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Corn productivity for silage depending on plant density in the conditions of the Northern Steppe of Ukraine

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Abstract. At the current stage of agricultural development, the adoption of advanced technologies for corn cultivation is of paramount importance. Climatic conditions significantly influence the technology used for corn farming, making it essential to select agro-technological operations suitable for a specific climate. Corn cultivation technology includes the proper selection of a hybrid based on the production needs. It is also crucial to consider the resistance of hybrids to diseases and pests, which can significantly affect the final outcome. The experimental studies conducted in the conditions of the Northern Steppe of Ukraine were aimed to establish the optimal plant density for silage corn to ensure high yield and elevated quality indicators of this crop. Four corn hybrids have been studied: KWS Gendalf (FAO 250), KWS Burito (FAO 380), KWS BigBit (FAO 290), and DN Anshlah (FAO 420) at six different plant densities – 50, 60, 70, 80, 90, and 100 thousand plants/ha. According to the research results, the corn plant mass tended to decrease with increasing plant density of the silage corn from 50 to 100 thousand plants per hectare across all the maturity groups of the hybrids. Specifically, the plant mass gradually decreased from 281.2 to 190.3 g in the mid-late variety DN Anshlah in the BBCH 19 stage; from 278.6 to 244.0 g in the mid-season variety KWS Burito; from 361.4 to 292.3 g in the early-mid variety KWS Gendalf; and from 431.3 to 298.9 g in the early-mid variety KWS BigBit. The leaf area of mid-late DN Anshlah increased linearly from 2,011 to 3,197 cm² when the plant density rose from 50,000 to 70,000 plants/ha, showing a 58.9% increase. However, increasing the density further to 80,000 plants/ha resulted in a 17.1% decrease in the leaf area per plant. The corn cob mass at the BBCH 75 stage displayed a similar trend in the plant mass, namely a decrease with increasing crop density. Gradual decreases in the corn cob mass were noted, specifically, from 329.9 to 213.4 g in the medium-late DN Anshlah variety; from 272.3 to 198.2 g in the medium-ripening KWS Burito variety; from 293.2 to 241.2 g in the medium-early KWS Gendalf variety; and from 348.9 to 244.3 g in the medium-early KWS BigBit variety. The yield of silage corn was the highest at the BBCH 75 growth stage with a plant density of 50,000-70,000 plants per hectare. At different densities, the yield ranged, specifically, 34.91 to 50.41 tons per hectare in medium-late DN Anshlah; 32.85 to 50.86 tons per hectare in medium-maturity KWS Burito; 35.72 to 53.72 tons per hectare in medium-early KWS Gendalf; and 49.13 to 50.87 tons per hectare in medium-early KWS BigBit. The medium-late hybrid DN Anshlah produced the maximum yield of 50.41 tons per hectare with a plant density of 50,000 plants per hectare, while the medium-maturity variety KWS Burito produced 50.86 tons per hectare at 70,000 plants per hectare. The medium-early hybrids KWS Gendalf (52.03 and 53.72 tons per hectare) and KWS BigBit (50.35 and 50.87 tons per hectare) produced such yields at plant densities of 60,000 and 70,000 plants per hectare, respectively. The highest yield was produced by the KWS BigBit hybrid (50.87 tons per hectare) at a density of 70,000 plants per hectare, while the lowest yield (49.13 tons per hectare) was recorded at a density of 90,000 plants per hectare. Thus, the optimal plant density for achieving the highest green mass yield of corn under irrigation in the Northern Steppe region of Ukraine is 70,000 plants per hectare. These results highlight the importance of optimizing plant density to maximize silage corn yield. The identified patterns can serve as a basis for recommendations regarding agronomic practices aimed at improving the efficiency of corn production under various growing conditions.

Keywords: silage corn; plant density; plant height; corn ear weight; moisture; yield.

Introduction

Based on the current trends in agricultural cultivation of forage crops, corn is the one grown most widely. As noted by scientists, it is a high-energy feed with low protein content (Varela et al., 2023; García-Chávez et al., 2022). At a certain plant density within a single agroecosystem, corn hybrids produce varying yields, depending on their genetically determined potential (Neumann et al., 2021; Egon et al., 2021; Ali et al., 2019). This means that the correct selection of plant density is critically important for achieving maximum yield and quality of silage (Camarasa et al., 2019). The climatic conditions for growing corn significantly influence its cultivation technology, so it is necessary to select agronomic operations suited to the specific climate. For example, in regions with frequent droughts, the implementation of irrigation systems should be considered to ensure a stable water supply during critical growth phases. The technology for growing the crop includes the correct selection of hybrids to meet specific production needs. Currently, the market offers many options from various seed producers, and each feed producer selects a hybrid according to their growing conditions (Marchesini et al., 2019). It is also important to consider the resistance of hybrids to diseases and pests, which can significantly affect the final result.

Recently, in the Northern Steppe region of Ukraine, there have been frequent droughts during the growth and development of corn.

This negatively affects the productivity of this crop when grown for silage, as a lack of moisture during critical growth and development phases leads to a significant decrease in yield (Fernandes et al., 2020). This factor indicates the need to introduce irrigation into the corn cultivation technology to ensure optimal yields. As Munkvold (2019) noted, corn can be contaminated by toxic secondary metabolites (mycotoxins) produced by fungi. This can be prevented by using resistant hybrids to infection, so it is essential to implement new corn hybrids in production.

The key to high-quality silage is the grinding of the whole grain, which can be achieved by timely mowing of the green mass at a moisture content of 65–75%. Ferreira (2023) and Gutiérrez (2024) note that proper grinding of corn kernels during harvest increases the digestibility and availability of starch, which, in turn, improves cow nutrition and increases milk production. Therefore, the green mass of corn should be harvested at optimal times to obtain high-quality silage.

Digital technologies are becoming increasingly widespread in crop production. Advanced mathematical analysis and modeling technologies are starting to be used to predict the future yield of agricultural crops. Khan (2023) notes that at the current stage of software development for building yield models, digital technologies can be utilized as they provide accurate forecasts of agricultural productivity. In the study of the forecasting corn productivity using neural networks, Khaki (2019) found that such models allow for accurate yield predictions; however, weather conditions remain an inherent factor influencing the modeling, as they are difficult to predict.

Considering these factors, the technologies for growing corn for silage must always be improved. Stem density is an important factor for forming high corn yields. Optimal density provides the best conditions for plant development, allows for maximum utilization of available resources, and ensures an even distribution of plants in the field. In our opinion, studying the impact of plant density on the productivity of green mass of corn hybrids under irrigation conditions in the Northern Steppe of Ukraine is an important component of improving the production technology for this crop.

At the same time, it is important to consider not only quantitative yield indicators but also qualitative characteristics, such as the nutrient content in the green mass, resistance to diseases and stress conditions, as well as the adaptation of hybrids to local agro-climatic conditions. The continuous implementation of new scientific achievements and technologies in agricultural practice will enhance the efficiency of corn production for silage and ensure a stable supply of high-quality feed for livestock.

Materials and methods

The field research has been conducted in the conditions of the Peremoha AVK farm in Dnipropetrovsk Oblast, Dniprovskyi District, 48.56910º N, 34.96815º E. The research has been carried out from 2021 to 2023. The soils of the experimental plots have been represented by typical low-humus, medium-loamy black soil. The thickness of the humus horizon was approximately 45 cm. The nitrogen content in the upper part of the humus horizon measured 0.19%, phosphorus accounted for 0.14%, potassium equaled 2.2%, and humus amounted to 3.2%. The soil type was medium-loamy black soil.

The agronomic practices for growing corn have followed the zonal recommendations for the Steppe zone. The preceding crop was winter wheat. Tillage was performed to a depth of 23–25 cm, and in spring, the autumn tillage has been leveled with tooth harrows. Fertilizer (N_{50}) was applied during the pre-sowing cultivation. The corn hybrids were sown at optimal agronomic times, when the soil temperature at sowing depth reached +12 °C, using a Gaspardo row-crop planter. Fertilizers at a rate of $N_{24}P_{24}K_{24}$ were introduced simultaneously with sowing. Irrigation was conducted during the critical growth stages, with total water availability for the plants on the research plots, including rainfall, amounting to 270 mm throughout all years of the trial. The plot layout in the experiment was randomized. The sowing area of each plot accounted for 11.2 m × 33 m = 369.6 m². The total research area was 2.66 ha. The weather conditions during the research years were generally favorable for the growth and development of corn for silage, with the exception of a drought period in spring (May) 2020 and during the summer (June, August) in 2021 and 2023.

The objective of the study was determining the optimal plant density of corn for silage to ensure high yield indicators of the crop.

The experimental design included the use of different seeding rates for corn hybrids of various maturity groups: DN Anshlah (mid-late), KWS Burito (mid-maturity), KWS Gendalf (mid-early), and KWS BigBit (mid-early) (Table 1).

Table 1

Experimental design for studying the effectiveness of plant density of corn hybrids for silage of different maturity groups (corn hybrids and their density, thousand plants/ha)

DN Anshlah (mid-late) FAO 420	KWS Burito (mid-maturity) FAO 290	KWS Gendalf (mid-early) FAO 250	KWS BigBit (mid-early) FAO 290
50	50	50	50
60	60	60	60
70	70	70	70
80	80	80	80
90	90	90	90
100	100	100	100

The variety DN Anshlah is one of the promising high-yield hybrids that ensures stable yields even under challenging growing conditions. It was developed for intensive cultivation and is suitable for use in various agro-climatic zones. It belongs to the mid-late maturity group (FAO 420), and can effectively utilize the growing season and accumulate maximum dry matter. The plants typically reach a height of 250–270 cm, contributing to high productivity under adequate moisture conditions. The root system is well-developed, providing high resistance to lodging and allowing for effective moisture utilization from the soil. The grain is yellow and medium-sized, typical of most modern high-yield hybrids. In terms of disease resistance, DN Anshlah demonstrates high resistance to major corn diseases such as head smut, fusarium head blight, and root diseases, reducing the need for fungicide treatments. It is noted for its high drought resistance, making it suitable for cultivation in moisture-deficient conditions. It can produce yields of 12–14 t/ha with proper agronomic care, although this figure may vary depending on growing conditions and the level of agronomy applied. The hybrid is well-suited for mechanized harvesting due to the simultaneous maturation of ears and the strength of the stalk.

KWS Burito belongs to the mid-early hybrids with a maturity index of FAO 290. It has a number of key characteristics that make it popular among farmers for cultivation in various climatic conditions.

This corn hybrid has excellent drought resistance, making it effective for regions with insufficient moisture. It is resistant to common corn diseases such as fusarium and head smut. The hybrid tolerates stressful conditions, including temperature fluctuations. It forms large ears with well-developed grains, ensuring a high 1,000-kernel weight. A strong root system provides stability for the plants in the field and increases resistance to lodging. This hybrid is suitable for cultivation in both the Forest-Steppe zone and the Steppe zone, including arid areas. It is characterized by rapid moisture loss, which facilitates harvesting and reduces the need for additional grain drying. The hybrid is noted as an economically advantageous option for cultivation due to its adaptability and high productivity.

KWS Gendalf belongs to the mid-early hybrids with FAO 250, combining high productivity and excellent adaptability to various growing conditions. Due to its agronomic characteristics, it is used in different climatic zones.

The root system is strong and resilient, providing good absorption of moisture and nutrients, enhancing the overall plant stability. It has high resistance to lodging, thanks to its sturdy stalk and well-developed root system. The hybrid also exhibits resistance to diseases and stress factors, including drought, making it suitable for use in regions with moisture deficits. It tolerates diseases such as head smut, fusarium ear rot, and other fungal infections. It is characterized by rapid moisture loss, which facilitates harvesting and reduces drying costs for the grain.

This hybrid is suitable for cultivation in the Forest-Steppe and Steppe zones of Ukraine, demonstrating stable results under various conditions. It has several advantages, including high yield potential in intensive agricultural settings, even during dry periods. Its rapid moisture loss helps reduce post-harvest processing costs. Additionally, it is characterized by high resistance to diseases and pests, ensuring economic viability in cultivation.

KWS BigBit belongs to the mid-early hybrids with FAO 290 and is characterized by high yield potential and versatility in application.

This hybrid is designed to ensure stable yields even under challenging agro-climatic conditions. The grain is dented, which contributes to better moisture loss during maturation and easier harvesting. The yield potential is very high, with stable yields in various conditions. The root system is strong and deep, ensuring good use of soil resources. The moisture loss is rapid, facilitating harvesting and reducing drying costs. Its drought resistance is high, allowing for stable yields even under moisture deficit conditions. It has excellent resistance to major corn diseases, such as fusarium, head smut, and other fungal infections. The hybrid exhibits high resilience due to its strong stalk and well-developed root system. Its advantages are high yield potential, rapid moisture loss that minimizes drying costs, and resistance to adverse conditions, enabling it to maintain stable productivity even under stress.

During the biometric measurements, we used well-known research methods in agronomy. In particular, the plant height was measured using a specialized ruler, which precisely measures the distance from the soil surface to the top of the plant. The leaf area was determined using the leaf section method, also known as the 'grid method,' which is one of the ways to assess the leaf area of corn. The main steps of the method include dividing the leaves into small segments of equal size using a grid, measuring the area of each segment using image analysis software, and summing the obtained values to determine the total leaf area of the corn plants.

The harvest accounting and accompanying observations were carried out according to the standard methodologies outlined in the works of Steel (1997) and Ushkarenko (2008). The harvest has been conducted at the milk maturity stage of the grain, with the moisture content of the green mass at 65–75%.

The data analysis was conducted using the Statistica 10.0 software (StatSoft Inc., USA). Yield is presented as x ± SD (mean ± standard deviation). The differences between the control and experimental variants were assessed using the Tukey's test with a significance level of $P < 0.05$, accounting for the Bonferroni correction.

Results

Silage corn is a valuable forage crop, and the production of high yields depends on many factors, including crucial ones such as the physical mass of the plants and the size of the ear. The mass of the plants and ears of silage corn are important indicators that directly affect its yield. The mass of the above-ground part of corn plants is an indicator of their biomass and accumulated energy that is used for crop formation.

According to our research results, the mass of corn plants has tended to decrease with increasing planting density of silage corn from 50 to 100 thousand plants per hectare across all maturity groups of hybrids, in particular, a gradual decrease in height was from 281 g to 190 g at the BBCH 19 stage in the medium-late hybrid DN Anshlah; from 279 to 244 g in the medium-maturing hybrid KWS Burito; from 361 to 292 g in the early-maturing hybrid KWS Gendalf; and from 431 to 298 g in the early-maturing hybrid KWS BigBit. A larger plant mass indicates a robust vegetative mass, which, in turn, ensures better nutrient absorption from the soil and enhanced photosynthetic activity. This contributes to the active accumulation of dry matter in the ears. The large leaf area mass is also significant as it increases the surface area for photosynthesis, positively influencing grain development in the ears and overall plant productivity. Additionally, the development of a strong root system, which correlates with the mass of the above-ground part, ensures more effective absorption of moisture and mineral nutrients, which is important for increasing yield under unstable climatic conditions (Table 1).

The leaf area of the late-maturing hybrid DN Anshlah, when increasing planting density from 50 thousand plants per hectare to 70 thousand plants per hectare, demonstrated a linear increase in the leaf area from 2,011 to 3,197 cm², with an increase of 58.9%. However, an increase in planting density to 80 thousand plants per hectare resulted in a 17.1% decrease in the leaf area per plant. Further increasing the density from 80 thousand plants per hectare to 100 thousand plants per hectare led to a slight 22.8% increase in leaf area. When increasing the planting density from 50 thousand plants per hectare to 80 thousand plants per hectare, the mid-maturing hybrid KWS Burito exerted a linear increase in leaf area from 2,599 to 3,335 cm², a change of 28.3%. At a planting density of 90 thousand plants per hectare, a 7.3% reduction in leaf area was observed. When the density was increased from 90 to 100 thousand plants per hectare, an 8.6% increase in the leaf area was observed. In the early-maturing hybrid KWS Gendalf, a linear 32% increase in the leaf area was noted. After increasing the planting density from 50 thousand plants per hectare to 70 thousand plants per hectare, the early-maturing hybrid KWS BigBit demonstrated a linear increase in the leaf area from 2,781 to 3,680 cm², or a 32.3% increase. Increasing the planting density of corn plants to 80 thousand plants per hectare led to a 13.3% reduction in the leaf area. An increase in the planting density from 80 to 90 thousand plants per hectare resulted in a 7.9% increase in the leaf area, while further increasing the plant density from 90 to 100 thousand plants per hectare led to a 5.6% decrease in the leaf area. The minimum leaf area values in the late-maturing hybrid DN Anshlah at a planting density of 50 thousand plants per hectare were recorded at 2,011 cm², while the maximum leaf area values in the KWS BigBit variant at a density of 70 thousand plants per hectare were recorded at 3,680 cm².

The mass of the corn ear at BBCH growth stage 75 plays a significant role in increasing the mass of corn silage, showing a similar trend to the mass of the plant, specifically decrease with increasing planting density. A gradual decrease in the ear mass was observed, measuring from 329.9 to 213.4 g in the late-maturing hybrid DN Anshlah; from 272.3 to 198.2 g in the mid-maturing hybrid KWS Burito; from 299.9 to 241.2 g in the early-maturing hybrid KWS Gendalf; and from 348.9 to 244.3 g in the early-maturing hybrid KWS BigBit.

The mass of the ears is a key indicator for assessing the grain productivity of silage corn, as greater ear mass means higher grain content per plant, which directly affects the overall yield. The ear consists of a cob and kernels, and it is the number and mass of kernels that are decisive for the yield. Increase in kernel mass is achieved through better growing conditions, including adequate plant nutrition and sufficient moisture during the growing season. The formation of large ears means higher number of kernels per unit area, which is a direct factor in enhancing yield. The mass of the ear in the medium-late hybrid DN Anshlah at a density of 50,000 plants per hectare was 329.9 g per ear, and it gradually decreased with increasing planting density. At a plant density of 100,000 plants per hectare, the ear mass was at its minimum – 213.4 g, or 36.4% lower than at 50,000 plants per hectare. In the hybrid KWS Burito, with a planting density of 50,000 plants per hectare, the mass of one ear accounted for 272.3 g. The mass of the ear of this hybrid also gradually decreased with increasing density, and at 100,000 plants per hectare, it decreased to 198.2 g, or by 26%. In the hybrid KWS Gendalf, with a planting density of 50,000 plants per hectare, the ear mass was 293.2 g, and it also gradually decreased with denser planting. At a density of 100,000 plants per hectare, the ear mass was at its minimum – 241.2 g, or 18% lower than the control. In the hybrid KWS BigBit, with a planting density of 50,000 plants per hectare, the ear mass was 348.9 g, and it also gradually decreased with denser planting. At the maximum density of 100,000 plants per hectare, the ear mass was 244.3 g, or 32% lower.

The mass of plants and ears of silage corn are decisive indicators of its yield. A high vegetative mass contributes to improved photosynthetic activity and plant nutrition, creating favorable conditions for the formation of large and heavy ears. However, the optimal balance between the mass of the plant and the ears must be achieved through rational management of agronomic practices such as fertilization, irrigation, and selection of varieties.

The yield of silage corn was highest at the BBCH 75 stage with planting densities of 50–70 thousand plants per hectare. At different densities, the yield ranged 34.91 to 50.41 t/ha in the medium-late hybrid DN Anshlah; 32.85 to 50.86 t/ha in medium-early KWS Burito; 35.72 to 53.72 t/ha in early-medium KWS Gendalf; and 49.13 to 50.87 t/ha in early-medium KWS BigBit.

The medium-late hybrid DN Anshlah prodrced the highest yield of 50.41 t/ha at a planting density of 50 thousand plants per hectare, while medium-early KWS Burito reached 50.86 t/ha at 70 thousand plants per hectare. At the same time, early-medium KWS Gendalf (52.05 t/ha, 53.72 t/ha) and KWS BigBit (50.35 t/ha, 50.87 t/ha) achieved their highest yields at planting densities of 60 and 70 thousand plants per hectare, respectively.

The KWS BigBit hybrid produced the highest yield (50.87 t/ha) at a density of 70 thousand plants per hectare. The lowest yield (49.13 t/ha) was recorded at a density of 90 thousand plants per hectare. Analysing the research results, it should be noted that, first and foremost, as corn planting density increases, the height of the plants generally increases. This can be explained by competition among plants for sunlight, which stimulates the height growth of corn plants. Plant height correlates with vegetative mass, which positively influences the productivity of silage corn.

The second pattern is that with the increase in corn planting density, the mass of the ear on the plant usually decreases. This is due to increased competition among plants for nutrients, which, in addition to this, also uses nutrients for the formation of generative organs. In the case of the highest planting density, the generative organs were smaller because a larger portion of energy was used for the development of vegetative mass.

Analyzing the results of the research allows us to hypothesize that the optimal planting density of corn for achieving maximum yield can be determined by balancing vegetative and generative mass. The conclusions drawn from the analysis confirm the recommendations regarding the optimal density for growing corn.

Table 1

Biometric indicators of corn plants of different maturity groups depending on plant density, averaged over 2021–2023, BBCH 75 (x ± SD, n = 10)

Corn hybrids	Plant density, thousand plants per hectare	Mass of corn plants, g (growth stage BBCH 19)	Leaf area of one plant, cm² (growth stage BBCH 19)	Height of corn plants, m (growth stage BBCH 75)	Weight of the corn ear, g (growth stage BBCH 75)	Green mass yield, t/ha (growth stage BBCH 75)
DN Anshlah (medium-late)	50	281.2 ± 6.1^{e}	2011 ± 35^{e}	2.54 ± 0.14^{c}	329.9 ± 7.7^{ab}	50.41 ± 0.69^{ab}
	60	269.2 ± 5.8^{e}	3032 ± 39^{c}	2.78 ± 0.15^{b}	282.3 ± 8.0^{bc}	45.25 ± 0.58^{c}
	70	272.3 ± 4.9^{e}	3197 ± 41^{bc}	2.55 ± 0.15^{c}	244.1 ± 7.8^{cd}	48.43 ± 0.65^{b}
	80	268.9 ± 6.0^{e}	2653 ± 36^{d}	2.70 ± 0.16^{b}	242.0 ± 6.9^{cd}	42.69 ± 0.59^{c}
	90	202.1 ± 4.6^{h}	3064 ± 42^{c}	2.82 ± 0.15^{b}	233.1 ± 7.2^{cd}	41.37 ± 0.55^{c}
	100	190.3 ± 4.2^{h}	3260 ± 43^{bc}	2.91 ± 0.12^{ab}	213.4 ± 6.8^{d}	34.91 ± 0.48^{de}
KWS Burito (medium-early)	50	278.6 ± 5.9^{e}	2599 ± 37^{d}	2.81 ± 0.17^{b}	272.3 ± 8.1^{bc}	44.07 ± 0.65^{c}
	60	279.8 ± 5.4^{e}	2859 ± 38^{b}	2.65 ± 0.16^{bc}	258.8 ± 7.3^{c}	42.72 ± 0.63^{c}
	70	271.1 ± 6.4^{e}	2970 ± 41^{c}	2.65 ± 0.14^{bc}	242.3 ± 7.5^{cd}	50.86 ± 0.69^{ab}
	80	268.9 ± 5.3^{e}	3335 ± 43^{ab}	2.72 ± 0.13^{bc}	229.2 ± 7.1^{cd}	42.21 ± 0.58^{c}
	90	253.1 ± 5.1^{g}	3093 ± 41^{c}	2.82 ± 0.15^{b}	227.4 ± 7.0^{cd}	33.90 ± 0.54^{e}
	100	244.0 ± 4.8^{g}	3362 ± 40^{b}	2.82 ± 0.14^{b}	198.2 ± 6.8^{d}	32.85 ± 0.51^{e}
KWS Gendalf (medium-early)	50	357.3 ± 7.8^{c}	2527 ± 34^{d}	2.71 ± 0.12^{bc}	293.2 ± 8.0^{b}	41.12 ± 0.63^{c}
	60	361.4 ± 7.9^{c}	2707 ± 36^{cd}	2.71 ± 0.17^{bc}	299.9 ± 9.8^{b}	52.03 ± 0.70^{a}
	70	305.5 ± 7.0^{f}	2919 ± 38^{c}	2.74 ± 0.18^{b}	301.3 ± 9.6^{b}	53.72 ± 0.68^{a}
	80	306.1 ± 7.2^{f}	2927 ± 39^{c}	2.70 ± 0.13^{bc}	265.2 ± 9.2^{c}	38.35 ± 0.51^{cd}
	90	304.5 ± 7.8^{f}	3341 ± 42^{b}	2.89 ± 0.18^{ab}	254.5 ± 9.3^{c}	36.34 ± 0.50^{d}
	100	292.3 ± 7.2^{f}	3336 ± 43^{b}	2.81 ± 0.19^{b}	241.2 ± 8.6^{cd}	35.72 ± 0.52^{d}
KWS BigBit (early-medium)	50	431.3 ± 8.1^{a}	2781 ± 39^{cd}	2.72 ± 0.18^{bc}	348.9 ± 9.8^{a}	49.80 ± 0.54^{ab}
	60	383.8 ± 7.4^{b}	3204 ± 42^{bc}	2.85 ± 0.15^{b}	321.3 ± 9.5^{ab}	50.35 ± 0.53^{ab}
	70	370.1 ± 7.1^{b}	3680 ± 45^{a}	2.88 ± 0.16^{ab}	312.3 ± 9.3^{ab}	50.87 ± 0.57^{ab}
	80	349.4 ± 6.8^{c}	3247 ± 42^{bc}	2.92 ± 0.18^{ab}	278.2 ± 9.1^{bc}	50.02 ± 0.49^{ab}
	90	331.3 ± 6.4^{d}	3504 ± 45^{ab}	3.00 ± 0.17^{a}	281.3 ± 9.7^{bc}	49.13 ± 0.61^{ab}
	100	298.9 ± 5.9^{f}	3317 ± 41^{b}	3.10 ± 0.17^{a}	244.3 ± 7.9^{cd}	50.37 ± 0.63^{ab}

Note: different letters indicate values that significantly differ from each other within the column of Table 1 based on Tukey's test comparison ($P < 0.05$) with the Bonferroni correction.

Discussion

Research by scientists, including Marchesini et al. (2019) and Egon et al. (2021), revealed a direct relationship between corn planting density and its yield. This underscores the necessity for careful analysis of density in the context of growing crops, as changes in plant population directly affect their productivity. The consideration of the genetic potential of hybrids and climatic conditions is a key aspect in determining the optimal planting density for corn. This highlights the importance of an integrated approach to plant cultivation based on scientific research and practical experience.

The experiments (Marchenko, 2019) have demonstrated the positive effect of irrigation on the productivity of cultivated plants, especially in conditions where adequate moisture is provided to achieve higher yields. Additionally, the effective use of resources, particularly nitrogen fertilizers, was highlighted in the studies (Ernst et al., 2021) revealing the contribution of nitrogen to the growth of the vegetative mass of plants, which is important for growing silage corn. In particular, the studies (Zhang et al., 2021; Luis et al., 2023) confirmed that nitrogen significantly affects the maturation rate of corn grain.

In the context of irrigation, the studies (Rasool et al., 2020) indicated the effectiveness of drip irrigation; however, the limitations of this technique on large production areas lead to a reconsideration and search for more optimal irrigation methods. For instance, the research by Chavez et al. (2020) demonstrated that drip irrigation can be more cost-effective as it saves water while maintaining productivity. Therefore, it is important to continue studying and developing irrigation methods to optimize corn cultivation in various climatic conditions.

Poulyakov et al. (2021) noted a decrease in the water consumption coefficient with an increase in planting density. This may be related to the active development of the corn root system and its more efficient use of water in the soil.

The observations by Wang et al. (2021), Tomchuk et al. (2021), and Agnew et al. (2022) highlight the importance of corn cultivation technology, including precision planting and management of planting density. Considering these aspects maximizes the crop productivity and ensures the quality of silage.

The analysis of scientific publications on the selected topic revealed that this area of research in corn cultivation is unique and unprecedented. This indicates the relevance of this work for further study and analysis, as cultivation technologies are constantly evolving and improving, stimulating scientific progress.

Practically all the patterns and trends mentioned above were confirmed by our research. However, to ensure optimal silage corn yield, we established that the most rational planting density is 70 thousand plants per hectare, regardless of the specific hybrid. Among the various hybrids compared, the highest yield was recorded for the KWS Gendalf hybrid, which provided a yield of 53.7 tons per hectare.

A detailed analysis of the yield of all corn hybrids revealed one common pattern: yields increase up to a certain planting density, after which they gradually decrease. The maximum values of silage yield were observed at a planting density of 70 thousand plants per hectare, indicating the optimal planting density for corn silage in the Northern Steppe region of Ukraine. That is, at a planting density of 70 thousand plants per hectare, more developed generative organs are formed (ear weight 0.3 kg) compared with a planting density of 90 thousand plants per hectare, where ear weight was 0.27 kg. Thus, the optimal planting density for corn to obtain high-quality silage in the Northern Steppe region of Ukraine is 70 thousand plants per hectare.

Conclusions

The mass of corn plants tended to decrease with the densification of planting density from 50 to 100 thousand plants per hectare across all maturity groups of the hybrids. In particular, it gradually decreased from 281.2 to 190.3 in the mid-late hybrid DN Anshlah g at the BBCH 19 stage; from 278.6 to 244.0 g in the mid-season hybrid KWS Burito; from 357.3 to 292.3 g in the early-mid hybrid KWS Gendalf; and from

431.3 to 298.9 g in the early-mid hybrid KWS BigBit. With an increase in planting density from 50 thousand plants per hectare to 70 thousand plants per hectare, the leaf surface area of the mid-late hybrid DN Anshlah exerted a linear increase from 2,011 to 3,197 cm², with a growth of 58.9%. However, with an increase in planting density to 80 thousand plants per hectare, the leaf surface area of one plant decreased by 17.1%.

The mass of the corn ear at the BBCH 75 stage displayed the same trend as the plant mass, specifically a decrease with increased planting density. Thus, the ear mass decreased from 329.9 to 213.4 g in the mid-late hybrid DN Anshlah; from 272.3 to 198.2 g in mid-season KWS Burito; from 293.2 to 241.2 g in early-mid KWS Gendalf; and from 348.9 to 244.3 g in early-mid KWS BigBit. The yield of silage corn was maximal at the BBCH 75 stage with planting densities of 50-70 thousand plants per hectare. At different densities, the yield ranged 34.91 to 50.41 t/ha in mid-late DN Anshlah; 32.85 to 50.86 t/ha in mid-season KWS Burito; 35.72 to 53.72 t/ha in early-mid KWS Gendalf; and 49.13 to 50.87 t/ha in early-mid KWS BigBit. The mid-late hybrid DN Anshlah had a maximum yield of 50.41 t/ha at a planting density of 50 thousand plants per hectare, while mid-season KWS Burito achieved 50.86 t/ha at 70 thousand plants per hectare. Early-mid KWS Gendalf produced 52.03 t/ha and 53.72 t/ha and KWS BigBit produced 50.35 t/ha and 50.87 t/ha at planting densities of 60 and 70 thousand plants per hectare, respectively. The KWS BigBit hybrid produced the highest yield (50.87 t/ha) at a density of 70 thousand plants per hectare. The lowest yield (49.13 t/ha) was recorded at a density of 90 thousand plants per hectare.

Given the changing climatic conditions, the constant emergence of new promising corn hybrids, and the introduction of advanced agricultural technologies, research in this field should continue to identify the most effective technology for cultivating corn for silage under irrigation conditions.

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