AGRONOMIC PERFORMANCE OF LINSEED AS A FUNCTION OF PLANT ARRANGEMENT

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ABSTRACT - The objective of this work was to understand the agronomic performance of flaxseed cultivated in different spacings between rows and plant density, identifying associations between traits for indirect selection. The experiment was carried out in the municipality of Augusto Pestana - RS, in the years 2020 and 2021, using a randomized block experimental design organized in a 6x3x2 three-factor scheme, with six sowing densities (30, 60, 90, 120, 150 and 180 plants per linear meter), three spacings between rows (0.18 m, 0.36 m, .0.54 m), and two crop seasons (2020 and 2021). Ten plants were measured in each plot, having evaluated phenotypic characteristics of plant height, height of insertion of the first capsule, number of basal branches, stem diameter, number of branches on the stem, number of main branches, number of capsules, mass of capsules, number of grains per plant, weight of 100 grains and weight of grains per plant. Grain yield is enhanced in row spacing of 18 cm with densities of 74 seeds per linear meter in crops with favorable conditions. In flaxseed, the number of capsules, number of grains and the mass of grains per plant exhibit a linear association with grain yield and can be used for indirect selection.

Key words: *Linum usitatissimum* L., seeding density, row spacing.

DESEMPENHO AGRONÔMICO DA LINHAÇA EM FUNÇÃO DO ARRANJO DA PLANTA

RESUMO - O objetivo deste trabalho foi compreender o desempenho agronômico da cultura da linhaça cultivada em diferentes espaçamentos entre fileiras e densidade de plantas, identificando associações entre caracteres para seleção indireta. O experimento foi conduzido no município de Augusto Pestana - RS, nos anos de 2020 e 2021, utilizando-se delineamento experimental de blocos ao acaso organizado em esquema trifatorial 6x3x2, sendo seis densidades de semeadura (30, 60, 90, 120, 150 e 180 plantas por metro linear), três espaçamentos entre fileiras (0,18 m, 0,36 m, ,0,54m), e duas safras de cultivo (2020 e 2021). Foram mensuradas 10 plantas em cada parcela, tendo-se avaliado caraterísticas fenotípicas de altura de plantas, altura da inserção da primeira cápsula, número de ramificações basais, diâmetro da haste, número de ramificações na haste, número de ramificações principais, de cápsulas, massa de cápsulas, número de grãos por planta, massa de 100 grãos e massa de grãos por planta. Além disso foi estimada a produtividade de grãos e o estande de plantas. A produtividade de grãos é potencializada em espaçamentos entre fileiras de 18 cm com densidades de 74 sementes por metro linear em safras com condições favoráveis. Na cultura da linhaça, o número de cápsulas, número de grãos e a massa de grãos por planta exibem associação linear com a produtividade de grãos e podem ser usadas para seleção indireta.

Palavras-chave: *Linum usitatissimum* L., densidade de semeadura, espaçamento entre fileiras.

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INTRODUCTION

Linseed (*Linum usitatissimum* L.) is an autogamous species of the Linaceae family, characterized by having oleaginous and functional seeds. This crop has great social importance, standing out as a food of plant origin with high levels of fatty acids, high amounts of fiber, proteins and phenolic compounds (Goyal et al., 2014). Linseed oil is rich in alpha-linolenic acid, which represents about 50% of the total fatty acids in the oil, with its contents influenced by the conditions of the growing environment (Zhang et al., 2016). Being the most important fatty acid in linseed oil and seed (Shah et al., 2018).

With 39% of oil in the composition of the seeds, linseed becomes a relevant crop from the point of view of the production of bioenergy and biofuels, which promotes the current increase in its cultivation, as it has characteristics that favor the production of biodiesel and its residue is used in the production of animal feed (Kumar et al., 2018). Fostered by market demand and associated with the economic return of the crop, Brazilian production units increase the cultivation of linseed (IBGE, 2020). However, research and development are still incipient, with a lack of basic scientific information about the crop, such as row spacing and adequate seeding densities. Added to this, there is the need to understand the linear relationships between characters, providing technical subsidies for indirect selection in the development of superior genotypes that can enhance grain yield (Ertiro et al., 2020).

Among the practices used to maximize the agronomic performance of the crop, spatial arrangement of plants with reduction in the row spacing between sowing rows promotes the best equidistance between plants. However, it should be noted that there is a maximum limit of plants in a given space depending on the morphological and physiological adjustment between plants. Grain yield is associated with the incidence of solar radiation, use of photosynthetically active radiation and minimal energy expenditure with respiration, as well as competition between plants for water resources and nutrients (Petter et al., 2016). Thus, knowledge of the optimal plant arrangement is essential to achieve high grain yields in crops. In this sense, the objective of this work was to understand the agronomic performance of the linseed crop grown in different plant arrangements anchored by the variability in the row spacing and in the seeding density.

MATERIALS AND METHODS

The experiment was carried out in the municipality of Augusto Pestana (28º14'S, 52º22'W), in the state of Rio Grande do Sul, Brazil. The soil analysis of the experimental area showed the following characteristics: Clay = 66%; pH = 5.3; SMP index = 5.6; P = 20 mg dm^3; K = 165 mg dm^3; MO = 2.2%; Al = 0.5 cmolc/dm^3; Ca = 3.41 cmolc/dm^3; Mg = 1.25 cmolc/dm^3; Cu = 6.93 mg dm^3; Zn = 1.52 mg dm^3; Mn = 23.3 mg dm^3 and S = 8.7 mg dm^3.

Sowings were carried out on June 3, 2020 and May 30, 2021, simultaneously with sowing fertilization, with application of 300 kg ha^{-1} of N-P-K formula 05-25-25. The topdressing fertilization consisted of 100 kg ha^{-1} of nitrogen in the amide form. The phytosanitary managements were carried out in a preventive way to minimize the biotic effects on the results of the experiment.

The experimental design used was randomized blocks organized in a factorial scheme, with six seeding densities (30, 60, 90, 120, 150 and 180 seeds per linear meter) x three row spacing (Arrangement I: 0,18 m, Arrangement II: 0,36 m, and Arrangement III: 0,54 m) x two crop yields (2020 and 2021), with treatments arranged in four replications. The experimental units were ten meters long and five meters wide, totaling 50 m^2. 10 plants were randomly collected per experimental unit (1,440 plants) to measure plant height (PH, cm), height of insertion of the first capsule (HIFC, cm), number of basal branches (NBB, unit), stem diameter (SD, mm), number of stem branches (NSB, unit), number of productive branches (NPB, unit), number of capsules (NCAP, unit), mass of capsules (MCP, g), number of grains per plant (NGPP, unit), hundred grain weight (HGW, g), weight of grains per plant (WGPP, g) and plant stand (STAND, plants m^2). During the harvest period, the grain yields (GY, kg ha^{-1}) of the experimental units were evaluated by harvesting the four central lines of each experimental unit with weight of grains adjusted to 13% moisture and weighted by the final stand of plants. Meteorological data distributed by the variables medium air temperature (Tmed, ºC), maximum air temperature (Tmax, ºC), minimum air temperature (Tmin, ºC) and rainfall (Prec, mm) were obtained.

The data obtained were submitted to the assumptions of normality of errors by Shapiro Wilk test and homogeneity of residual variances by Bartlett, and then the analysis of variance was performed at 5% of significance by F test. Main effects and effects of interaction of the quantitative factors were submitted to regression analysis with the adjustment of the highest degree of polynomial. Tukey's test was applied at 5% probability to compare the means of qualitative treatments. With the need to understand the linear relationships between measured variables, a linear correlation analysis was performed with a significance of 5% by T test. The analyzes were performed using R software (R Core Team, 2021).

RESULTS AND DISCUSSION

Higher average temperatures were observed during flaxseed cultivation in 2021, mainly from August onwards, compared to the 2020 crop (Figure A and D). A similar trend is observed in the occurrence of the maximum mean air temperature, where in the 2021 crop there were temperatures above 27.5 °C in the reproductive stage of the crop, while in the 2020 crop the maximum temperature did not exceed 25.5 °C (Figure B and E). Likewise, a higher minimum average temperature was observed in the 2021 crop, reaching temperatures close to 15 °C, while in the 2020 crop there were temperatures below 12 °C (Figure C and F). However, it is possible to observe the occurrence of the highest number of days with minimum temperature below 0 °C in the 2020 harvest. Therefore, rainfall was higher in the months of June and July in 2020 concomitant with the vegetative period of the crop, which is favorable for the development of linseed plants (Figure 1G). In 2021, due to the low rainfall, mainly in the month of July, there were plants with inferior morphological characteristics (Figure 1H). Water deficit decreases the photosynthetic rate, multiplication and cell expansion, which promotes reduced growth and influences plant development (Taiz et al., 2017).

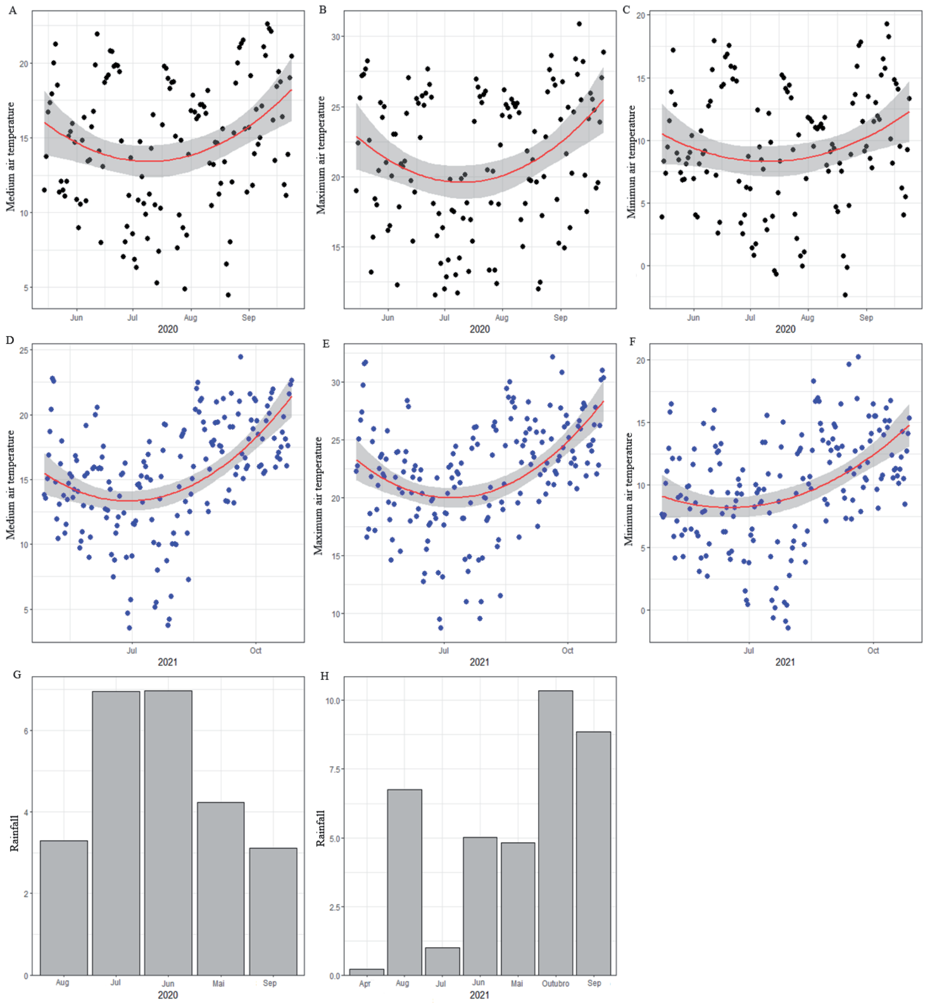

Figure 1 **-** Descriptive analysis of meteorological variables during the 2020 and 2021 crop yields.

The analysis of variance revealed a significant effect for the interaction between crop yields x row spacing x seeding densities for grain yield (Table 1). There were interactions between crop yields x row spacing and row spacing x seeding densities for stem diameter and number of stem branches. A significant effect of the harvest was observed for all the variables measured, being the factor that culminated in the greatest contribution to the effects of the interaction. The linseed crop, due to fluctuations in meteorological variables between crops, justifies the need to consider several crops to infer about the stability of the characters of interest (Stanck et al., 2017).

The coefficient of variation of the six characters ranged from 4,15% (hundred grain weight) to 32.68% (number of stem branches). The coefficients of variation are in agreement with previous research that showed coefficients of variation from 11,44 to 45,57% in the linseed crop (Rossi et al., 2014). For Cargnelutti Filho et al. (2016), this coefficient reached 48,30% of variation for the same crop. The coefficients of variation between plants, in relation to the characters evaluated, grant suitability for the study of seeding densities and row spacing, as well as linear correlation analysis. Thus, in relation to the adequate variability of the data, associated with the expressive number of plants evaluated (1,440 plants), it can be understood that the database offers reliability to the study of regressions and linear relationships between the variables.

Table 1 - Summary of analysis of variance for the three row spacing x six linseed seeding densities x two crop yields.

AV	DF	Mean square					
		HIFC	PH	SD	HGW	NSB	GY
Blocks	2	85.14*	34.77	0.14219	0.00106	3.21	29232.73
Crop yields (CY)	1	6888.02*	5036.16*	1.41*	1.02*	1139.88*	2591491.25*
Row spacing (RS)	2	9.65	22.75	0.05	0.00065	5.12	122136.93
Seeding densities (SD)	5	35.48	85.77	0.54*	0.00014	16.58*	126761.57
CY*RS	2	39.42	55.84	0.05	0.00031	13.84*	1015121.98*
CY*SD	5	46.17	104.98	0.30*	0.00062	12.99*	222756.93
RS*SD	10	20.19	49.94	0.26*	0.00033	1.80	109700.73
CY*RS*SD	10	13.19	36.23	0.06	0.00033	2.49	199812.99*
Residue	70	23.85	47.26	0.13	0.00036	4.22	97386.97
Total	105						
CV (%)		8.81	9.95	17.02	4.15	32.68	29.58

*significant at 5% probability by F test. CV: coefficient of variation. PH: plant height, HIFC: height of insertion of the first capsule, SD: stem diameter, HGW: hundred grain weight, NSB: number of stem branches, GY: grain yield.

In 2020, the height of insertion of the first capsule, plant height and hundred grain weight (Table 2) showed superiority. This was a result of the better distribution of rainfall in this season, as well as the accumulated volumes in June and July directly directed to the crop yield. Linseed cultivation in the Northwest Region of Rio Grande do Sul is affected by several meteorological variables, with low rainfall being the main limiting factor for the development of the crop.

For the simple effects of the crop yields x row spacing interaction (Table 2) it is observed that there was a positive effect of the 2020 season on the morphological aspects of the branches regardless of row spacing (8,65 to 10,60 branches). Arrangement I in the 2020 crop provided a greater number of stem branches due to less intraspecific competition of plants in the sowing line. However, arrangement III did not differ statistically from the other spacing, indicating high culture plasticity. In the 2021 crop, the row spacing did not differ statistically for the magnitude of branching on the stem. Santos et al. (2014) showed superior responses in the number of branches at lower plant densities. Flaxseed has the ability to compensate for low densities when there is a greater spacing between rows, increasing the number of branches (Hassan and Leitch, 2001; Gabiana et al., 2005).

The stem diameter was modified by arrangements II and III at a density of 30 seeds per linear meter. However, plants with larger stem diameters were observed in the two smallest row spacing at a density of 60 seeds per linear meter. The favorable environmental conditions favored the number of branches in 2020 regardless of seeding densities, as well as the stem diameter was inversely proportional to the increase in population of plants. Gabiana et al. (2005) also reported that the expression of the number of branches was potentiated in a cultivation environment favorable to the development of the crop. In addition, they showed a linear increase in stem diameter at lower sowing densities. Similarly, Rossi et al. (2014) describe that the stem diameter tends to be maximized at lower plant densities.

Table 2 - Means comparison test for main effect of crop yields and simple effects of crop yields x row spacing, row spacing x seeding density and crop yields x seeding densities.

Crop Yields	Height of insertion of the first capsule (cm)	Plant height (cm)	Hundred grain weight (g)
2020	63.41 a	75.95 a	0.55 a
2021	47.44 b	62.29 b	0.36 b

Number of stem branches

Crop Yields	Row spacing		
	Arrangement I	Arrangement II	Arrangement III
2020	10.60 aA	8.65 aB	9.35 aAB
2021	2.72 bA	3.16 bA	3.22 bA

Stem diameter (mm)

Spacing	Seeding density					
	30	60	90	120	150	180
Arrangement I	1.96 b	2.50 a	2.18 a	2.17 a	2.11 a	1.70 a
Arrangement II	2.61 a	2.34 ab	1.92 a	2.08 a	2.11 a	1.89 a
Arrangement III	2.31 ab	1.93 b	2.22 a	2.09 a	2.19 a	1.79 a

Stem Diameter (mm)

Crop Yields	Seeding density					
	30	60	90	120	150	180
2020	2.59 a	2.4 a	2.13 a	2.04 a	2.33 a	1.9 a
2021	1.99 b	2.11 a	2.09 a	2.19 a	1.94 b	1.69 a

Number of stem branches

Crop Yields	Seeding density					
	30	60	90	120	150	180
2020	12.39 a	10.08 a	9.98 a	7.77 a	9.48 a	7.46 a
2021	3.11 b	3.00 b	3.33 b	3.22 b	3.00 b	2.55 b

Lowercase letters compare column averages and uppercase letters compare row averages. Significant at 5% probability by Tukey test.

For grain yield in 2021, regardless of spacing and seeding densities used, the highest averages were observed (Table 3). The higher water supply in the period most required by the crop promoted the number of capsules and weight of grains per plant. In 2020, productivity was stable between all spacing and densities of 30, 60, 90 and 150 plants per linear meter. However, specificity was expressed in arrangements I and II, which potentiated productivity when using 120 seeds per linear meter. In 2021, it is evident that, regardless of seed spacing and densities, grain yield did not differ in most spacing and seeding densities. However, superiority was established in arrangement I, using 90 seeds per linear meter. These results corroborate those found by Muraro et al. (2018), who reveal higher linseed productivity in smaller spacings between rows. Also, according to the same authors, a better arrangement of plants improves the spatial distribution of leaves and roots of the crop, reducing intraspecific competition. In this situation, the ability to intercept solar radiation and the use of water and nutrients is potentiated by plants, which promotes greater photosynthetic capacity (Taiz et al., 2017), maximizing grain yield.

Table 3 - Test of comparison between means for interaction between crop yields, row spacing and seeding densities for linseed grain yield.

Seeding density	Crop yields					
	2020			2021		
	Row spacing					
	Arrangement I	Arrangement II	Arrangement III	Arrangement I	Arrangement II	Arrangement III
30	1214.87 aA	837.33 bA	893.85 aA	1070.69 aA	1346.08 aA	1243.62 aA
60	744.29 bA	800.00 aA	689.73 bA	1469.24 aA	1281.64 aA	1610.42 aA
90	1113.33 bA	977.54 aA	868.05 bA	1649.39 aA	905.57 aB	1398.92 aAB
120	1171.54 aA	985.56 aAB	477.93 bA	929.89 aA	1458.56 aA	1325.09 aA
150	1127.77 aA	917.74 aA	818.91 aA	747.92 aA	1128.18 aA	1280.16 aA
180	1479,25 aA	631.54 aB	455.54 bB	476.79 bA	1061.50 aA	1127.66 aA

Lowercase letters compare row spacing within the crop yields and seeding densities combination. Capital letters compare in row crop yields within the combination of row spacing and seeding densities. Significant at 5% probability by Tukey test.

From this perspective, the year 2020 reduced the stem diameter and the number of stem branches in the same direction as the seeding density is increased (Figure 2A and D), these variables being potentiated when using 30 seeds per linear meter. Therefore, when using low seeding densities in crops with well-distributed rainfall and maximum temperatures of 20 to 26ºC, the diameter and number of branches on the stem and the indirect production capacity of the plants are potentiated, as well as lower probabilities of lodging. These results agree with those evidenced by Gabiana et al. (2005) in which they observed an increase in the stem diameter at lower sowing densities. Rossi et al. (2014), although using seeding densities that do not reflect the densities used in the crops, showed a greater stem diameter with a density of 117 plants m^2.

Arrangement I results in the maximum stem diameter concomitant with the seeding density of 90 seeds per linear meter (Figure 2B). This indicates the best fit of plants to minimize lodging and maximize tolerance to plant tipping, which will result in better conditions to support productive branches and capsules per plant. Arrangement II (Figure 2C) together with the increase in seeding density decreases the stem diameters. This indicates that there is greater competition between plants in the seeding row due to the number of plants, since to maintain the seeding density increasing the spacing it is necessary to use a greater number of seeds per linear meter. This scenario tends to potentiate the lodging of plants, due to the lower carrying capacity of the stems of smaller diameter, promoting a reduction in grain productivity.

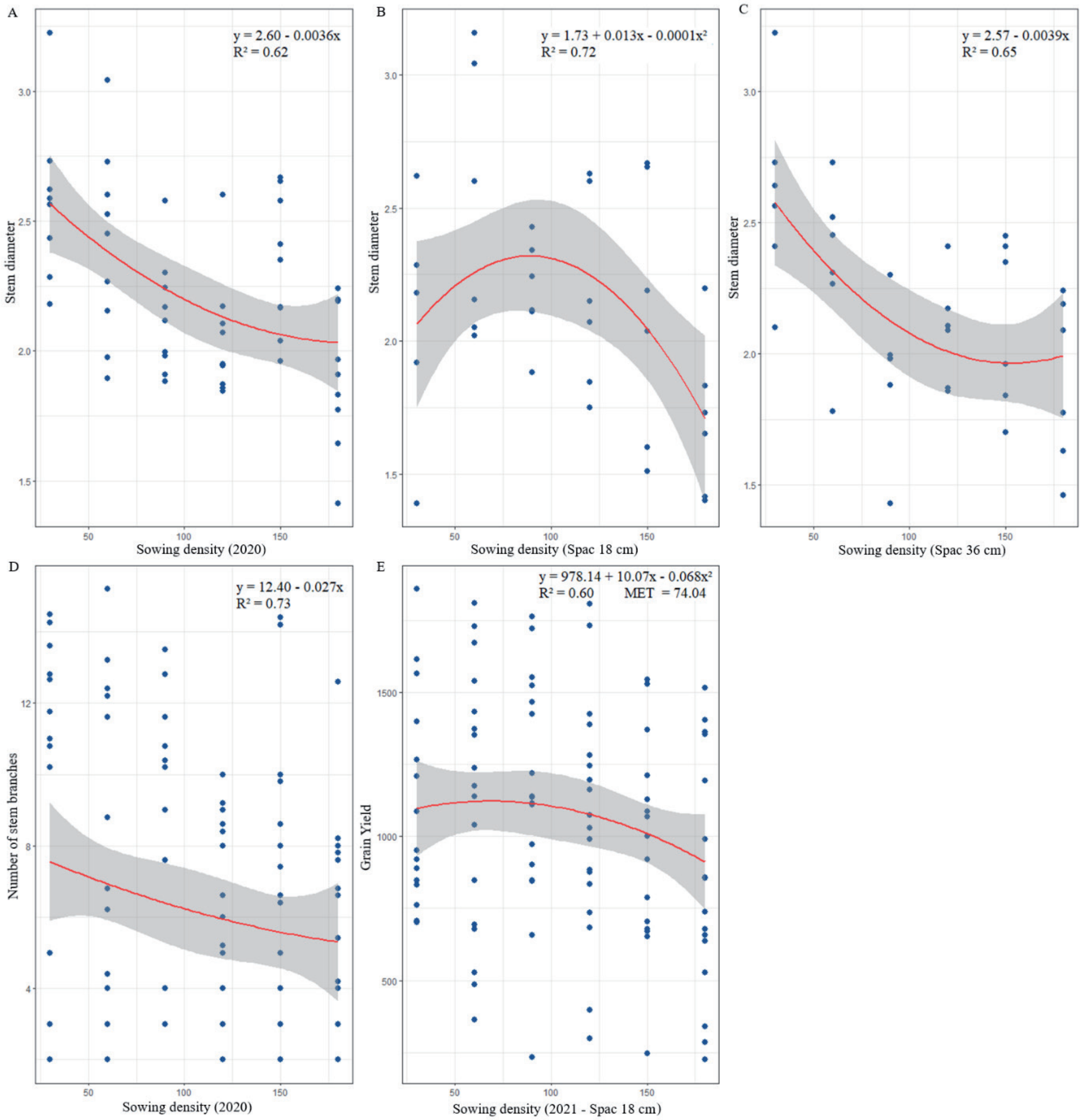

Figure 2 - Regressions for the effects of interactions for stem diameter (A, B and C), number of stem branches (D) and grain yield (E) in linseed. R^2: coefficient of determination, MET: maximum technical efficiency.

Maximum yields in 2021 were obtained in arrangement I and at the seeding density of 74 seeds per linear meter, which resulted in 1,350 kg ha^{-1} of grains. Similar results were evidenced by Muraro et al. (2018), where arrangement I enhanced linseed grain yield (Figure 2E). Santos et al. (2014) revealed similar results, in which all flaxseed grain yield components tend to be potentiated in lower row spacing. Silva et al. (2019), attribute this increase in smaller spacings to less competition for water, radiation and nutrients between plants in the seeding row. Therefore, determining the ideal spacing that combines increased values of productivity components and number of plants is essential for the success and profitability of flaxseed. In view of the above, it can be inferred that under conditions of smaller row spacing, it is recommended to use lower seeding densities, reducing competition between plants in the sowing line, mainly for water and nutrients. In addition, the greater proximity between plants in arrangement I tends to favor faster soil cover, promoting soil moisture retention and, mainly, the suppression of invasive plants, especially *Brassica rapa* and *Conyza bonariensis*, considered difficult to control because of the few alternatives. Lower seeding densities show better distribution of plants in the row, which minimizes the effects of intraspecific competition between plants and, thus, can explain the higher agronomic performance of linseed plants under these conditions associated with lower row spacing. These results corroborate those of Muraro et al. (2018), in which they showed a greater productive potential of flaxseed in smaller spacings between rows. Farinelli et al. (2012) and Vazquez et al. (2012) also showed that corn grain yield was potentiated in reduced row spacing attributed to equidistant distribution of plants.

The linear correlation between linseed characters, as well as meteorological variables (Figure 3) ranged from -0,53 to 0,95, revealing positive and negative associations that confirm the existence of patterns in the linearity of responses. The estimation of these coefficients for traits of interest to genetic improvement facilitates identification of promising genotypes, where it becomes possible to use their results for indirect selection (Carvalho et al., 2015). Linear relationship studies are currently applied in soybean (Loro et al., 2021a), corn (Carvalho et al. 2021), wheat (Loro et al., 2021b) and oat (Verdi et al., 2019), providing relevant information for indirect selection. However, there is still little information in this area, addressing the linseed crop.

In this sense, it is evident that the height of plants and insertion of the first capsule reveal a positive linear association with all agronomic characters of the crop. Similar results were observed by Cargnelutti Filho et al. (2016), where they showed coefficients of 0,44 and 0,40 between plant height and number of branches and between plant height and number of capsules, respectively. On the other hand, plant height and insertion of the first capsule show negative associations with grain yield, which indicates that linseed plants with high heights and insertion of the first capsule express lower grain yields. This result can be explained by the trend towards higher levels of lodging in tall plants. All morphological and productive characters of the crop exhibit positive relationships and coefficients between 0,25 and 0,95. In turn, grain yield tends to be positively related to the number of capsules, number of grains, weight of grains per plant and plant stand.

Therefore, these results suggest that linseed plants with a higher number of capsules, number of grains and weight of grains per plant associated with a higher plant stand potentiate the crop's grain yield. Thus, selection based on these characters can be a reliable approach for the development of genotypes with superior agronomic performance. Reddy et al. (2013), Tariq et al. (2014) and Siddiqui et al. (2016) also identified positive associations of grain yield with the number of capsules per plant.

In general, the stand of linseed plants showed a negative linear association with all agronomic characters. Therefore, these results suggest that high seeding densities reduce the morphological potential and expression of traits associated with grain yield. This confirms the results obtained in the linear regression analysis for the stem diameter and the number of branches, emphasizing the need to understand the seeding densities and the adequate row spacing for linseed.

A positive association between maximum temperature, medium air temperature and the weight of grains per plant was verified, it is inferred that there is a tendency for linseed grain yield to be dependent, mainly on these meteorological variables. Rainfall exhibits a positive relationship with plant height and stem diameter, thus it is understood that environments with favorable conditions of rainfall tend to enhance the height of linseed plants, not only because of the greater availability of water, but also increased absorption of nitrogen and other nutrients.

Due to the availability of soil resources and the need for a larger stem diameter to support tall stature, plants tend to potentiate the production of cellulose microfibrils, included in a matrix of pectins and hemicelluloses, to increase wall rigidity cell growth and secondary stem growth (Taiz et al., 2017). Thus, a positive correlation of stem diameter with plant height and rainfall is evidenced.

For linseed cultivation, it is suggested to use arrangement I with a density of up to 74 seeds per linear meter. In this scenario, in addition to enhancing the characteristic of interest, there is a lower cost in the acquisition of seeds, greater suppression of invasive plants and efficiency in the use of nitrogen, due to the better distribution of plants in the cultivation area. Few studies are reported on the linear relationships between morphological and productive characters of linseed. Thus, in addition to evidencing the associations to promote the indirect selection of genotypes, it is worth mentioning that if there is a linear relationship, mainly between the number of capsules per plant and grain yield, indirect selection is possible, without the destruction of the plants and in an anticipated.

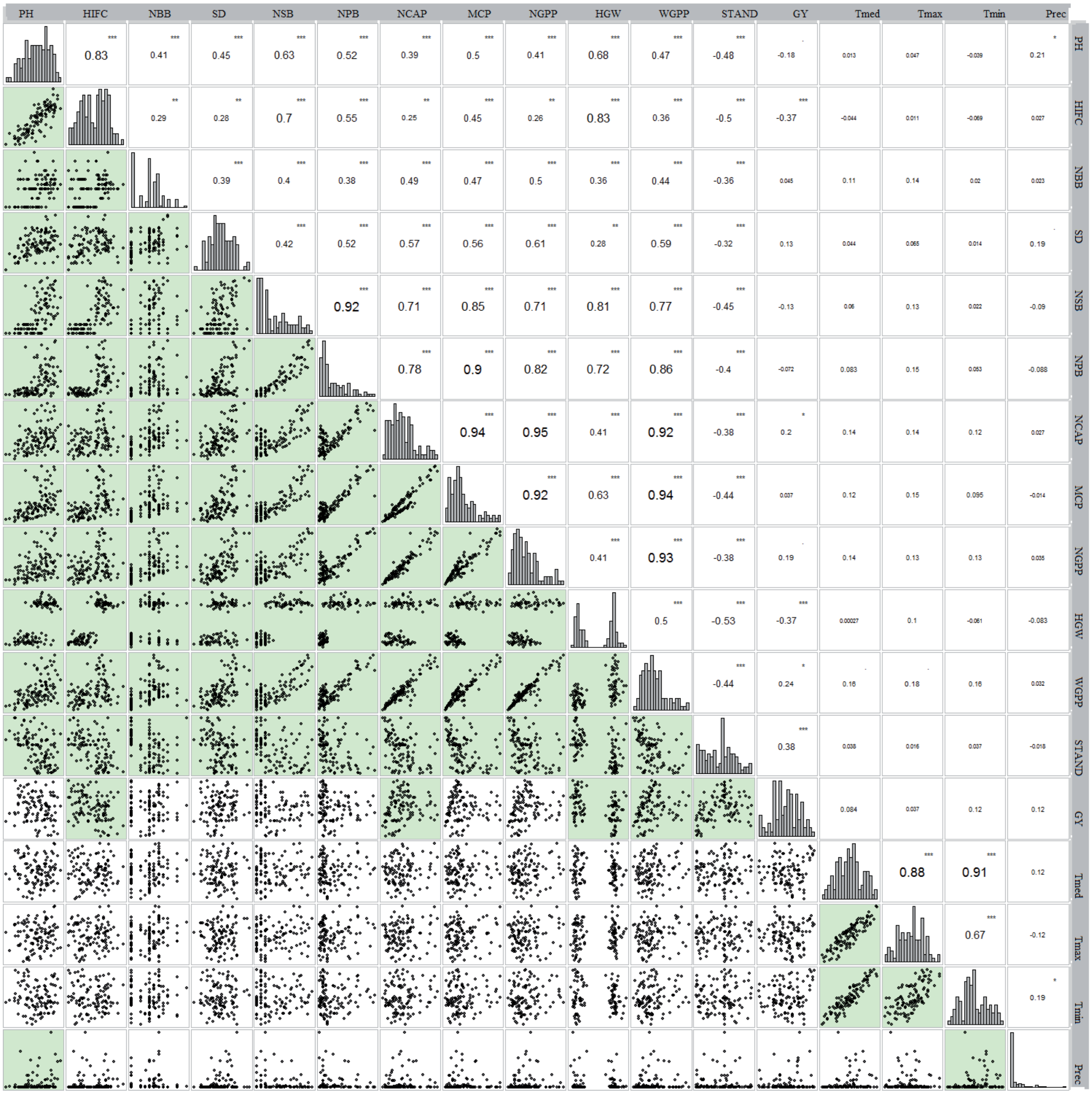

Figure 3 - Pearson's linear correlation (n=1440), significant at 5% by *Student's* T test, for variables.

CONCLUSION

Grain yield is enhanced in arrangement I with densities of 74 seeds per linear meter.

In linseed, the number of capsules, number of grains and the weight of grains per plant exhibit a linear association with grain yield and can be used for indirect selection.

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