджень полягала у визначенні посухостійкості гібридів кукурудзи розлусної за умов повітряної і ґрунтової посухи. **Матеріали та методи.** Матеріалом для проведення досліджень були 58 гібридів кукурудзи розлусної, які проходили конкурсне випробування. За стандарти використовували середньоранній гібрид Шанс і середньостиглий гібрид Гостинець. Досліди проводилися впродовж 2020–2021 рр. у лабораторії селекції кукурудзи харчового напряму використання на Синельниківській селекційно-дослідній станції ДУ Інститут зернових культур НААН України. Для вивчення реакції гібридів на посуху був використаний індексний підхід, який базувався як на стійкості, так і на чутливості генотипів до дефіциту вологи. **Результати.** Вегетаційний період 2020 р. був жарким і посушливим на відміну від 2021 р. Середні значення врожайності зерна у несприятливий за погодними умовами рік, у порівнянні зі сприятливим, були меншими для середньоранніх гібридів у 3,1 рази, а для середньостиглих – у 3,2 рази. Такі погодні умови забезпечили оцінку гібридів кукурудзи розлусної на стійкість до посухи. Було встановлено, що 22 гібрида (36,7 %) визнані посухостійкими, оскільки мали відповідні індекси за 5–7 показниками. Стандарт середньоранньої групи, гібрид Шанс, також був посухостійким. **Висновки.** За результатами проведених досліджень встановлено, що у середньоранній групі високу врожайність зерна й посухостійкість мали експериментальні гібриди F1 (ІКР 30 С × ІКР 2-3 ВС); F1 [(ІКР 2-3 × ІКР 9-2) × ІКР 4] та F1 [(ІКР 30 С × ІКР 24 ЗС) × ІКР 37], а у середньостиглій – F1 (ІКР 11-9 × ІКР 16/75/24-5); F1 [(ІКР 15-2 × ІКР 37/17/72-5) × ІКР 21] та F1 (ІКР 30 × ІКР 2-1).

Ключові слова*: кукурудза розлусна, селекція, стійкість, посуха, індекси посухостійкості, врожайність зерна*