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Determination of sowing density and row spacing on the susceptibility of lupine seeds to mechanical damage

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Abstract: Appropriate agrotechnical measures make it possible to optimise plant cultivation and obtain yields of the highest quality with an appropriate economic production index. The aim of the study was to evaluate different sowing density and row spacing on the morphological and mechanical properties of white lupine (*Lupinus albus* L.) seeds. The field experiment was conducted at the Experimental Station for Variety Evaluation in Przecław (50°11'25.2" N, 21°28'55.0" E). The experiment was established at two row spacings (15 cm and 30 cm) and three sowing densities (60, 75, 90 plants per m^2). Mechanical parameters evaluated included destructive force F_D (N), relative deformation D_R (%) and destructive energy E_D (mJ). Seed morphological properties such as weight, length and width were also assessed. Sphericity was also calculated. In the present study, improvements in the mechanical properties of the seeds were obtained by increasing the plant density per unit area of the experiment. In the case of morphological characteristics, only the weight of the analysed lupine seeds changed significantly as a result of row spacing. On the other hand, sowing density did not significantly affect morphological traits. of white lupine seeds. Apart from the spacing and sowing density of plants, the weather conditions in particular years of research were an important factor determining the properties of seeds. Determining the optimum sowing density and row spacing in the field contributes to the optimisation of the production process. Quasi-static mechanical tests are often used to obtain reasonable data on the physical properties of plant materials.

Keywords: lupine seeds, mechanical damage, physical characteristics, row spacing, sowing density

INTRODUCTION

Legumes are among the most promising crops in the European Union countries. This may be related to the growing demand for food and animal feed containing significant amounts of protein, or by the positive effect of legume cultivation on soil fertility. It is important from an environmental and economic perspective [Panasiewicz *et al.* 2020]. White lupine (*Lupinus albus* L.), a member of the genus *Lupinus* from the Fabaceae family, is an annual legume plant traditionally grown in the Mediterranean, and currently in Australia, which is the biggest manufacturer and exporter of lupine in the world [FAO undated; Prusinski 2017]. White lupine is mainly grown as a feed for ruminants but is also used as a green manure as a soil enrichment method. It is also used in the formulation of food products due to the high protein and oil content of the seeds [Damalas *et al.* 2022]. Nevertheless, white lupine is not consumed as often as other legume seeds, which may be due to a lack of knowledge about its nutritional value or a lack of a habit of consuming it. Moreover, it occupies a small position among other legumes, therefore research on this plant is significantly limited compared to other legumes [Lucas *et al.* 2015; Mierlita *et al.* 2018].

Appropriate agrotechnical procedures allow to optimise the cultivation of plants and obtain the highest quality crop with an appropriate economic production ratio. In modern agriculture, there is a desire to obtain the highest possible yields, which are characterised by appropriate high quality. It is also extremely important to limit losses during the production and processing of raw materials. Reducing row spacing and increasing seeding density are important strategies for maximising yields and have long been seen as potential systems to optimise yield and maturity in regions with short growing seasons or with limited yield potential [Ethridge *et al.* 2022; Roche, Bange 2022]. However, for the effectiveness of this strategy plant population densities should not result in interspecific crop competition that may negatively affect yields. The use of higher seeding densities or narrow row spacing must take into account light capture and plant efficiency to maintain or increase yields. Therefore, it is important that the method of planting allows light to penetrate the lower layers within the plant [Stewart *et al.* 2003].

The study of mechanical properties is the elementary measurement of the texture and plasticity of biological material [Miraei Ashtiani *et al.* 2016]. Knowledge of the mechanical properties of agricultural products is one of interest to agri-food industry specialists, as quasi-static mechanical tests can be a useful tool to obtain data on the mechanical and textural properties of crops [Lu, Abbott 2004]. Vegetable raw materials show viscoelasticity under the influence of mechanical stress, which depends both on the applied force and the speed of the load. However, the behaviour can be considered elastic in the first part of the load-strain curve, where the stress-strain relationship is linear under quasi-static conditions [Bentini *et al.* 2009]. Legumes are more susceptible to mechanical damage than cereals and oilseeds. The related monetary losses are much higher compared to similar amounts of cereals because legumes have a higher market price [Szpunar-Krok *et al.* 2021].

Early identification of factors influencing raw material damage enables timely decisions on the specialisation of production to reduce economic losses. In recent years, many studies have been performed on the mechanical properties of various seeds, including legumes [Hashemi, Mousavi 2017; Paixão *et al.* 2017; Shahbazi 2017]. Most of the reports in the professional literature indicate the influence of humidity on the mechanical parameters of seeds of many plant species [Champathi Gunathilake *et al.* 2019; Mishra *et al.* 2019]. The research of other authors also focused on demonstrating the effect of sowing density and row spacing on seed yield and post-harvest quality, and not on the impact of sowing density and row spacing on their mechanical properties. The row spacing determines the spatial distribution of plants in the field, which affects the degree of light, water and nutrient consumption, which is why it is an important element in optimising plant growth, biomass growth and yield. Reducing the row spacing increases the seed yield. In favourable humidity conditions, higher yields can be obtained with a smaller row spacing, while in dry conditions it gives higher yields with a larger row spacing. Hence, the use of an appropriate row spacing, and sowing density is an important tool that allows to maximise the obtained seed yield, and thus reduce production costs [Cox, Cherney 2011; De Bruin, Pedersen 2008; Devlin *et al.* 1995; Randelović *et al.* 2020].

Reducing the row spacing and increasing the seeding density causes the plants to overlap, which reduces the light reaching them and ultimately reduces the rate of photosynthesis [Cheng *et al.* 2020]. With a smaller row spacing and a higher sowing density, mutual shading of plants leads to changes in the spatial structure of the plant population and may affect the quantity and quality of the crop measured by mechanical properties. Therefore, an appropriate row spacing and sowing density in field cultivation of seedlings can improve the morphometric features of plants, contribute to better use of light energy and positively affect the productivity of this species.

The aim of the study was to investigate the effect of different sowing density and different row spacing on the mechanical and morphological features of white lupine seeds. The results obtained can be recognised as useful in the development and optimisation of harvesting, transport and processing of legume seeds. Row spacing determines the spatial arrangement of plants in the field, which influences the degree of light, water and nutrient consumption and is an important tool for optimising plant growth and yield.

MATERIALS AND METHODS

EXPERIMENTAL DESIGN

The field experiment was conducted in 2016–2019 at the Experimental Station for Cultivar Assessment in Przecław (Pol. Stacja Doświadczalna Oceny Odmian w Przecławiu) (south-eastern Poland, 0°110' N, 21°290' E, altitude 185 m a.s.l). The experiment was located in soil originated from clay loam classified as Fluvic Cambisol (CMfv), according to WRB FAO [2014]. The white lupine cv. 'Butan' (HR Smolice, Poland) was used in the experiment. The experiment was carried out as a two-factor split-plot experiment in four replications (24 plots per year with an area of 19.5 m^2 for sowing and 16.5 m^2 for harvesting). The experimental factors were varying row spacing and varying sowing density. The method of sowing seeds in individual variants of the experiment is presented in Table 1.

Table 1. Variants of white lupine sowing

Variant	Row spacing (cm)	Sowing density (plants per m^2)
15/60	15	60
15/75	15	75
15/90	15	90
30/60	30	60
30/75	30	75
30/75	30	90

Source: own elaboration.

Each time the forecrop for the experiment was sugar beet. After harvesting the forecrop, winter plowing was carried out. In the spring, a cultivating unit was used. Subsoil mineral fertilisation was applied before sowing, in accordance with the recommendations for the species (30 kg N·ha^{-1}, 60 kg P_2O_5·ha^{-1} and 80 K_2O·ha^{-1}). The seeds were originally inoculated with *Bradyrhizobium japonicum* and each sowing was made in the third decade of March at a depth of 3–4 cm. After sowing, herbicide spraying was applied (Boxer 800 EC (prosulfocarb) 4 dm^3·ha^{-1}). The seeds were harvested in the phase of technical maturity, each time in the first ten days of August.

WEATHER CONDITIONS

Weather conditions were recorded at the Experimental Station for Cultivar Assessment in Przecław. The weather in the years 2016–2019 was described based on the Sielianinov hydrothermal (K) index (Fig. 1) [Skowera *et al.* 2014] according to the formula:

$$K = \frac{P}{0.1\Sigma t} \tag{1}$$

where: K = value of hydrothermal coefficient, P = monthly sum of precipitation, Σt = monthly sum of air temperatures >0°C from a given month.

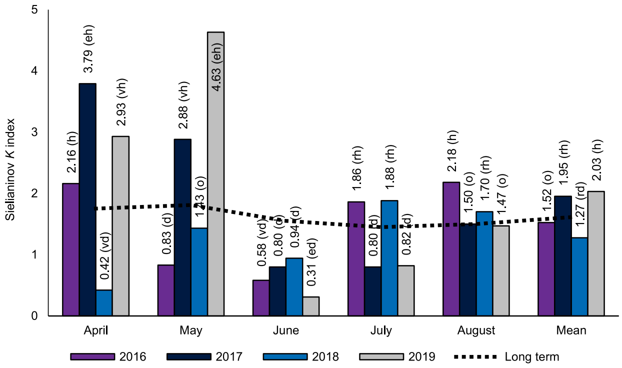


Fig. 1. The hydrothermal index (K) during the growing season of white lupine; Sielianinov (K) index: $K \leq 0.4$ extremely dry (ed), $0.4 < K \leq 0.7$ very dry (vd), $0.7 < K \leq 1.0$ dry (d), $1.0 < K \leq 1.3$ relatively dry (rd), $1.3 < K \leq 1.6$ optimal (o), $1.6 < K \leq 2.0$ relatively humid (rh), $2.0 < K \leq 2.5$ humid (h), $2.5 < K \leq 3.0$ very humid (vh), and $K > 3.0$ extremely humid (eh); source: own elaboration

During the growing season, the weather conditions varied. April 2018 and June 2016 and 2019 were dry, which was reflected in very low hydrothermal index values. In contrast, high rainfall was recorded in April 2017 and May 2019, with the hydrothermal coefficient value being highest in these months. The most favourable hydrothermal conditions were recorded in August 2017, May 2018, August 2019. In synthetic terms, 2016 was optimal, 2017 was relatively humid, 2018 was relatively dry, while 2019 was humid.

SAMPLE PREPARATION AND EVALUATION OF LUPINE SEED PROPERTIES AND COMPRESSION PARAMETERS

Lupine seeds were collected immediately after harvest each time. For each treatment, 15 seeds were randomly selected and the average values of all 15 tests were reported. Desired moisture level (13%) of seeds was reached by adding the calculated amount of distilled water and closing in separate polyethylene bags. The seeds were stored in a refrigerator (5°C, 7 days) to distribute moisture evenly. Before testing, the samples were stored outside the refrigerator to align their temperature with ambient conditions [Gely, Panago 2017; Razari *et al.* 2007]. The seeds have been measured (length, width, and thickness – tolerance 0.01 mm), weighed (tolerance 0.001 g) and then the sphericity factor (sphericity) φ (%) was calculated. The degree of sphericity (φ) is expressed by the equation [Szpunar-Krok *et al.* 2021]:

$$\varphi = \frac{(LWT)^{\frac{1}{3}}}{L} 100\% \tag{2}$$

where: φ = sphericity (%), L = length (mm), W = width (mm), T = thickness (mm).

MEASUREMENT OF MECHANICAL PROPERTIES

The destructive force of seeds was determined using a Zwick/Roell Z020 testing machine (Germany), under quasi-static loading conditions, according to the methodology [Kuźniar *et al.* 2016; Nasirahmadi *et al.* 2014]. The load was applied perpendicularly to the seeds (cotyledon division plane), with a constant speed value v = 0.17 mm·s^{-1}. The seed was compressed between two parallel plates until it breaks. Following parameters indicating the strength of the resistance of the seeds to mechanical damage were investigated: the destructive force F_D causing sample fracture, the maximum deformation D at the moment of fracture (mm), and the destructive energy E_D which destroy the sample (mJ). The relative deformation D_R was calculated as the ratio of the maximum deformation D_R and the thickness of the seed according to formula [Altuntas, Yildiz 2007; Kulig *et al.* 2015]:

$$D_R = \frac{D}{T} 100\% \tag{3}$$

where: D_R = relative deformation (%), D = maximum deformation (mm), T = thickness of seed (mm).

STATISTICAL ANALYSIS

Statistical analysis was performed using the TIBCO Statistica 13.3.0 software (USA). For the results corrected during the experiment, two factor analysis of variance (ANOVA) was performed. In order to compare the mean values Tukey's post-hoc test was performed at the significance level of 5%.

RESULTS AND DISCUSSION

One of the important problems in the cultivation of legumes is the high sensitivity of their seeds to mechanical damage arising during threshing, cleaning, drying, transport, processing and storage, which manifests itself in significant quantitative and qualitative losses [Arevalos *et al.* 2019]. The force-displacement curve at small distortions is determined by the mechanical properties of the skin, but also features of other tissues. There are three main structural factors that influence the mechanical properties of plant materials at the cellular and tissue level: turgor pressure in individual cells (i.e., the force exerted on the cell membrane by the intracellular fluid), the stiffness of the cell wall, and the cell – cell adhesion, determined by the integrity of the middle lamina and plasmodesmata [Alzamora *et al.* 2008]. Early identification of factors damaging plant material allows timely decisions to be made regarding the production course to significantly reduce economic losses [Hashemi *et al.* 2017], and the influence of machine working parts on the properties of the raw material during harvesting, transport, storage, handling, cleaning or processing is extremely significant and has been the subject of research by many scientists [Azadbakht *et al.* 2015; Zhiguo *et al.* 2011].

The interactions between optimising density reduction for better light availability in the canopy and increasing crop density to maximise yield, as well as high seed costs, are part of the main trade-offs to be resolved with innovative production strategies. These parameters can significantly affect canopy architecture, inter-row closure rates or biomass production. In addition, they can influence the reduction of disease and weed severity and the productivity of individual plants [Riberio *et al.* 2017]. In the study presented here, increasing plant density per unit area improved the mechanical properties of the seeds. Selecting the right number of plants per unit area has a positive effect on the technical quality of the seeds, which contributes to improving their quality and enables appropriate control of post-harvest processes.

In the case of the analysed white lupine seeds, significant relationships were found between seed resistance to mechanical damage expressed by F_D, D_R and E_D parameters in individual years of the experiment, taking into account sowing density and row spacing. Synthetically, row spacing was characterised by higher F_D values at 15 cm spacing (Fig. 2.), as confirmed by statistical analysis. Analysis of the results obtained with variable sowing density showed that the highest F_D was recorded for a sowing density of 90 plants per m^2 and the lowest for 75 plants per m^2. Analysing the timing of the experiment, the highest F_D values were recorded in 2017, which was a relatively humid year. Significantly lower values were obtained for the other years of the study. According to De Bruin and Pedersen [2008], under favourable moisture conditions, higher yields can be obtained with smaller row spacing, while under drought conditions yields are higher with greater row spacing, but in the case of lupines in the present experiment, this relationship cannot be clearly confirmed. The lowest F_D values were obtained in 2019, when the seeds were also characterised by the smallest dimensions. The reduction in seed dimensions and increase in sphericity resulted in a reduction in F_D.

In the case of D_R (Fig. 3), seeds obtained in 2018 deformed the most and those obtained in 2016 deformed the least. Synthetically, there were no significant differences between the D_R values and the row spacing used. For sowing density, the highest values were obtained for 90 plants per m^2, while the lowest values were obtained for a spacing of 75 plants per m^2.

When analysing the values obtained for E_D (Fig. 4), there were no significant differences between the row spacings used. In the case of sowing density, a density of 90 plants per m^2 was found to be significantly higher compared to the other variants. The seeds harvested in 2016 had the highest E_D needed to destroy the sample, and significantly lower in the other years of the study.

The variability in the physical properties of legume seeds depends on a number of external factors, as well as their species and variety. Not only the wide range of variation between species, but also between varieties within legume species can have a significant impact on seed mechanical properties [Rybiński *et al.* 2015]. Studies show that there are significant differences between

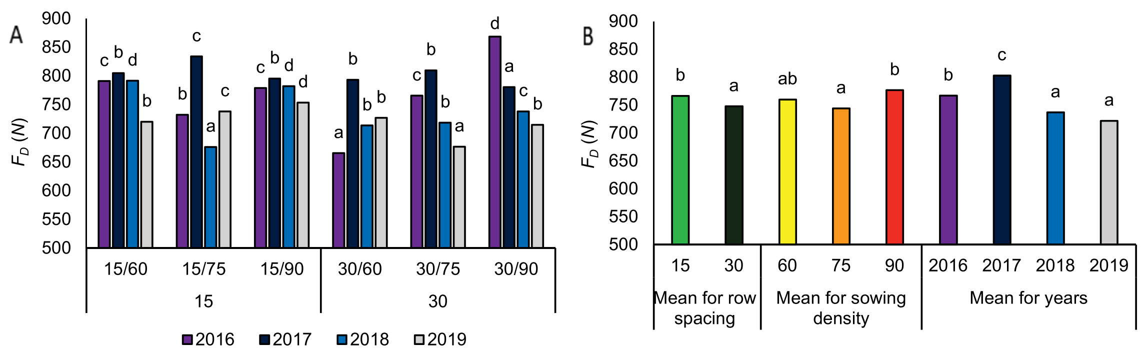
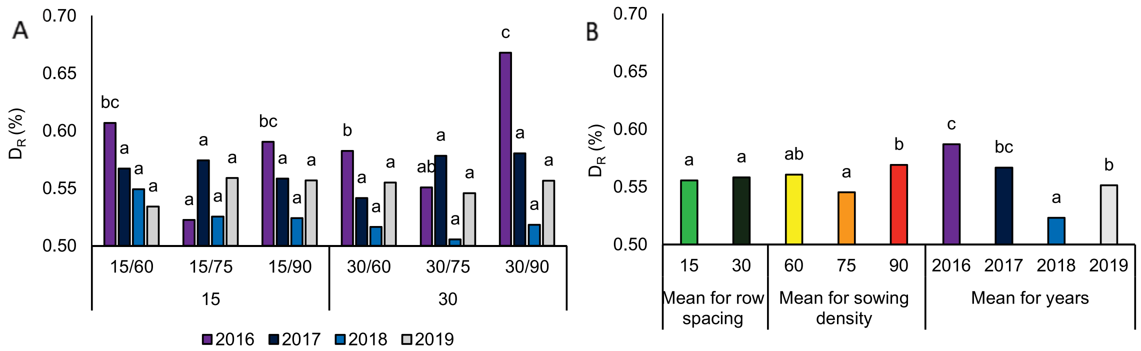


Fig. 2. The value of the destructive force of lupine seeds F_D (*N*) depending on the sowing density and row spacing in the years of research (A); average values of the parameter for the levels experimental factors and years of research (B); data are expressed as mean ±*SD*; different letters show significant differences ($p < 0.05$) according to Tukey's test; source: own study



Fig; 3. The value of the relative deformation of lupine seeds D_R (%) depending on the sowing density and row spacing in the years of research (A); average values of the parameter for the levels experimental factors and years of research (B); explanations as in Fig. 2; source: own study

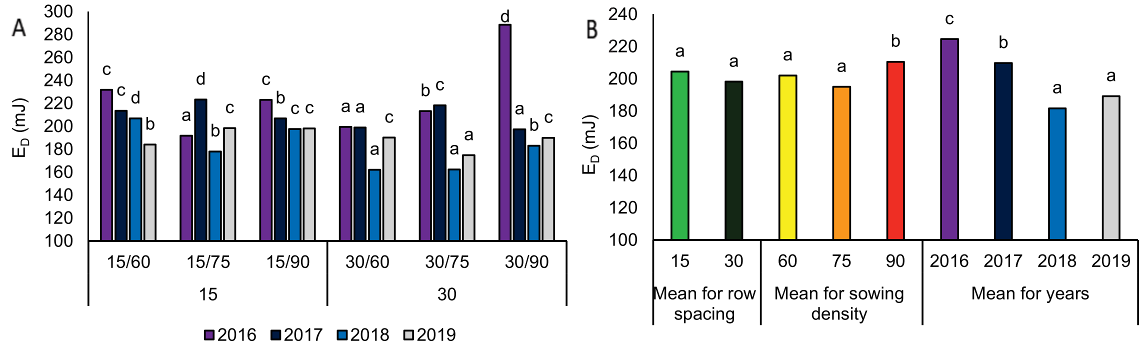


Fig. 4. The value of the destructive energy of lupine seeds E_D (mJ) depending on the sowing density and row spacing in the years of research (A); average values of the parameter for the levels experimental factors and years of research (B); explanations as in Fig. 2; source: own study

breaking strength and deformation resistance values within a species, even with similar geometrical parameters [Rybiński *et al.* 2013; 2014].

In addition to species and varietal factors, the change in mechanical behaviour is influenced by the physical properties of the pressed seeds [Herák *et al.* 2012; Isik 2007]. Heavier seeds were damaged at lower F_D and E_D values and were less deformed. This relationship was shown for different sowing densities, row spacing and years of testing. Kuźniar *et al.* [2013] showed that seeds of varieties belonging to different legume species (narrow-leaf and yellow lupine, faba bean and soybean) with higher weight and thickness were less susceptible to mechanical damage.

The high susceptibility of legume seeds to mechanical damage is mainly due to their structure. Unlike cereal grains, they contain two cotyledons, between which a gap can form at low water content, making them easier to damage, for example by breaking the seed in half. The moisture content of the seed is also a very important factor in the occurrence of seed damage, which affects the elasticity and resistance to damage of not only the cotyledons, but also the seed coat. The size and shape, the thickness of the seed coat and the chemical composition also have a significant effect on the occurrence of seed damage [Kuźniar *et al.* 2013]. Synthetically, row spacing only significantly affected the weight of the analysed lupine seeds. Plants grown at 15 cm spacing were characterised by higher weight. For the other parameters, row spacing had no effect on the physiological properties of lupine. On the other hand, sowing density did not significantly affect the morphological characteristics of white lupine seeds. Meteorological conditions in individual years of the study significantly determined morphological parameters of white lupine seeds. The lowest values for seed weight, length and width were recorded in 2019, while the highest values were recorded in 2017 for weight and in 2016 for width. No significant differences in seed length were observed in the other years of the experiment. For sphericity, an inverse relationship was observed. In 2019, when the seeds had the lowest weight and dimensions, the highest sphericity was recorded. This may be related to the thermal conditions prevailing at the seed formation stage in the pods. The analysed relationships are shown in Table 2. Seed weight, shape and size are important parameters during seed cleaning and transport, and seed shape and physical dimensions are important in sorting, screening and separation processes. The selection of the appropriate number of plants per area unit has a positive effect on the technical quality of seeds, which contributes to the

Table 2. Morphological features of the lupine seed depending on the row spacing (cm), sowing density (plants per m^2) and year of research

Variable						Weight (g)	Dimension (mm)		Sphericity (%)
							length	width	
Year	2016	Row spacing (cm)	15	Sowing density (plants per m^2)	60	344 ±43.5	9.88 ±0.30	9.88 ±0.45	81.0 ±1.80
					75	337 ±47.1	9.89 ±0.36	9.84 ±0.47	80.3 ±2.60
					90	337 ±43.0	9.94 ±0.37	9.90 ±0.42	81.3 ±2.91
			30		60	334 ±58.2	9.77 ±0.47	9.84 ±0.65	81.7 ±1.91
					75	340 ±37.4	10.0 ±0.32	9.93 ±0.43	80.2 ±1.62
					90	321 ±37.0	9.85 ±0.30	9.89 ±0.43	80.1 ±1.44
	2017		15		60	375 ±48.3	10.0 ±0.35	9.00 ±0.40	76.7 ±1.95
					75	388 ±61.3	10.4 ±0.53	9.25 ±0.37	75.6 ±1.83
					90	383 ±46.9	10.3 ±0.46	9.25 ±0.38	76.3 ±2.28
			30		60	378 ±55.2	10.1 ±0.64	9.22 ±0.49	77.1 ±3.45
					75	360 ±44.1	9.96 ±0.41	9.21 ±0.43	79.1 ±4.07
					90	353 ±41.3	9.98 ±0.46	9.18 ±0.35	76.8 ±2.07

cont. Tab. 2

Variable						Weight (g)	Dimension (mm)		Sphericity (%)
							length	width	
Year	2018	Row spacing (cm)	15	Sowing density (plants per m^2)	60	369 ±52.4	9.81 ±0.41	9.11 ±0.34	74.5 ±2.31
					75	371 ±59.7	9.98 ±0.39	9.28 ±0.32	72.6 ±2.74
					90	385 ±41.3	10.1 ±0.47	9.25 ±0.35	74.7 ±2.86
			30		60	377 ±43.5	9.87 ±0.57	9.22 ±0.47	74.6 ±3.44
					75	357 ±40.8	9.96 ±0.42	9.24 ±0.42	75.2 ±3.13
					90	349 ±47.0	10.1 ±0.23	9.15 ±0.34	75.1 ±2.59
	2019		15		60	276 ±42.0	8.83 ±0.50	8.46 ±0.55	80.6 ±2.56
					75	277 ±44.9	8.82 ±0.53	8.55 ±0.45	80.8 ±2.26
					90	278 ±42.1	8.83 ±0.67	8.83 ±0.58	82.0 ±3.82
			30		60	281 ±36.6	8.86 ±0.48	8.82 ±0.58	82.1 ±3.10
					75	283 ±383	8.80 ±0.48	8.79 ±0.67	82.8 ±3.39
					90	280 ±41.3	9.04 ±0.46	8.54 ±0.54	79.8 ±2.62
Mean for row spacing (cm)				15		343 ±43.7[b]	9.72 ±0.19[a]	9.22 ±0.36[a]	78.0 ±3.27[a]
				30		334 ±35.9[a]	9.69 ±0.49[a]	9.25 ±0.44[a]	78.7 ±2.88[a]
Mean for sowing density (plants per m^2)				60		336 ±42.3[a]	9.91 ±0.51[a]	9.38 ±0.48[a]	77.6 ±3.16[a]
				75		339 ±40.1[a]	9.72 ±0.58[a]	9.26 ±0.47[a]	78.3 ±3.45[a]
				90		336 ±25.3[a]	9.76 ±0.53[a]	9.25 ±0.47[a]	78.3 ±2.89[a]
Mean for years				2016		336 ±8.13[b]	9.89 ±0.08[b]	9.88 ±0.04[c]	80.8 ±0.67[b]
				2017		373 ±13.6[c]	10.1 ±0.20[b]	9.19 ±0.09[b]	76.9 ±1.18[a]
				2018		368 ±13.1[c]	10.0 ±0.10[b]	9.21 ±0.07[b]	74.5 ±0.94[a]
				2019		279 ±2.64[a]	8.86 ±0.09[a]	8.67 ±0.17[a]	81.3 ±1.11[b]

Explanations: data are expressed as mean ±*SD* values. Different letters in columns show significant differences ($p < 0.05$) according to Tukey's test.
Source: own study.

improvement of their quality and enables appropriate control of the processes related to harvesting, sorting, cleaning, or transporting seeds. Importantly, optimal selection of row spacing and seeding density can be used as part of an integrated weed control strategy preventing or reducing the production of new seed by weeds that have survived herbicide application or cultivation [Azadbakht *et al.* 2015].

CONCLUSIONS

The row spacing determines the spatial arrangement of the plants in the field, which affects the use of light, water and nutrients and is important for optimising plant growth. The introduction of appropriate species agroecology leads to the optimisation of plant yield. In the study presented here, increasing plant density per unit area improved the mechanical properties of the seeds. For the parameters analysed, the highest destructive force (F_D), relative deformation (D_R) and destructive energy (E_D) values were obtained at a sowing density of 90 plants per m^2. There was no significant effect of row spacing for D_R and E_D. Seeds obtained from plots with a row spacing of 15 cm were characterised by higher F_D values. In addition to plant spacing and sowing density, weather conditions in the individual years of the study were an important factor determining seed properties. However, there was no clear influence of the weather conditions in the individual years of the study on the mechanical properties of the seeds, so further research in this area is necessary. It is also important to supplement the results obtained by comparing them with the relative humidity of the seeds, which significantly determines the quality of the yield obtained and the costs associated with their storage and processing. The results obtained can be successfully used in selecting the appropriate number of plants per unit area, which can positively influence and contribute to the technical quality of the seeds. In addition, this knowledge can enable appropriate control of the processes involved in harvesting, sorting, cleaning or transporting seeds.

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