

EFFECT OF PLANT DENSITY ON THE GROWTH, DEVELOPMENT AND YIELD OF BRUSSELS SPROUTS (*Brassica oleracea* L. var. *gemmifera* L.)

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Abstract

Plant density is an important variable for achieving maximum yields and uniform vegetable maturity. Optimal plant density can be achieved by establishing appropriate distances both between the rows as well as in the rows of plants. The experiment was carried out between 2010–2012 at the experimental field of the Crimean Agrotechnological University in Simferopol, Ukraine. The experiment was established as randomised blocks with four replications. This study aimed to determine the effect of plant density on the growth, development and yield of Brussels sprouts. Increasing the area per plant resulted in a shortening of the time to the beginning of head formation, technical maturity and harvest. In all study years, increasing the distance between plants caused an increase in leaf assimilation area, stalk diameter and the number of heads per plant, however, the height of plants was lower. The most favourable parameters characterising marketable yield were found at an area per plant of 0.56 m², however, the maximum yield from 1 ha (determining the profitability of the cultivation) was found at an area of 0.49 m² per plant.

Key words: *Brassica oleracea* L. var. *gemmifera* L., biometric parameters, leaf assimilation area, spacing, marketable yield, quality of marketable heads

INTRODUCTION

Brussels sprouts (*Brassica oleracea* L. var. *gemmifera* L.) is a member of Brassicaceae family and researches on Brussels sprouts became dense on their cancer preventive effects, sowing and planting time, plant density, fertilizing, timing, stopping and relations between temperature and plant development [1].

Plant density is an important variable for achieving maximum yields and uniform vegetable ma-

turity. Differentiation of density of plants per unit of area gives possibility of regulation of the size of edible part of such vegetables as e.g. cauliflower [2], broccoli [3–4], kohlrabi [5] or lettuce [6]. Optimal plant density can be achieved by establishing appropriate distances both between the rows as well as in the rows of plants [7–9]. Recommended spacing of Brussels sprouts depending on the date of cultivation and cultivar amounted to 50–70 cm between the rows and 50–60 cm in row, what responding cultivation area per plant from 0.25 to 0.42 m² [10–11]. The effect of density on the yield and its quality in Brussels sprouts cultivation was investigated by Abuzeid and Wilcockson [12], Bortness [13], Everaarts and De Moel [14] and cabbage vegetables for early harvest by Lan Chow Wing and Rajkomar [15]. In the study by Whitwell et al. [16] was found that increase plant density caused increase yield of small heads and decrease yield of heads at diameter above 30 mm. However, plants density did not influence on the marketable yield level. Similar influence of Brussels sprouts density on the share of small heads in the marketable yield was achieved by Everaarts and De Moel [14]. A decrease in yield with an increase in plant density from 2.7 to 4.4 plants per 1 m² authors were found in only one year. In turn, Abuzeid and Wilcockson [12] reported that low planting densities gave high yields of small buds at early harvests but denser planting gave higher yields at later harvests. However, Bortness [13] was found that plant density had no significant effect on the yield of Class 1 sprouts, but a low density increased the sprout size. Studies involving broccoli, cauliflower [2] and head cabbage [17], demonstrated that increased plant densi-

ty via a reduction in the distance between plants in rows can cause an increase in yield. But Islam et al. [18] and Farooque and Islam [19] reported that the yield of cabbage cultivated at a spacing of 60 × 30 cm and 60 × 45 cm did not differ significantly. However, Moniruzzaman [20] was found that with an increase of cabbage spacing increase mass of heads but decrease marketable yield.

Plant density also influences biometric parameters of cultivated plants and consequently, the quality of edible parts. Within the range of 0.15 to 0.45 m² area per plant, which covers the range of commercial densities, no effect of plant density on bud initiation in Brussels sprouts, leaf area index (LAI) and stem length is observed [12, 21]. In turn, in the study by Sarker et al. [22] plant spacing had marked influence on the growth parameters like number of leaves per plant and diameter of head. Decreased plants density caused increase of investigated parameters, but had no influence on a plant height. In the study by Nweke et al. [23] decrease spacing of cucumber from 50 × 50 to 50 × 30 contributed to an increase the number and area of leaves and also increased almost 2 times the number of fruits.

This study aimed to determine the effect of plant density on the growth, development phenology and biometric parameters of Brussels sprouts plants and yields.

MATERIALS AND METHODS

The experiment was carried out in the years 2010–2012 at the experimental field of the Crimean Agrotechnological University in Simferopol, Ukraine, in the tectonic foreland zone of the Crimean Peninsula (44°56'N, 34°06'E). A field experiment was established on steppe black soil formed on carbonate. The soil organic matter content ranged from 2.0 to 2.9% and its humus horizon reached a depth of 60–70 cm. The soil reaction was slightly alkaline. The total content of nitrogen ranged from 2.75 to 7.02 g, phosphorus from 2.25 to 3.25, and potassium from 25.03 to 45.01 g × dm⁻³ of soil. Seeds of Brussels sprouts 'Franklin F₁' were obtained from the Dutch seed company Bejo Zaden. According to the producer the earliest yield of heads is possible to obtain after 128 days. The cultivar had a consistent growth and size of the heads on the stalk and a high resistance to stress. Cabbage is suitable for use both fresh and for freezing [24]. The experiment was established as randomised blocks with four replications. The effect of distance was investigated as follows:

- 70 × 50 cm; 0.35 m² area per plant (28571 plants × ha⁻¹) – control, distance recommended for species,
- 70 × 60 cm; 0.42 m² area per plant (23809 plants·ha⁻¹),

- 70 × 70 cm; 0.49 m² area per plant (20408 plants × ha⁻¹),
- 70 × 80 cm; 0.56 m² area per plant (17857 plants × ha⁻¹).

The effect of plant density on the growth, development and yield of 'Franklin F₁' Brussels sprouts was analysed. The area of a single plot for harvest was 21.5 m².

The field experiment was set up after tomato. Following the tomato harvest, postharvest residues and weeds were collected, then potassium and phosphorus fertilizers were applied at the following rates: 75 kg K₂O × ha⁻¹ and 125 kg P₂O₅ × ha⁻¹. At the end of September, ploughing was performed to a depth of 25–28 cm. In the spring at the end of February, shafting and harrowing was conducted to a depth of 10–12 cm. The planting of seedlings was preceded by an application of nitrogen fertilizer at the rate of 75 kg N × ha⁻¹.

Brussels sprouts transplants were grown in a non-heated greenhouse. The seeds were sown at the rate of 12–14 g × m⁻² in 15th of May in seedling containers. Seedling emergence occurred 9–10 days after sowing. Plants in the first-leaf phase (17 days after sowing) were removed and placed in pots (7 × 7 × 7 cm). Prior to transplantation, the plants had five to seven leaves, a short, thick stalk and a well-developed root system.

The transplants were planted in the field 50–51 days following sowing (3–4th July). Activities carried out during vegetation period consisted of loosening of the soil surface, weeding, irrigation and protection against diseases and pests.

The leaf area, plant height and stalk diameter were measured when the heads in the axils of the lower leaves reached a marketable size. Leaf area was estimated a direct non-destructive methodology based on linear measurement leaf. The measurement of leaf area relied on measuring the length of the major nerve. On the basis of repeated measurements of length and width of leaf was established the characteristic for cultivar dependence between this parameters and leaf area. On this basis, it made the measuring instrument in the form of ruler allowing for direct reading of the leaf area [25].

Yield harvest was performed once between 25–30 of November and marketable heads (t × ha⁻¹) had to conform to the requirements within the Ukraine [26].

The results of the experiment were analysed statistically using analysis of variance (ANOVA). The significance of differences was confirmed using Tukey's test at the significance level of $\alpha = 0.05$.

On the basis of the long-term mean the optimal thermal conditions for Brussels sprouts growing in the tectonic foreland zone of Crimean Peninsula is from June to October. A moderate reduction in temperature in October favoured head formation. According to long-term data, the amount of precipitation in June

and July ensures a sufficient water supply for seedlings. However, from August to October, the quantity

of rainfall is insufficient to obtain a good quality yield and irrigation is necessary (Fig. 1).

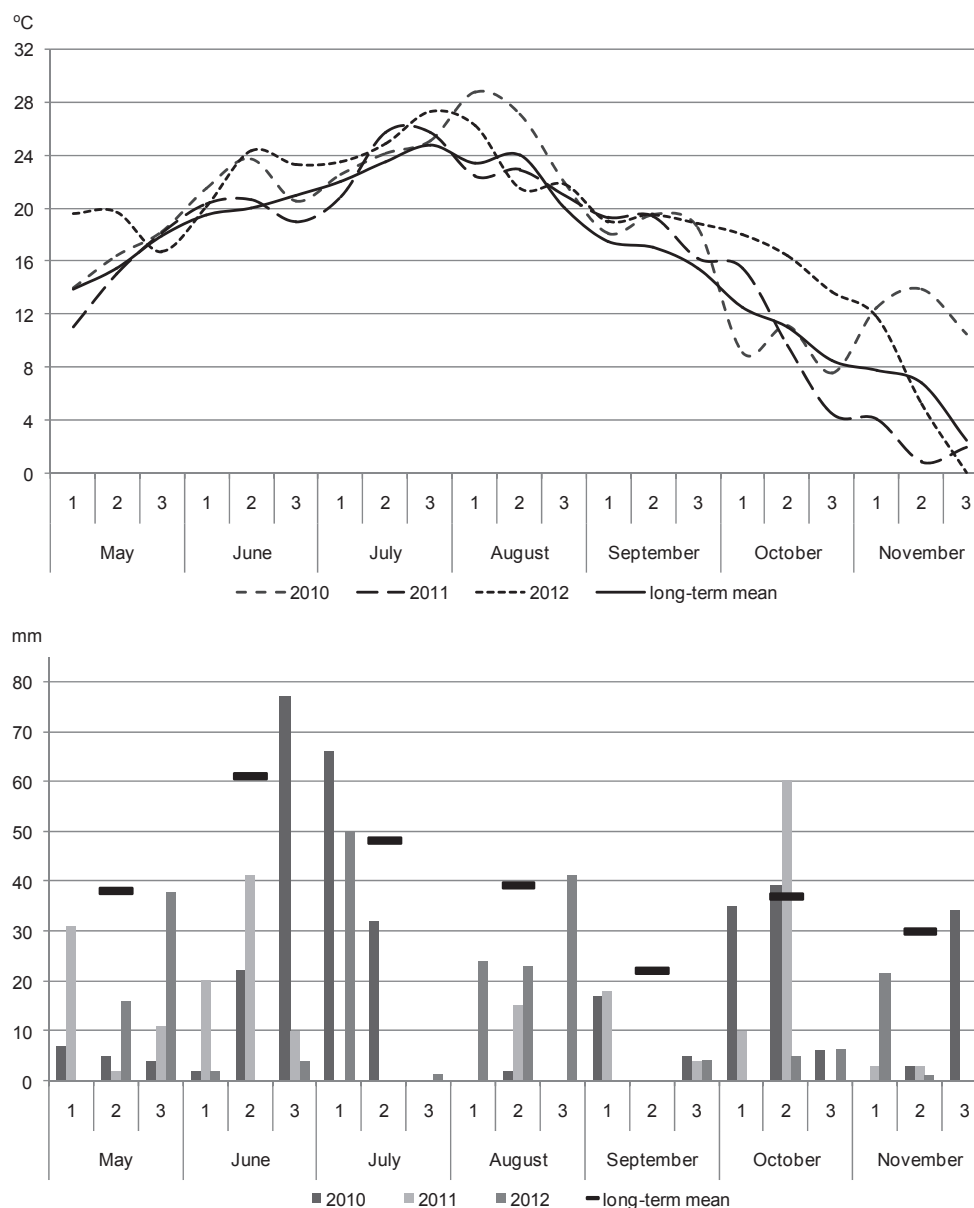


Fig. 1. Mean air temperatures and rainfall during the study

Air temperatures in the study years (2010–2012) exceeded the long-term mean from the second 10 days of July to the second 10 days of September, except for the third 10-days of August (Fig. 1). For the last 10 days of July and the first and second 10 days of August, temperatures reached maximum values for the growing period. Mean daily temperatures decreased in the last 10 days of August at the start of head formation and had a negative influence on head formation. No rainfall occurred at the end of July and the beginning of August 2010 and 2011, which also had a negative influence on plant growth and head formation.

The yield and yield quality of Brussels sprouts depended on the mean daily temperature in September, October and the first and second 10 days of November. The most favourable influence of thermal conditions on yield was in 2012, when high air temperatures were experienced until the end of the first 10 days of November. In 2010, thermal conditions in October and November were also favourable to obtain a high and good quality yield of Brussels sprouts. In 2011, decreased air temperatures for the second 10 days of October contributed to a reduction yield of heads compared with the other study years.

RESULTS

This study shows that a reduction in the area per plant caused an increase in the time taken until the onset of head formation, as well as that to reach technical maturity and harvest (Table 1). The longest time needed to reach these phases was found in control plants with the lowest area per plant (0.35 m²) and the shortest, in plants with the largest area of 0.56 m².

The mean leaf assimilation area was 25686.8 cm² in 2010, 17362.0 cm² in 2011 and 17350.0 cm² in 2012, depending on weather conditions (Table 2). The leaf assimilation area of Brussels sprouts ranged from 10998.0 cm² in 2011 at an area per plant of 0.35 m² to 31175.1 cm² in 2010, at an area per plant of 0.56 m². In all the study years, assimilation area of leaves increased together with decreasing plant density. In 2012, coefficients lied in critical partition values from 2010 and 2011.

An increased area per plant caused an increase in the stalk diameter, which ranged from 5.5 cm in 2011 in the control treatment to 10.1 cm in 2010 for plants with a spacing of 70 × 80 cm.

Plants cultivated at a low density were shorter than those at a high density, however, the number of heads increased with an increase the area per plant. In

the control, the number of heads was the smallest and ranged from 29.5 in 2011 to 46.0 in 2010. The maximum number of heads was obtained for plants with an area of 0.56 m² and ranged from 39.2 in 2011 to 63.2 in 2010 (Table 2).

The highest marketable yield in all the study years was obtained for a planting of 70 × 70 cm and an area per plant of 0.49 m² (Table 3). The yield was significantly higher compared with that of the other treatments. Although the maximum leaf area and the greatest number of heads were found for plants with an area of 0.56 m², the highest yield was obtained from plants with an area of 0.49 m² (Table 2, Table 3). An increased productivity in the third treatment was found, due to a difference in the number of plants within the cultivation area: 17857 plants × ha⁻¹ at 0.56 m² and 20408 plants × ha⁻¹ at 0.49 m², respectively.

The greatest number of heads from one plant (44.7 and 45.6), was obtained at an area per plant of 0.49 and 0.56 m², respectively. The number of marketable heads decreased when plant density was higher (Table 4). A similar dependence of the mean mass of marketable heads on distance was found; at a greater distance, the plants formed larger heads. The area per plant had no significant effect on the length of the stump.

Table 1
Growth and development of Brussels sprouts at different spacing (mean from 2010–2012)

Area per plant (m ²)	Number of days from sowing		
	Beginning of head formation	Technical maturity	Harvest
0.35	115	181	198
0.42	114	178	197
0.49	110	177	195
0.56	108	174	191

Table 2
Biometric parameters of Brussels sprouts during the harvest in 2010–2012

Area per plant (m ²)	Leaf area (cm ²)	Stalk diameter (cm)	Height of plants (cm)	Number of heads per plant
2010				
0.35	18908.4	8.1	92.9	46.0
0.42	24910.9	8.5	83.8	55.0
0.49	27752.9	9.8	78.8	62.7
0.56	31175.1	10.1	71.2	63.2
LSD _{0.05}	1273.8	0.7	4.2	3.1
2011				
0.35	10998.0	5.5	78.0	29.5
0.42	17163.8	5.8	60.9	36.7
0.49	19750.0	6.9	57.9	40.7
0.56	21536.3	7.1	53.6	39.2
LSD _{0.05}	692.4	0.4	2.7	2.8

2012				
0.35	14553.9	5.6	60.9	32.5
0.42	16499.7	5.8	52.4	37.6
0.49	17754.0	6.4	48.4	44.2
0.56	20592.4	6.5	42.6	46.4
LSD _{0.05}	874.3	0.3	3.3	2.8
Mean 2010–2012				
0.35	14820.1	6.4	77.3	36.0
0.42	19524.8	6.7	65.7	43.1
0.49	21752.3	7.7	61.7	49.2
0.56	24434.6	7.9	55.8	49.6

Table 3
Yield of marketable (t·ha⁻¹) heads of Brussels sprouts depending on area per plant in 2010–2012

Area per plant (m ²)	Years			
	2010	2011	2012	Mean
0.35	9.6	3.5	14.0	9.0
0.42	11.1	7.4	14.2	10.9
0.49	12.3	8.8	14.6	11.9
0.56	11.5	7.6	13.5	10.9
LSD _{0.05}	0.5	0.4	0.5	ns.

ns. – not significant

Table 4
Characteristic of marketable yield of Brussels sprouts (mean from 2010–2012)

Area per plant (m ²)	Number of marketable heads per plant	Mean weight of marketable heads (g)	Maximal diameter of marketable heads (cm)	Length of the stump (cm)
0.35	34.0	9.8	2.5	1.5
0.42	38.6	12.5	2.7	1.3
0.49	44.7	13.2	3.0	1.5
0.56	45.6	14.1	2.8	1.2
LSD _{0.05}	2.3	1.7	0.3	ns.

ns. – not significant

DISCUSSION

In the carried studies increased of plants density extended growing period and delayed Brussels sprouts harvest. In the contrary, Everaarts et al. [21] did not find any influence of plant density on the number of days to but initiation. Fawusi et al. [27] found that increasing plant density caused a delay in the time to flowering for green peas and maize.

In the investigated range of plants density an increase of area per plant contributed to significant increase of leaf assimilation area, stalk diameter and height of plants. Similar results were obtained by Cresswell and Causton [28] for Brussels

sprouts. In this study whole plant, stem, root and foliage, together with specific leaf area, leaf area ratio and number of leaves initiated were reduced by restricting cultivation area. In turn, Abuzeid and Wilcockson [12] was found that increasing plant density from 2.22 to 6.66 plants·m⁻² advanced and increased maximum LAI. However, Mortley et al. [29] found that the stalk diameter increased linearly with an increase in the distance between plants for Amaranthus cultivation. In the study by Nweke et al. [23] number of branches, number of leaves and vine length decreased as the cucumbers plant spacing increased from 50 × 30 cm to 50 × 40 cm. Michalik and Szwejkowska [30] showed a higher length

of leaves and higher individual plant mass of green celery at a lower spacing. Sarker et al. [22] was not noted change of cabbage plants height with change of plant density.

An increase of area per plant at a range from 0.35 to 0.49 m² contributed to increase the marketable yield of Brussels sprouts. Further increase of area per plant caused decrease of yield as a result of lower number of plants on the cultivation area. A similar dependence of productivity on density was found for Brussels sprouts by Everaarts and De Moel [14], for broccoli by Bracy et al. [7], who noted an increase in the yield by 36% with an increase in plant density from 34170 to 64582 ha⁻¹. Michalik and Szewjowska [30] observed a lower yield of green celery at a lower density because of fewer plants in the cultivation area. Bernsten [31] found a higher productivity at a lower plant density by analysing the effect of plant distance in rows spaced 30 and 50 cm apart (4.5 and 3.0 plants per m²) on the yield of Brussels sprouts, however, the yield of sprouts per hectare did not differ significantly. According to Bortness [13] low plant density increased the sprouts size, however, did not have influence on the yield of Class 1 sprouts.

Also in the present study was found that increasing of cultivation area per plant caused an increase number of marketable head per plant and an increase mass of marketable head. Similar dependence with respect to number of marketable heads was also found by Everaarts et al. [21], and to mass of heads by Whitwell et al. [16]. According to Abuzeid and Wilcockson [12] increase of plant density increased number of heads per plant growing on the 1 m², however the size of individual heads decreasing as a result of plants competition by light and reduced production of assimilates. Also in the study by Griffith and Carling [32] increase the number of plants from 2.8 to 14.8 per 1 m² caused linearly decrease the mass and diameter of heads.

Also Biesiada [5] found that a higher plant density had a significant favorable effect on the yield of kohlrabi, but decreased the mean bulb mass. Filh et al. [33] found that decreasing the distance between rows from 40 to 30 cm caused a decrease in the mean mass of lettuce heads from 406.3 to 321.1 g. Furthermore, other studies confirmed that decreasing the area per plant contributed to a higher yield but to a lower mass and diameter of the edible part of plants [3–4, 34–38]. This might be due to a less light reaching the plants [20,39]. Rekowski and Jurga-Szlemo [6] did not observe a significant effect on the mean mass of endive when the distance between plants in rows changed from 35 to 25 cm.

CONCLUSIONS

1. Increasing the area per plant resulted in a shortening of the time to the beginning of head formation, technical maturity and harvest.
2. In all the study years, increasing the distance between plants caused an increase in leaf assimilation area, stalk diameter and the number of heads per plant, however, the height of plants was lower.
3. The most favourable parameters characterising marketable yield were found at an area per plant of 0.56 m², however, the maximum yield from 1 ha was found at an area of 0.49 m² per plant.

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Authors' contributions

The following declarations about authors' contributions to the research have been made: concept of the study: VAT, ASS, field work: VAT, ASS, statistical calculations and writing: VAT, ASS, EK, RR.

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**Wpływ zagęszczenia roślin na wzrost, rozwój
i plonowanie kapusty brukselskiej
(*Brassica oleracea* L. var. *gemmifera* L.)**

Streszczenie

Gęstość sadzenia roślin jest ważną zmienną w uzyskiwaniu maksymalnego plonu i jednakowej dojrzałości warzyw. Optymalne zagęszczenie roślin można uzyskać poprzez ustalenie właściwych odległości zarówno w rzędzie jak i pomiędzy rzędami roślin. Doświadczenie prowadzono w latach 2010–2012 na polu doświadczalnym Katedry Warzywnictwa i Standaryzacji Krymskiego Uniwersytetu Agrotechnologicznego w Symferopolu. Doświadczenie założono metodą

losowanych bloków w czterech powtórzeniach. Celem badań było określenie wpływu powierzchni przypadającej na jedną roślinę przy różnej rozstawie na wzrost, rozwój i plonowanie kapusty brukselskiej. Wraz ze zwiększaniem powierzchni przypadającej na 1 roślinę skróceniu ulegał okres od wysiewu nasion do początku formowania główek oraz do osiągnięcia dojrzałości technologicznej i zbioru plonu. We wszystkich latach badań w miarę zwiększania rozstawy wzrastała powierzchnia asymilacyjna liści, średnica łodygi oraz liczba główek na roślinie, natomiast malała wysokość roślin. Najkorzystniejsze parametry charakteryzujące plon handlowy stwierdzono przy powierzchni przypadającej na roślinę wynoszącej 0,56 m², natomiast maksymalny plon z jednego hektara (decydujący o opłacalności uprawy) przy powierzchni 0,49 m².

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