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PRODUCTIVITY OF LEEK HYBRIDS DEPENDING ON PLANTING SCHEMES AND ETIOLATION METHODS

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ABSTRACT

The research aimed to evaluate whether plant population density of the leek cultivars 'Jumper' F1 and 'Matejko' F1, and the method of pseudostem etiolation could improve leek yield. The row spacing variants were 45 cm, 60 cm, and 70 cm, with a plant spacing of 15 cm within each row. Seedlings were planted either one or two per hole. Etiolation was launched at the BBCH 17 (7th leaf >3cm) growth stage, with the stems either hilled up with the soil from the inter-rows or shaded with vertical panels of black agrotextile, with a shading height of 20 cm. The planting scheme significantly affected leek growth and development parameters. The largest leaf area and plant and pseudostem mass were observed with the 70 × 15 cm planting; however, the yield per hectare was the lowest. The F1 Matejko cultivar yielded higher in the variant with a 45 × 15 cm planted singly and etiolated under black agrotextile. For growing F1 'Jumper', it is recommended to plant two seedlings per hole at a density of 45 × 15(2) or 60(2) x 15 cm, etiolated under black agro-textile. The obtained results will help to improve the leek cultivation technology.

Key words: agrotextile, hilling, planting density, productivity, pseudostem

INTRODUCTION

Leek is one of the allium vegetable crops grown worldwide, including in Europe. Available for raw consumption year round, it can be frozen and dried. Leeks are valued for theirs unique taste, vitamins, antioxidants and minerals. It is particularly high in potassium, iron, and selenium (Mladenović et al. 2011; Koca & Tasci 2016). The nutritional value and storage capacity of leeks are determined by the content of fructooligosaccharides (Grzelak-Blaszczyk et al. 2011). The total content of polyphenols, sulphur compounds, and antioxidant activity in the green part of leeks is statistically higher than in the blanched part (Čeryová et al. 2024).

In 2022, the total area under leek cultivation in the world was 131.7 thousand hectares, including 26.2 thousand hectares in Europe, 86.2 thousand hectares in Asia, and 2.4 thousand hectares in America. The average yield worldwide is 16.02 t·ha^{-1}, in Europe – 29.3 t·ha^{-1}, in Asia – 14.7 t·ha^{-1}, in America – 17.1 t·ha^{-1} (FAO 2022). In Europe, the most significant areas under leeks are in France (5.5 thousand hectares), Spain (2.7 thousand hectares), and the Netherlands (2.6 thousand hectares), with yields of 28.8 t·ha^{-1}, 26.0 t·ha^{-1} and 36.1 t·ha^{-1}, respectively. The highest yields of leek were recorded in Austria – 44 t·ha^{-1}, Germany – 37.6 t·ha^{-1}, and Belgium – 36.8 t·ha^{-1}. In Ukraine, the gross production of leeks and other onions averaged 27.9 thousand tonnes from 2018 to 2021 (State statistics of Ukraine 2021). In 2022, the area projected for allium vegetable crops in Ukraine was 5.5 thousand hectares, but the actual total production of open-field vegetables decreased by almost 25%.

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Vegetable growing needs scientific support of regionally adapted and effective growing technologies. The commercial product of leek is a blanched pseudo-stem, the yield and quality of which depends on the cultivation practices (Slobodianyk 2024). This study aims to determine the optimal planting density of the leek hybrids 'Jumper' and 'Matejko' and to improve the etiolation methods of a pseudo-stem in the Forest-Steppe condition.

A planting scheme should not reduce the total yield, crop quality, plant resistance to environmental conditions, diseases, etc. The vegetable crop productivity is significantly influenced by the aboveground biomass, root mass, and preservation of leaf activity until full maturity. The density of the crop population determines the nutrient supply to plants and the level of transpiration. For example, in thinned crops, soil and air temperatures above the soil are higher, which increases physical evaporation of moisture and transpiration (Postma et al. 2021). Irrigation and fertilization increased the yield of dense crops. The spread of leek diseases also depends on the density of plant populations (de Jong & de Bree 1995). The lowest infestation of onions with the pest *Delia alliaria fonseca* occurs at a lower plant density (Hermize 2015).

The phenotypic characteristics of plants vary depending on plant density and plant type. Excessive density negatively affects the stem diameter, but plant height and height-to-weight ratio can increase. The depth of rooting does not change significantly with excessive density, but the number of roots is lower. High crop density affects plants more considerably than a lack of nutrients, as phenotypic changes after shading are more active (Postma et al. 2021). Carbon and phosphorus absorption, as well as root growth, are reduced due to shading and density (Koide & Dickie 2002; Zhang et al. 2011; Li et al. 2016). Competition for soil resources negatively affects root growth (Coutinho et al. 2021). To optimize land use and aboveground space, and to determine the ideal crop density, it is necessary to know the productive capacity of each plant species (Favorito et al. 2011; Vasconcelos et al. 2017).

Optimum row and within-row spacing enable the full utilization of the genetic potential of high-yielding genotypes. Late-ripening onion cultivars showed a greater response to density and sowing date than early-ripening cultivars (Mondal et al. 1986). Early-ripening leek cultivars have smaller vegetative mass; therefore, it is possible to narrow inter-row spacing. Nevertheless, the width between rows must be sufficient for the formation of a fully developed etiolated pseudo-stem. It is possible to regulate the plant density and introduce irrigation to achieve a larger plant size *Alliaceae* (Leskovar et al. 2012). Plant density is determined depending on the purpose of the harvest. For example, garlic is planted at 12.5 cm in a row for elite planting material, and 7.5 cm for commercial crops (de Lima et al. 2021).

It is possible to increase leek density to 1 million plants per ha in hydroponics with intensive nutrition. However, since the cost of leek seedlings increases with higher planting density, the 605.6 plants$\cdot$ha^{-1} was economically feasible in hydroponics. The correlation coefficient between optimal density and economic profitability is $r = 0.67$ (Van de Sande 2023). A hydroponic system of leek growing with the plant density of 70 plants per m^2 makes it possible to obtain a pseudo-stem with the mass over 200 g (van Os et al. 2017). According to other data, leek yield is more affected by transplanting time, accumulated solar radiation, and positive temperatures than by planting density (Salter et al. 1986). To increase yield, leeks are planted at a density of 20–22 plants per m^2 (Coutinho et al. 2021). When early-maturing leeks are planted at a density of 30 plants per m^2, the height of the pseudo-stem is 15 cm (Ahamad et al. 2024). The length of the leek pseudo-stem increases directly (or linearly) with higher planting density, and vice versa (Peña Baracaldo 2015). With a planting scheme of 30 × 5 cm, the leek plants were tall, but thin and of a smaller mass.

It has been established that the nutrient supply area for seedlings influences the number of leaves and aboveground mass of annual leek (Weerasinghe & Fordham 1994; Khalikov et al. 2024). The spacing between plants and the cultivation periods significantly influenced the growth characteristics, flowering, yield, and quality indicators of onion and leek seed crops (Kumar et al. 2015; Slobodianyk et al. 2024). Typical planting scheme for leek seedlings is 70 × 10 cm.

The limited availability of agricultural land can be addressed by combining the cultivation of two plants on the same area (Lorina et al. 2015). In dense plantings, less light reaches the soil surface; therefore, weed infestations are lower; however, the quality of the vegetable crop decreases (Baumann et al. 2000, 2001). In the combined cultivation of broccoli and leek with row spacings of 50 cm and 70 cm, land-use efficiency was 11% higher, but economic efficiency did not increase. In the system of a combined cultivation with row spacing of 50 cm, the leaf surface of the leek was smaller compared to the row spacing of 70 cm. In combined cultivation with broccoli, leek yield was higher under the 70 × 50 cm scheme, but the maximum yield was in monoculture (Lorina et al. 2015). However, Baumann et al. (2000) found that in combined plantings of leek and celery, the total yield increases by 10%. The competitiveness of leeks is low in combined plantings. Under combined planting of leeks with red clover, row spacings of 50 cm and 70 cm did not affect their root mass (Båth & Kling 2001). With a planting scheme of 40 × 20 cm and weed control, the commercial yield of leeks was 33.5 $t \cdot ha^{-1}$, 76% of stems had a diameter greater than 2.5 cm, and the average plant weight was 288 g. In weedy fields, the yield of leeks was 1.5 times lower (Adamczewska-Sowińska & Kołota 2009).

Mulching leek beds with black and white mulch is effective because it reduces weed growth and fertilizer use. However, soil mulching did not significantly improved plant quality and weight (Benoit & Ceustermans 1994). Covering the seedlings with a dense, nontransparent film resulted in a lower plant mass. Under irrigation, soil mulching, especially with white material, significantly increased the diameter, mass, and quality of the pseudo-stem (Benoit et al. 2000). Leek is grown for its thickened etiolated pseudo-stem, with a minimum height of 14–15 cm required for market supply (van Os et al. 2012). The quality requirements for leek production include a high etiolated portion of the pseudo-stem, which should be at least half of its total height. Etiolation significantly impacts the product' taste and texture, improving its organoleptic properties, making the leek less pungent. The process of etiolation involves shading edible parts using entirely natural methods, without any chemicals. Blanching occurs concurrently with plant growth and development in the field. Any violation of the etiolation technology worsens the quality of the harvest. Growing leeks on raised ridges or in deep holes with hilling promotes taller pseudo-stems, but only on light loamy soils (Adamczewska-Sowińska & Kołota 2001). According to Peña Baracaldo (2015), hilling does not affect the mass and diameter of the pseudo-stem of leeks. De Haan & van Wijk (2007) suggest growing leeks using a closed hydroponic method in open soil, with etiolation of the pseudo-stem achieved by using non-transparent plastic tubes. It has been established that the diameter and height of the tubes affect the weight of the harvested leeks. In tubes with a 34 mm diameter, the plants had a greater mass, but the blanched portion was smaller. In a 10 cm-high tube, leeks grow more intensively because they receive more light.

The yield varies with genotype, photoperiod, population density, and growing method (Kiffo 2016; Abade et al. 2019; Almeida et al. 2020; Coutinho et al. 2021). The study provides new insights into the productivity of two leek F1 cultivars under different growing methods. The impact of plant density and the etiolation method of the pseudo-stem, achieved through hilling with soil or black agrotextile, on the growth and productivity of leeks has been determined in the conditions of Forest-Steppe zone of Ukraine.

MATERIALS AND METHODS

Soil and climatic conditions

The research was conducted at the Department of Horticulture of Uman National University of Horticulture from 2018 to 2021. The soil on the experimental plots is heavy clay podzolized black soil, containing 1.9% humus (according to the State Standard of Ukraine 4289:2004). The nitrogen content in the arable soil layer is 103 $mg \cdot kg^{-1}$ (according to the Kornfield method, the State Standard of Ukraine 7863:2015); the mobile compounds of phosphorus and potassium (according to the Chirikov method, the State Standard of Ukraine 4362:2004) amount to 122 $mg \cdot kg^{-1}$ and 135 $mg \cdot kg^{-1}$, respectively. The region's climate is moderately continental, characterized by variable precipitation.

Under drip irrigation, pre-irrigation soil moisture was maintained at no less than 70% of the field capacity. From 2018 to 2021, the lowest relative humidity levels at the beginning of leek vegetation were observed in April–May 2018, at 58%, and in the second half of the growing season, in August–September 2020, at 59–62%. The sum of active temperatures above +10°C during the leek growing season ranged from 2673°C (in 2021) to 3272°C (in 2019), with the highest value for the summer period recorded in 2020 – 1977°C. The average summer temperature across all study years was higher than the long-term average, and precipitation was unevenly distributed. The highest hydrothermal coefficient (HTC) in the summer of 2021 was 1.4, while the lowest in 2020 was 0.55. The period from September 2019 to 2021 was arid, with precipitation 2.1 to 3.8 times below normal, while September 2018 was excessively wet (HTC – 2.1). In general, the weather conditions of 2018–21 included periods unfavorable for leek growth, but they also allowed for assessing the impact of the studied cultivation methods on productivity.

Experimental design

Cultivars used in this study included F1 'Jumper' (early – 84 days, disease-resistant, and F1 'Matejko' (mid-early – 120 days, disease resistant, high yielding, high commercial quality). Analyses are carried out independently for each cultivar. The seedlings were planted in the field on April 10.

The planting schemes were as follows: wide-row planting with one plant per hole – 45 × 15 cm (148.1 thousand plants·ha^{-1}) – control, 60 × 15 cm (111.1 thousand plants·ha^{-1}), 70 × 15 cm (95.2 thousand plants·ha^{-1}); and cluster planting with two plants per hole – 45 × 15(2) cm (296.3 thousand plants·ha^{-1}), 60 × 15(2) cm (222.2 thousand plants·ha^{-1}), 70 × 15(2) cm (190.5 thousand plants·ha^{-1}).

The methods of blanching the pseudo-stem included hilling with soil from the interrows (control) or covering with black agrotextile. The black agrotextile with a density of 60 g·m^{-2} and a width of 30 cm was secured vertically along both sides of the row using support stakes and twine. The lower edge of the agrotextile was covered with soil. The pseudo-stem of the leek was shaded at the BBCH 17 growth stage (7th leaf >3cm clearly visible). The height of the agrotextile sheets and the hilled soil ridges was up to 20 cm. The arrangement of variants in the experiment was the randomized split-plot design in four replications, and the area of each experimental plot was 80 m².

Leaf area measurement

The leaf surface area of leek at BBCH 49 (stage growth complete) was calculated according to the formula: S=(0.67×a×b)×n (where, S – single leaf area (cm^2); 0.67 is the leaf configuration coefficient; a – the largest leaf width (cm); b – leaf length (cm); n – number of leaves) with further conversion to leaf area index (LAI, the ratio of the total leaf area of plants to the area of soil on which they are located – on 1 m^2) (Bondarenko & Yakovenko 2001).

Measurement of plant dry matter

The dry mass increase of leek plants was assessed after drying raw samples in a laboratory drying oven with forced ventilation at 70°C until a constant weight was achieved. Ten plants were sampled from each experimental plot in four replications on August 5 and October 20. The entire plants (leaves and pseudo-stems) were weighed before drying, then cut into 0.5 cm segments for drying. After drying, the dry mass was recorded. The increase in mass per plant (in grams) was calculated by the difference in the average dry mass between August 5 and October 20.

Determination of the net photosynthetic productivity (NPP)

The following formula was used: $NPP = 2(B_2-B_1)/[T(L_1+L_2)]$, where NPP is the net photosynthetic productivity (g per m^2 per day); B_1, B_2 is the dry weight of plants at the beginning and end of the recorded period (g); (B_2-B_1) – dry matter increase within T days (g); L_1 and L_2 – leaf area at the beginning and end of the recorded period. (Bondarenko & Yakovenko 2001).

Estimation of chlorophyll content

Chlorophyll content was determined in the middle part of the leaves. The content of the sum of chlorophyll (a+b) in the leaves at stage BBCH 19 (9th leaf >3cm clearly visible) was determined as follows: pigment extract was prepared by extracting 100 mg of crushed leaves in 10 ml of 100% acetone. The optical density of the extracts was measured in cuvettes with a 10 mm path length using a Visible Spectrophotometer 721G. The calculations were performed in accordance with the generally accepted methodology of Von Wettstein (1957): $C_{chl.a+b} = 5.134 \times D_{662} + 20.436 \times D_{644}$, where: $C_{chl.a+b}$ represents the concentration of chlorophylls a and b (mg·L^{-1}), and

D is the optical density of the solution at the corresponding wavelengths. The recalculation of the obtained results into mg per 1 g of raw material was performed using the formula: $A = C \times V/H \times 1000$, where: C is the concentration of pigments (mg per L); V is the volume of the extract (mL); H is the weight of the plant material (g).

Determination of ascorbic acid and nitrate content

The ascorbic acid content (mg per 100 g raw weight) of leek pseudo-stems was determined by visual titration of raw plant extracts in 6% trichloroacetic acid with Tillman's reagent, following the AOAC (2012) methodology. Five grams of raw leek leaves were homogenized in a porcelain mortar with 5 mL of 6% trichloroacetic acid and quantitatively transferred to a measuring cylinder. The volume was adjusted to 80 mL using trichloroacetic acid, and the mixture was filtered through filter paper 15 minutes later. The ascorbic acid concentration was determined based on the volume of Tillman's reagent used for the titration of the sample. The nitrate content (mg per kg of raw mass) was determined according to the State Standard of Ukraine 4948:2008 (2008). Nitrate was assessed in raw pseudo-stems using an ion-selective electrode with ionomer i-160MI. 12.5 grams of crushed pseudo-stems were homogenized and mixed with 50 mL 1% potassium aluminum sulfate. The resulting suspension was analyzed using the ionomer for nitrate determination.

Statistical analysis

The factors studied were: years of study (Y), etiolation method of the pseudo-stem (E) and the planting schemes (P) with four replications. Data were based on annual averages and standard deviation. All data were analyzed using a multivariate analysis of variance (ANOVA) in Statistica 10.0. In cases where a significant ANOVA result was obtained, as well as when it was not, the variables were further tested using the Tukey procedure. Significant differences between means were determined using a Tukey test at $p = 0.05$.

RESULTS AND DISCUSSION

Vegetative development of leek plants depends on cultivar characteristics, climate conditions, and cultivation method. The study of optimal plant density involves determining the patterns of intraspecific competition in the agrocenosis. Excessive density reduces the supply of light, water, nutrients, and CO_2, thereby reducing plant growth and productivity (Alves et al. 2020).

Leaf area

The application of black agrotextile significantly increased leaf area per plant and leaf area index compared with hilling with soil (Table 1). The significant effect of the etiolation factor confirms that the change in microclimate conditions was favorable for the intensive growth of assimilation leaves.

Table 1. Average leaf area (leaf surface, cm^2 per plant) and leaf area index (LAI) of leek hybrids depending on studied factors (averages ± SD over the period from 2018 to 2021, BBCH 49)

Factor		F1 'Jumper'		F1 'Matejko'	
		Leaf area	LAI	Leaf area	LAI
Etiolation method [E]	Hilling	1158b±258	1.90b±0.42	1438a±450	2.27a±0.31
	Black agrotextile	1302a±239	2.18a±0.57	1489a±479	2.34a±0.32
Planting scheme (cm) [P]	45 × 15	1247c±144	1.85d±0.22	1704c±109	2.52b±0.17
	60 × 15	1446b±177	1.61e±0.20	1879b±119	2.09e±0.14
	70 × 15	1522a±159	1.45f±0.15	2100a±126	2.00f±0.12
	45 × 15(2)	904f±102	2.68a±0.30	919f±81	2.72a±0.24
	60 × 15(2)	1096e±165	2.44b±0.36	1037e±96	2.30c±0.22
	70 × 15(2)	1168d±167	2.22c ±0.31	1144d±117	2.18d±0.23
Year [Y]	2018	1239b±257	2.05b±0.49	1487b±460	2.34b±0.27
	2019	1243b±231	2.06b±0.50	1416c±463	2.21c±0.25
	2020	1086c±219	1.80c±0.45	1361d±454	2.13d±0.26
	2021	1353a±259	2.24a±0.54	1591a±461	2.53a±0.33
p-value	E	<0.01	<0.01	<0.01	<0.01
	P	<0.01	<0.01	<0.01	<0.01
	E×P	<0.01	<0.01	<0.01	0.23
	Y	<0.01	<0.01	<0.01	<0.01

Means ± standard deviation followed by different letters are statistically significantly different at Tukey test at $p \leq 0.05$,
LAI – leaf area index; Means were compared among etiolation method, planting scheme and years

The planting scheme exerted a statistically significant effect on leaf area. Increasing the inter-row spacing from 45 to 70 cm increased leaf area per plant, while the leaf area index decreased. Excessive planting density negatively affects the assimilating area of plants. When two plants were planted in a hole, the average leaf area per plant of ‘Matejko’ decreased by 45–46% compared to a single-plant per hole. At the same time, the leaf area index was 1.1 times higher. In the treatments where two plants of the ‘Jumper’ hybrid was planted per hole, the leaf area index increased by 1.4–1.5 times. It is consistent with the data from other studies (Broome 2009; Coutinho et al. 2021). On average, the interaction between the etiolation method and planting scheme was not statistically significant ($p > 0.23$), indicating no modifying effect of one factor on the other.

Vegetable yields are 80–90% dependent on assimilative leaf area and plant density (Khareba & Komar 2017). For example, the leek ‘Tango’ was less productive than ‘Goliath’ due to the formation of a larger leaf surface (Karpenko et al. 2020). Other authors also argue that the morphological characteristics of leeks are more determined by genotype, and the distance between plants does not significantly affect the number and area of leaves, whereas yield depends on the planting scheme (Coutinho et al. 2021; Zahro & Koentjoro 2024). The efficiency of photosynthesis, dry matter accumulation, leaf area, and signs of nutrient deficiency were interrelated (Busato et al. 2010). Yield and leaf area index are related to planting density (Castellanos et al. 2004). Excessive plant density reduces the leaf area and the number of leaves per plant (Moravčević et al. 2011; Coutinho et al. 2021). Planting density affects the leaf structure in the *Alliaceae* family. Leaf blades in thinned plantings are thicker and have larger cells (Weerasinghe & Fordham 1994). The diameter and height of leaves in *Allium fistulosum*, *Allium cepa*, and *Allium schoenoprasum* increased by 2 cm with every 1 cm increase in the distance between plants (Broome & Peffley 2005). In dense plantings, onions had a smaller photosynthetic leaf area, and the leaves dried out earlier. Leek plants differ from other onion species in having a large number of leaves (10–15) that form throughout the growing season (Tsouvaltzis et al. 2010). The size of the leek’s pseudo-stems depends on the characteristics of leaf formation and the expansion of leaf bases. In dense plantings, cultivar types with an erect (vertical) leaf arrangement are preferred. At the same time, the leaves of the classic form cover the inter-rows, retain moisture, and reduce the soil temperature between the rows. The impact of planting schemes is reflected in plants’ physiological and morphological traits, altering their architecture, productivity, and quality. According to de Resende et al. (2013), the width, length, and leaf area of garlic are directly related to the formation of the marketable yield. Plant density has the most decisive influence on the leaf area index and the least effect on the area of a single leaf (Moravčević et al. 2011).

Chlorophyll content

The use of black agrotextile for etiolating the pseudo-stem of ‘Jumper’ does not inhibit chlorophyll synthesis in the leaves of leek compared with hilling. At each planting density, agrotextile increased chlorophyll content, but the difference was significant only at 60 x 15 cm . Chlorophyll content was significantly reduced by planting two seedlings in one hole (Fig. 1).

In ‘Matejko’, the tendency was similar; at each density, chlorophyll content in leaves of plants belonging to the group covered with agrotextile was higher when they were planted singly. It was contrary to double planting, where hilling was more beneficial (Fig. 2).

The assessment of chlorophyll content provides additional information on the characteristics of crop production formation in agricultural plants (Serrano 2008). In bulb onions, chlorophyll content increased significantly when mulched with colored polyethylene film (Sarkar et al. 2019). The content of photosynthetic structures depends on plant genotype and growth stage. According to von Wettstein (1957) and Moldovan et al. (2009), the pigment content in the leaves and plant yield are interconnected. Excessive planting density reduces chlorophyll content in leek plants. Plants with a larger nutrient supply area remain more photosynthetically active than those grown at a shorter distance. A larger leaf surface area increases light interception, while thicker leaves typically have higher chlorophyll content and higher photosynthesis rates (Pettigrew et al. 1993).

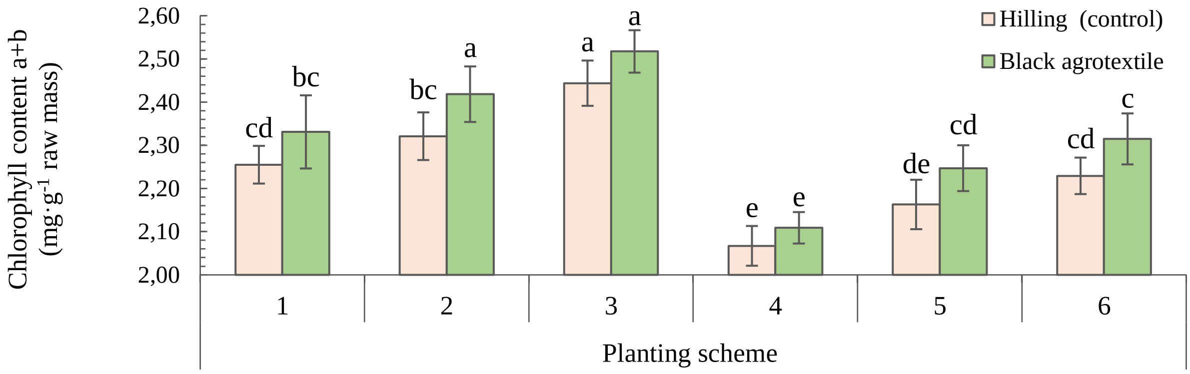

Figure 1. Chlorophyll *a* + *b* content (BBCH 19, averages over 4 years) of leek F1 'Jumper', depending on the studied factors
1 – 45 × 15 cm (control); 2 – 60 × 15; 3 – 70 × 15; 4 – 45 × 15(2); 5 – 60 × 15(2); 6 – 70 × 15(2) cm; p-value E <0.01, p-value P <0.01, p-value E×P – 0.88; means followed by different letters are statistically significantly different at Tukey test, p = 0.05

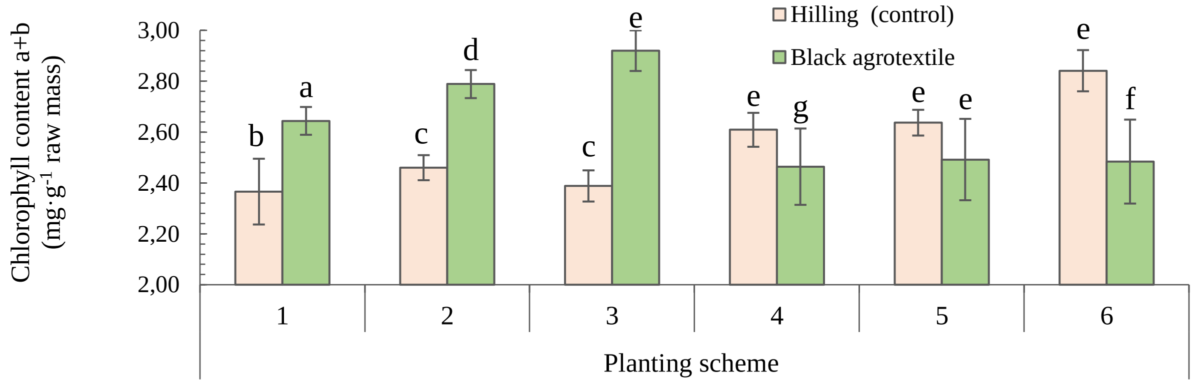

Figure 2. Chlorophyll *a* + *b* content (BBCH 19, averages over 4 years) of leek F1 'Matejko' depending on studied factors
Note: see Figure 1; p-value E <0.01, p-value P <0.01, p-value E×P <0.01

Mass of plants and net photosynthetic productivity
The low efficiency of the photosynthetic apparatus can be explained by the fact that, despite having a large leaf area, plants do not produce more photopigments. The number of leaves and their area correlate with plant raw and dry mass, while biomass production is 90% related to photosynthetic carbon assimilation (Rahman & Khan 2001; Sarkar et al. 2019). In dense plantings, the lower leaves are shaded, reducing photosynthetic efficiency and resulting in lower biomass (Coutinho et al. 2021; Postma et al. 2021). At the same time, vegetable yield needs to be increased through increased photosynthetic productivity (Khareba & Komar 2017). The productivity of photosynthesis and transpiration in leek plants depends on the cultivar, temperature, and leaf maturity (Doran et al. 2004). The lowest intensity of dry mass gain was observed in the period from August 5 to October 20 with the planting scheme of 45 × 15(2) cm under the etiolation of pseudo-stem by soil hilling (Table 2, 3). Dry mass gain was higher under etiolation with black agrotextile. The studied growing factors significantly affected the photosynthetic productivity of the leeks. From August 5 to October 20, the highest net photosynthetic productivity (NPP) in 'Jumper' was observed at a planting density of 45 × 15 cm. Still, in double planting, it was 60 × 15. Black agrotextile almost doubled the increase in dry mass. In 'Matejko', planting of two seedlings in one hole was especially unfavorable for the increase in dry mass, total plant mass, and pseudo-stem mass.

According to Benjamin (1984), the variation in leek plant mass is influenced not by the row spacing, but by the number of plants per 1 m². Excessive plant density significantly reduces the wet and dry mass of each plant (Coutinho et al. 2021; Zahro & Koentjoro 2024) and leads to the formation of very thin, non-commercial pseudo-stems (Sampaio et al. 2018; Coutinho et al. 2021).

Table 2. Mass of plants and net photosynthetic productivity (NPP) of leek F1 'Jumper' depending on studied factors (averages ± SD over 2018–2021)

Factor		Increase in dry mass over August 5 – October 20 (g per plant)	NPP over August 5 – October 20 (g per m² × day)	Total plant mass (BBCH 49) (g)	Pseudo-stem mass (g per plant)
Etiolation method [E]	Hilling	19.5b±3.7	2.63b±0.31	295b±63	176b±49
	Black agrotextile	27.9a±4.4	3.18a±0.31	327a±62	202a±54
Planting scheme (cm) [P]	45 × 15	26.9a±5.4	3.16a±0.49	344c±28	220c±23
	60 × 15	27.3a±5.7	2.71c±0.39	366b±31	237b±22
	70 × 15	26.2b±4.0	2.74c±0.44	381a±35	250a±23
	45 × 15(2)	16.5e±4.5	2.70c±0.54	214e±17	115e±13
	60 × 15(2)	22.2d±4.2	3.15a±0.26	280d±27	154d±16
	70 × 15(2)	23.0c±3.1	2.99b±0.17	283d±27	158d±17
Year [Y]	2018	23.6b±6.0	2.94a±0.42	319a±66	190b±53
	2019	23.7b±5.6	2.92a±0.43	307b±63	197a±56
	2020	22.4c±5.8	2.91ab±0.41	293c±58	174c±49
	2021	25.1a±5.9	2.86b±0.41	326a±67	196a±52
p-value	E	<0.01	<0.01	<0.01	<0.01
	P	<0.01	<0.01	<0.01	<0.01
	E×P	<0.01	<0.01	0.22	<0.01
	Y	<0.01	<0.01	<0.01	<0.01

Note: see Table 1

Table 3. Mass of plants and net photosynthetic productivity (NPP) of leek F1 'Matejko' depending on studied factors (averages ± SD over 2018–2021)

Factor		Increase in dry mass over August 5 – October 20 (g per plant)	NPP over August 5 – October 20 (g per m² × day)	Total plant mass (BBCH 49) (g)	Pseudostem mass (g per plant)
Etiolation method [E]	Hilling	23.3b±9.2	2.31a±0.58	350a±131	201b±78
	Black agrotextile	26.7a±10.2	2.47a±0.29	355a±128	218a±88
Planting scheme (cm) [P]	45 × 15	32.2c±3.9	3.01a±0.24	468b±23	276c±14
	60 × 15	33.8b±3.5	2.53b±0.17	482a±22	295b±21
	70 × 15	35.9a±4.1	2.42c±0.21	485a±39	300a±23
	45 × 15(2)	13.2f±2.9	2.01e±0.45	195d±11	109e±8
	60 × 15(2)	16.7e±2.7	2.21d±0.35	246c±14	139d±10
	70 × 15(2)	18.2d±3.7	2.17d±0.46	242c±17	139d±10
Year [Y]	2018	25.7b±9.3	2.15c±0.59	353b±129	210b±85
	2019	24.0c±9.6	2.40b±0.41	350b±129	208b±83
	2020	21.9d±9.6	2.41b±0.37	336c±124	199c±80
	2021	28.5a±9.9	2.60a±0.34	370a±135	220a±86
p-value	E	<0.01	<0.01	0.16	<0.01
	P	<0.01	<0.01	<0.01	<0.01
	E×P	<0.01	<0.01	0.91	<0.01
	Y	<0.01	<0.01	<0.01	<0.01

Note: see Table 1

It is well known that increasing density enhances total yield per area, but reduces the average plant size (Rumpel & Felczynski 2000; Moravčević et al. 2011; Coutinho et al. 2021; Postma et al. 2021). Similarly, in the present study, at a row spacing of 60–70 cm, the weight of the pseudo-stem tended to increase compared to 45 cm. In the wide-row planting, the total weight and pseudo-stem weight were higher than in two-plants-per-hole planting. It is worth noting that, in the wide-row planting schemes, the proportion of pseudostem weight was 60–73% of the total plant weight. The pseudo-stem weight of the 'Jumper' increased to 15% under etiolation with black agrofibre, compared to 9% with 'Matejko' under soil hilling. All other methods of pseudostem etiolation, other than hilling, also resulted in increased weight, as reported by Coutinho et al. (2021).

The nutrient supply area of leek plants influences the quality of the pseudo-stem. Excessive planting density can increase the length of the pseud-stem and create a self-lighting effect in the aboveground part. However, the stem mass will not be larger due to the small diameter. Excessively dense leek crops achieve marketable maturity later (Ahamad et al. 2024), and root development is suppressed due to competition for light and nutrients (Sampaio et al. 2018).

Three species of *Allium* grown in dense plantings had etiolated stems at harvest, as spectral absorption was very low (Broome 2009). Hydroponic planting of leek plants in a non-transparent plastic tube yielded significantly better results than shading the pseudo-stem with agrotextile (Tongaram et al. 1994). The depth of planting leek seedlings is essential for etiolating the pseudo-stems, with better results achieved by growing one plant per hole at a depth of 15 cm (Ahamad et al. 2024). Deep planting of leek seedlings promotes an increase in the length of the pseudo-stem by 10–20%, but negatively affects the yield (Kołota & Adamczewska-Sowińska 1993). A smaller distance between leek plants in a row promotes the growth of taller pseudo-stems (Coutinho et al. 2021).

Total yield

A key factor in yield levels is the effective use of land area, as achieving high-quality appearance does not necessarily increase total gross yield (Favorito et al. 2011; de Lima et al. 2019; Coutinho et al., 2021). However, a greater number of plants per unit area, even if they compete for nutrients, ultimately has a positive effect on yield, within limits suitable for the formation of a marketable crop. The marketable yield of leek 'Kylim' increased on 8.2 $t \cdot ha^{-1}$ as the plant density increased from 40 to 80 plants per m^2 (Kołota & Adamczewska-Sowińska 1994). According to other data, yields of onions in dense plantings are 14% higher (Leskovar et al. 2012).

The use of black agrotextile significantly increases leek yield compared to hilling with soil at all planting densities (Table 4). The average yield of the 'Jumper' increases by 5.7 t ha^{-1} with etiolation under black agrotextile. Etiolation under black agrotextile increased the yield of the 'Matejko' by an average of 1.1 $t \cdot ha^{-1}$, but this increase was insignificant in the 45 × 15 cm and 70 × 15 cm planting schemes. By etiolating under black agrotextile, the pseudo-stems were taller, with sufficient diameter and a high-quality blanched part. In this study, the highest yield of leeks was observed at 45 cm row spacing, while the lowest yield was recorded at 70 cm row spacing. This pattern is consistent with the results of Zahro & Koentjoro (2024). With a planting pattern of 70 × 15 cm, the yield of the 'Jumper' was on average 29% lower than the control. The maximum yield of the 'Jumper' was observed in the 45–60 × 15(2) cm density. Therefore, an optimal combination of plant spacing and the number of plants per hole tends to increase yield. In the planting schemes of the 'Matejko', the yield was lower than the control, and its maximum yield was 69.3 $t \cdot ha^{-1}$ in the 45 × 15 cm variant. As a result of excessive density (190.5–296.3 thousand plants per hectare) of the 'Matejko', the low weight of the pseudo-stem did not lead to an increase in yield. According to Alves et al. (2020), excessive density suppressed plant development and significantly reduced their mass.

The single-row method is commonly used for planting leek seedlings. Planting garlic with two cloves per hole at a 15 × 10 cm spacing increased the yield by 2.3–3.2 times per unit area compared to planting one clove per hole (Krestini et al. 2022). The yield level of leek varies significantly depending on the growing conditions (Kołota & Adamczewska-Sowińska 2007). According to other data, the marketable yield with the 75 × 15 cm planting scheme was only 0.5 $t \cdot ha^{-1}$ lower than the total yield (Siwek et al. 2013). Given the profitability of cultivation, it is recommended to plant garlic at a density of 30–42 plants per m^2, even though the maximum yield was achieved at 60 plants per m^2 (Castellanos et al. 2004).

Ascorbic acid content and nitrate levels

The biochemical composition of onion vegetable plants depends on cultivar characteristics, with significant variation in dry matter content (González et al. 2009). The content of ascorbic acid and mineral substances in leek is not significantly affected by application of organic or mineral fertilizers (Termine et al. 1987). The distance between leek and onion plants did not affect the content of macroelements (Kołota & Adamczewska-Sowińska 1994).
No patterns were found regarding the influence of the etiolation method and planting schemes on the content of ascorbic acid in the 'Jumper' (Fig. 3). The pseudo-stem of the 'Jumper' contained more nitrates when etiolated under black agrotextile. By the hilling with soil and minimal planting density of the 'Matejko', the pseudo-stem contained more ascorbic acid and nitrates (Fig. 4). The content of ascorbic acid and nitrates revealed significant variability depending on the year of the study.

The nitrate content in plants depends on leaf structure, the size of leaf veins, the genetically determined level of nitrate reductase, and the physiological maturity at the time of harvest. The nitrate content in leek is higher than in onion. The highest nitrate content was found in the etiolated part of the pseudo-stem of leek – 963.93 mg·kg^{-1}, and in the green part – 803.70 mg·kg^{-1} (Koca et al. 2016). Nitrate content can be reduced by optimizing nutritional conditions.

Increasing the distance between garlic plants reduces dry matter and total sugar content (de Lima et al. 2019). At the same time, Olfati et al. (2016) argue that different distances between garlic plants (15–35 cm) do not affect the content of dry matter. With greater plant spacing, soluble dry matter content decreases due to increased transpiration (Vidya et al. 2013).

Therefore, leek plantings can be densified up to the limit that does not harm their productivity potential. The combined effect of planting schemes and etiolation methods varied across the studied leek plants. Our studies indicate the effectiveness of etiolating the pseudo-stem under black agrotextile. The plants of the 'Matejko' should be planted according to the 45 × 15 cm scheme, and. 'Jumper' according to the scheme 60 × 15(2) cm.

Table 4. Total yield of leek hybrids depending on studied factors (averages t·ha^{-1} ± SD over 2018–2021)

Factor		F1 'Jumper'	F1 'Matejko'
Etiolation method [E]	Hilling (c.)	48.4±9.9B	54.0±8.6A
	Black agrotextile	54.1±11.5A	55.1±8.5A
Planting scheme (cm) [P]	45 × 15 (c.)	51.0±4.2 C	69.3±3.5 A
	60 × 15	40.7±3.4 D	53.6±2.6 C
	70 × 15	36.3±3.3 E	46.2±3.8 D
	45 × 15(2)	63.3±5.1 A	57.6±3.5 B
	60 × 15(2)	62.3±6.0 A	54.6±3.4 C
	70 × 15(2)	54.0±5.1 B	46.1±3.3 D
Year [Y]	2018	52.4±11.1 A	55.2±8.3 B
	2019	50.5±10.6 B	53.9±8.1 B
	2020	48.4±11.0 C	52.0±8.2 C
	2021	53.6±11.3A	57.3±8.8 A
p-value	E	<0.01	<0.01
	P	<0.01	<0.01
	E×P	<0.01	<0.24
	Y	<0.01	<0.01

Note: see Table 1

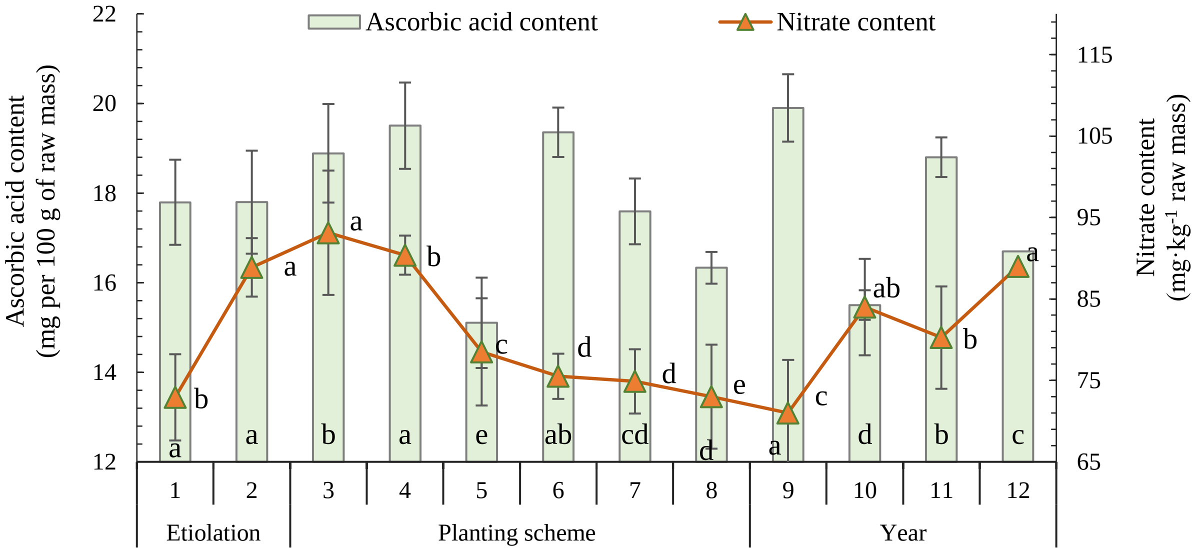

Figure 3. Content of ascorbic acid and nitrates in the pseudo-stem of leek F1 'Jumper' (averages over 4 years) depending on the studied factors

1 – hilling; 2 – black agrotextile; 3 – 45 × 15 cm; 4 – 60 × 15; 5 – 70 × 15; 6 – 45 × 15(2); 7 – 60 × 15(2); 8 – 70 × 15(2) cm; 9 – 2018; 10 – 2019; 11 – 2020; 12 – 2021; p-value ascorbic acid: E – 0.97; P <0.01; E×P <0.01; Y <0.01; p-value nitrate: E <0.01; P <0.01; E×P <0.01; Y – 0.02; means followed by different letters are significantly different at Tukey test, p = 0.05

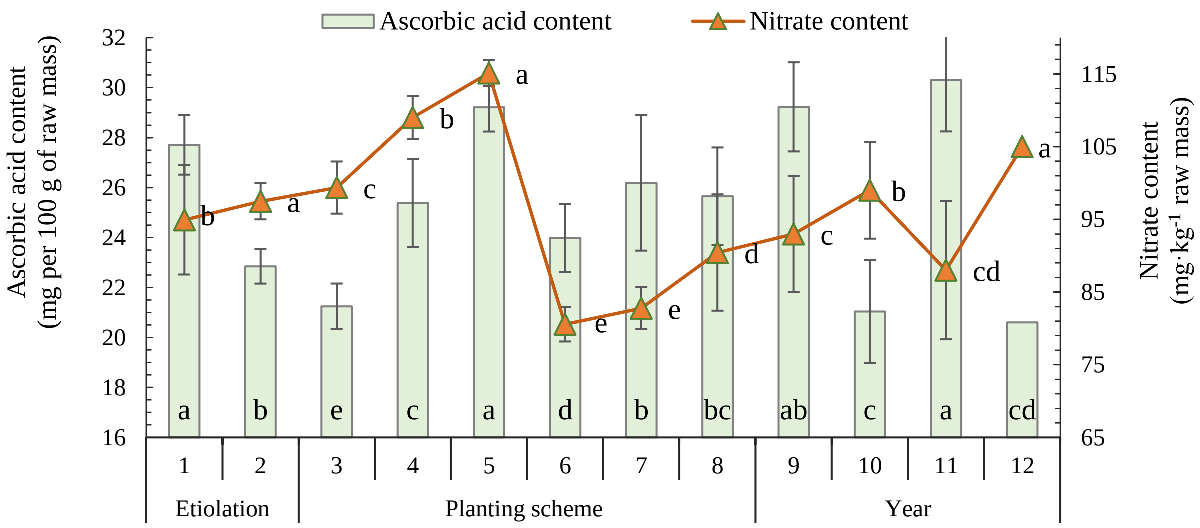

Figure 4. Content of ascorbic acid and nitrates in the pseudo-stem of leek F1 'Matejko' (averages over 4 years) depending on the studied factors

Note: see Figure 3; p-value ascorbic acid: E <0.01; P <0.01; E×P <0.01; Y – 0.04; p-value nitrate: E <0.01; P <0.01; E×P <0.01; Y – 0.03

CONCLUSION

The productivity potential and product quality of leeks are closely related to the cultivation system used. The highest total yield of both cultivars was obtained at the lowest plant density, 45 × 15 cm. Planting of two seedlings in one hole further increased total yield in 'Jumper' but decreased it in 'Matejko'. The mass of pseudo-stems increased with density in both cultivars and was much higher at single than at double planting. Double planting reduced the mass of pseudo-stems, especially in 'Matejko'. Etiolation under black agrotextile leads to higher rates of plant mass growth, net photosynthetic productivity, and chlorophyll content, resulting in an increase in the mass and yield of the leek of 'Jumper', but had almost no effect on 'Matejko'. However, by hilling with soil, leeks accumulate more ascorbic acid and contain less nitrates. In further optimization, leek planting density should be associated with fertilization levels.

Conflict of interest

The authors declare that there are no conflicts of interest.

Author contribution statement

HS – A – Research concept and design, B – Collection and/or assembly of data, D – Writing the article, F – Final approval of the article
OO – B – Collection and/or assembly of data
ZK – C – Data analysis and interpretation
AT – A – Research concept and design, F – Final approval of the article
OV – D – Writing the article, E – Critical revision of the article, F – Final approval of the article
IZ – B – Collection and/or assembly of data
VV – D – Writing the article

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