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Agronomic performance and yield stability of yellow flax genotypes in the state of Santa Catarina, Brazil

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Abstract – The objective of this work was to evaluate the performance and yield stability of yellow flax genotypes, as well as to identify the best ones for breeding. Nineteen lines and a local variety were cultivated in the 2018, 2019, and 2020 crop seasons in two environments (municipalities) in the state of Santa Catarina, Brazil. Number of capsules per plant, plant yield, grain yield, and final stand were determined. Data were analyzed across genotypes within each environment and across environments within genotypes. Genotype × environment interactions were evaluated by a joint analysis, in which stability and adaptability parameters were estimated. Correlations between final plant stand and yield components were also estimated. There is a high variability in the productive performance among genotypes. The genotype × environment interactions influenced plant traits. The effect of factors related to soil, climate, and population density on number of capsules and grain weight must be considered. The flax genotypes present high grain yield means in all environments. The analysis of stability and adaptability reveals that genotypes LINPG87 and LINPG88 stand out in productive performance and stability.

Index terms: *Linum usitatissimum*, correlation, cultivars, genetic interaction.

Desempenho agronômico e estabilidade produtiva de genótipos de linho amarelo no estado de Santa Catarina, Brasil

Resumo – O objetivo deste trabalho foi avaliar o desempenho e a estabilidade produtiva de genótipos de linhaça amarela, bem como identificar os melhores para seleção. Dezenove linhagens e uma variedade local foram cultivadas nas safras de 2018, 2019 e 2020, em dois ambientes (munícipios) no estado de Santa Catarina, Brasil. Foram determinados número de cápsulas por planta, rendimento de plantas, rendimento de grãos e estande final. Os dados foram analisados entre genótipos dentro de cada ambiente e entre ambientes dentro dos genótipos. As interações genótipo × ambiente foram avaliadas por análise conjunta, em que foram estimados os parâmetros de estabilidade e adaptabilidade. Também foram estimadas as correlações entre o estande final de plantas e os componentes da produção. Há alta variabilidade no desempenho produtivo entre os genótipos. As interações genótipo × ambiente influenciaram as características das plantas. Deve-se considerar o efeito de fatores relacionados ao solo, ao clima e à densidade populacional sobre o número de cápsulas e o peso de grãos. Os genótipos de linho apresentam elevados rendimentos médios de grãos em todos os ambientes. A análise de estabilidade e adaptabilidade revela que os genótipos LINPG87 e LINPG88 se destacam em desempenho e estabilidade de produção.

Termos para indexação: *Linum usitatissimum*, correlação, cultivares, interação genética.

Introduction

Flax or linseed (*Linum usitatissimum* L.) is a dual-purpose winter crop with stems used for the extraction of textile fibers and oil-rich seeds for human consumption and oil extraction (Saleem et al., 2020). The crop is known for its high-quality oil and its use as a raw material in agroindustries (Terfa & Gurmu, 2020).

In the past, the flax crop had a great economic importance in Southern Brazil, but was replaced by wheat (*Triticum aestivum* L.) in the 1980s (Tomasini, 1980). However, currently, flax has regained prominence in locations in this region as a low-cost crop suitable for cultivation during the fallow period of summer crops, such as soybean [*Glycine max* (L.) Merr.] and corn (*Zea mays* L.). Despite this, there is a lack of flax cultivars adapted to the South of the country. To address this issue, flax breeding programs have sought to select superior genotypes (Bosco et al., 2021).

In Brazil, average production is 953 kg ha^{-1} (FAO, 2021), below that of 1,099 kg ha^{-1} of Argentina, the greatest flax producer in South America, and of 1,432 kg ha^{-1} of Canada, the main producer worldwide (Saleem et al., 2020). Yield gains can be achieved by the selection of genotypes with a greater yield stability and adaptation to local environmental conditions. Since flax shows a high variability regarding agronomic traits such as plant height, flowering and maturity stages, number of capsules per plant, yield per plant, and yield per area (Kumar et al., 2021; Fioreze et al., 2022), a strategy used by genetic improvement programs is the estimation of genetic variability.

In breeding programs, information on genotype × environment interactions is crucial for the phases of cultivar selection and recommendation, which is a challenging task for breeders who work with comparative tests since, the greater the interactions between genotypes and environments, the greater the importance of interaction effects (Borém & Miranda, 2017). However, to obtain detailed information on the performance of each genotype regarding environmental variations, adaptability (responsiveness to environmental stimuli) and yield stability (behavioral predictability) are also key parameters used for the identification, selection, and recommendation of superior genotypes (Cruz et al., 2012). Therefore, selected genotypes should have high mean yields and stability or predictable behavior in different environments.

The parameters of interest can be estimated by different methods, such as that of Lin & Binns (1988) used by breeders due to its easy interpretation and reliable results. Lin & Binns (1988) proposed a nonparametric approach to estimate a measurement (P_i) that represents the superiority of a genotype in a set of environments, in which P_i describes the performance of a given genotype compared with a superior genotype in each tested environment. According to Cruz et al. (2012), genotypes with a good adaptability and yield stability are the ones with the lowest P_i estimates and a low contribution of the i-th genotype to the genotype × environment interaction.

The objective of this work was to evaluate the performance and yield stability of yellow flax genotypes, as well as to identify the best ones for breeding.

Materials and Methods

The experiments were performed in two municipalities in the state of Santa Catarina, Brazil: in Curitibanos, in the 2018, 2019, and 2020 crop seasons; and in Campos Novos, only in 2020. The municipality of Curitibanos is located in one of the two microregions of the Serrana mesoregion of Santa Catarina (at 1,040 m above sea level), also called Curitibanos, whereas Campos Novos is located in the Curitibanos microregion (at 947 m above sea level), 72 km away from the municipality of Curitibanos. In Curitibanos, the soil is a Cambissolo Háplico, and, in Campos Novos, a Cambissolo and Nitossolo Vermelhos according to the Brazilian soil classification system (Santos et al., 2018). The climate in both experimental sites is of the Cfb type according to Köppen.

The experimental sites were sowed with soybean or corn as summer crops under a no-tillage system. Soil acidity was corrected based on the soil analysis, and fertilization followed the recommendations for the flax crop (Manual..., 2016).

For the experiments, 19 lines (genotypes) from a participatory breeding program, involving local farmers, agricultural extension companies, and plant breeders, plus a locally grown variety (Common yellow), were used. The lines present a desirable performance for cycle duration, plant height, and

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resistance, but it is still necessary to identify those that stand out in terms of yield components, which is the focus of the present study.

In Curitibanos, the experiments were installed in 6/2/2018, 6/11/2019, and 7/3/2020. In Campos Novos, the experiments were installed in 6/29/2020. The experimental design was a randomized complete block with three replicates. Each plot consisted of a row with a length of 2.0 m, in 2018 and 2020, or of 1.0 m in 2019. Sowing was carried out at a spacing of 0.34 m between rows, at two different densities: 1,470,000 seeds per hectare in 2018 and 2,940,000 seeds per hectare in 2019 and 2020.

Data on emergence, flowering, and maturation date were used to determine cycle duration, expressed as mean values. The genotypes were evaluated for the following traits: number of capsules per plant, plant yield (g), grain yield (kg ha^{-1}), and final stand density (plants per square meter). The assumption of homoscedasticity, normality of residuals, and independence of residuals was checked using the tests of Bartlett, Lilliefors, and Durbin-Watson, respectively, all at $\alpha = 0.05$. The data of each environment was subjected to the one-way analysis of variance (ANOVA). Significance was tested using the F-test, at $\alpha = 0.05$ and $\alpha = 0.01$. The data were also subjected to factorial ANOVA. Genotypic variance, genotype × environment interaction variance, and heritability coefficients were estimated using the mathematical expectations of mean squares. Correlations between final plant stand and yield components were obtained by the t-test, at $\alpha = 0.05$. In addition, adaptability and stability parameters were estimated by the Lin & Binns (1988) method, and analyses were performed by the Genes software (Cruz, 2001).

Results and Discussion

Genotypes emerged at 8 days after sowing in 2018 and 2019 and 10–12 days after sowing in 2020. The environment in which the crops emerged later had lower temperatures than those in which seed germination occurred faster (Figure 1). Casa et al. (1999) concluded that air temperatures from -7 to -4°C during the germination stage can inhibit emergence due to seed freezing, which was not the case in the present study, in which temperatures remained above 5°C during seed germination. Guo et al. (2012) added that water deficit inhibits plant development, especially of the root system, which did not occur in any environment in this stage of the flax crop cycle (Figure 1).

Flowering began 58–74 days after emergence, with the latest flowering date observed in plants sown earlier in Curitibanos, in 2019. In the 2020 crop season in Curitibanos, characterized by low temperatures, seeds were sown at a later date, which resulted in a shorter interval between emergence and flowering, as well as in a shorter cycle duration (Figure 1). Darapuneni et al. (2014) found that flowering in flax is highly influenced by interactions between environmental conditions (such as photoperiod and vernalization) and genotype. Although flax plants do not necessarily require vernalization for flowering induction (Bosco et al., 2021), low temperature conditions typically reduce the number of days to flowering, particularly when associated with long photoperiods (Darapuneni et al., 2014), despite the facultative response of the plant to photoperiod (Sun et al., 2019). Therefore, a delay in sowing tends to shorten the whole developmental cycle, including the vegetative stage (Mirzaie et al., 2020). In 2020, between emergence and flowering, rainfall was higher in Curitibanos than in Campos Novos (Figure 1). Čeh et al. (2020) concluded that flax varieties used for oil production have a low water requirement of 450 to 750 mm of rain evenly spread throughout the growing season, which was reached only in one of the environments although all the others presented values close to this threshold (Figure 1).

The longest period between flowering and maturation was observed in Curitibanos, in 2019, probably due to the greater rainfall volumes and higher temperature variations in the environment (Figure 1). During this period, high amounts of rainfall can promote the development of new shoots and lead to uneven maturation, whereas water deficit, in the reproductive stage, causes flower abortion, reducing the number of capsules per plant and seeds per capsule (Bosco et al., 2021). Čeh et al. (2020) also found that water shortage affects flax seed yield, shortening the plant growth cycle, and that weather conditions could greatly impact the length of the crop growing season.

The duration of the period from emergence to maturity ranged from 117 to 150 days for plants sown late and early, respectively (Figure 1), with shorter cycles in the environments with a reduced rainfall between flowering and maturation. In the literature, shorter crop cycles were reported in Ethiopia (Terfa & Gurmu 2020), with durations similar to those observed in Brazil by Casa et al. (1999) and Bosco et al. (2021). These are important results since longer cycles can impact the planting schedule of subsequent crops.

For an optimal plant development, thermal limits should also be considered (Bosco et al., 2021). However, in the case of flax, these limits are not clearly defined, varying according to genotype. Therefore, studies explaining environmental and genotypic effects are crucial for the advancement of flax production in Brazil.

The yellow flax genotypes differed significantly for all evaluated traits and showed different behaviors in different environments, as indicated by the significance of the genotype × environment interaction (Table 1). This result reflects the sensitivity of the genotypes to differences in environmental conditions, such as locations and crop seasons. Therefore, knowledge of the significance and strength of the genotype × environment interaction is important because these parameters influence heritability estimates and, consequently, the genetic gains expected from selection (Cruz et al., 2012). Previous studies reported the occurrence of genotype × environment interactions on flax grain yield components in Chile (Berti et al., 2010), India (Paul et al., 2015), and Slovenia (Čeh et al., 2020). However, in Brazil, there is not much data on genotypes evaluated over several seasons and in different environments (locations and years), precluding comparison.

The magnitude of genotypic variance and genotype × environment variance components reflects on the differential behavior of genotypes in the face of environmental variations. For all evaluated traits, the variance component was higher for the interaction than for the genotype. The obtained genotypic variance estimates indicate, with reasonable precision, differences in traits between genotypes (Table 2).

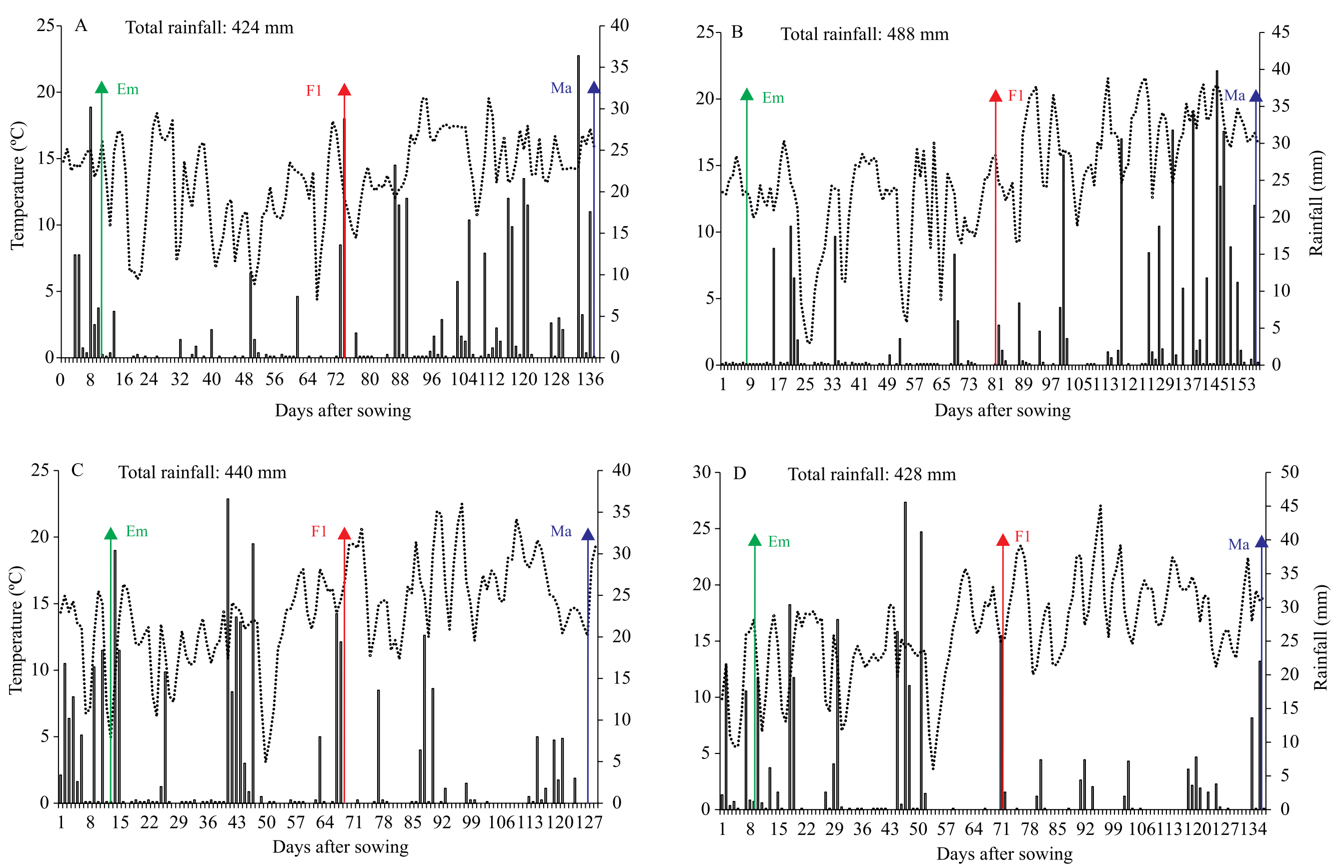

Figure 1. Duration of stages of the crop cycle of yellow flaxseed (*Linum usitatissimum*) genotypes and climatic conditions in two municipalities in the state of the state of Santa Catarina, Brazil: Curitibanos, in 2018 (A), 2019 (B), and 2020 (C); and Campos Novos, in 2020 (D). Em, emergence; Fl, flowering; Ma, maturation.

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Grain yield had the lowest heritability coefficient of 0.46 among all traits (Table 2). This value is similar to that found by You et al. (2017) when evaluating several flax genotypes in two sites in Canada. Given that grain yield is a polygenic trait, it is more affected by environmental conditions, a factor that negatively influences heritability. In contrast, number of capsules per plant and plant yield showed high heritability values (Table 2). For these two traits, Bhateria et al. (2006) obtained much lower values of 0.02 and 0.16, respectively, when analyzing flax genotypes in two environments in India. As it expresses the confidence of the phenotypic value as an estimator of the genetic value, heritability plays an important role in predicting genetic gain; however, higher heritability values do not necessarily result in better responses to selection since a high heritability can occur in traits with a small additive genetic variance due to the low influence of the environment. Therefore, it can be suggested that the greater the heritability, the closer the expected response will be to the used selection differential.

Different environments had varying effects on the yield parameters of the studied genotypes (Table 3). Regarding mean plant yield in Curitibanos, the lowest value of 1.5 g per plant was observed in 2018, showing a slight increase of 2.4 g in 2019. Comparing both environments in 2020, yield ranged from 2.5 to 6.4 g per plant in Curitibanos and from 1.6 to 4.4 g per plant in Campos Novos. In Curitibanos, grain yield differed the most between the lines, ranging from 725.5 to 1,571.9 kg ha^{-1} in 2018 and from 2,345.1 to 3,902.7 kg ha^{-1} in 2020. The occurrence of rain and strong winds in 2018, during plant maturation, led to lodging, which might have affected grain yield, particularly in Curitibanos. The mean grain yields were 2,862.2 and 2,325.0 kg ha^{-1}, respectively, in Curitibanos, in 2019, and Campos Novos, in 2020. All lines differed in yield parameters between environments, which is a common behavior given that grain yield is influenced by a variety of factors, including the environment.

Overall, yields in all environments were higher (Table 3) than the Brazilian average of 950 kg ha^{-1} (FAO, 2021). The mean grain yield obtained in the present study is similar to that of 1,600 to 2,860 kg ha^{-1} found for Canadian cultivars, such as CDC Bethune, in different environments (Kumar et al., 2015; Booker et al., 2021). In Europe, yields of 0.8 to 1.1 Mg ha^{-1} have been reported (FAO, 2021). It has been observed that grain yield varied according to genotype, with values from 2.35 to 2.6 Mg ha^{-1} in conventional farming systems in Germany and from 1.4 to 1.9 Mg ha^{-1} in organic systems in Switzerland (Klein et al.,

Table 1. Results of the analysis of variance for number of capsules per plant (NCP), plant yield, and grain yield of 20 genotypes of yellow flax (*Linum usitatissimum*) in four environments, in the state of Santa Catarina, Brazil.

Source of variation	Degrees of freedom	NCP	Plant yield	Grain yield
Genotype (G)	19	1,051.8**	2.1**	318,367.6*
Environment (E)	3	13,808.4**	60.6**	44,495,203.3**
G × E	57	786.5**	2.1**	266,777.6*
Error	152	289.4	0.9	173,358.2

* and **Significant by the F-test at $p \leq 0.05$ and $p \leq 0.01$, respectively.

Table 2. Genetic parameters for number of capsules per plant (NCP), plant yield, and grain yield of 20 genotypes of yellow flax (*Linum usitatissimum*) in four environments, in the state of Santa Catarina, Brazil.

Genetic parameters	NCP	Plant yield	Grain yield
Coefficient of variation (%)	26.2	35.4	18.2
Overall mean	64.8	2.6	2,286.5
Genotypic variance	63.5	0.1	12,084.1
Genotype × environment variance	124.3	0.3	23,354.8
Heritability	0.73	0.58	0.46

2017). These results are an indicative that yellow flax genotypes, which have been selected and evaluated since 2017, have a high production potential, being promising candidates as commercial cultivars.

Number of capsules per plant, number of seeds per capsule, and seed weight are also highly affected by management conditions, such as population density and environmental conditions during the vegetative growth and reproductive stages (Mirzaie et al., 2020). Sowing density was 2,940,000 seeds per hectare in Curitibanos, in 2019 and 2020, and in Campos Novos, in 2020, only differing in Curitibanos, in 2018, where it was 1,470,000 seeds per hectare (Table 4). Although a lower sowing density was used in Curitibanos, in 2018, the final plant stand was similar to that in Curitibanos, in 2020, where a later emergence was observed, affecting final stand density.

Table 3. Mean plant yield and grain yield of 20 genotypes of yellow flax (*Linum usitatissimum*) in the municipalities of Curitibanos, in 2018, 2019, and 2020 (CB2018, CB2019, and CB2020, respectively), and of Campos Novos, in 2020 (CN2020), in the state of Santa Catarina, Brazil.

Genotype	Plant yield (g per plant)				Grain yield (kg ha^{-1})			
	CB2018	CB2019	CB2020	CN2020	CB2018	CB2019	CB2020	CN2020
Common yellow(1)	1.2	2.3	3.3	2.3	725.5	2,554.9	2,984.5	2,289.8
LINPG10	1.7	2.0	2.9	1.8	1,048.4	3,386.4	2,605.5	2,492.5
LINPG35	1.4	2.2	3.7	2.5	786.3	2,860.0	2,795.9	2,105.7
LINPG42	2.0	3.3(2)	2.8	1.6	892.3	2,369.3	2,782.9	2,046.7
LINPG49	1.4	2.8	6.4(2)	3.4	877.4	2,889.7	3,902.7(2)	2,315.7
LINPG50	1.1	2.1	2.8	2.2	855.2	2,841.0	2,650.8	2,746.7
LINPG57	1.0	2.0	5.5	4.4(2)	908.8	2,866.0	3,022.6	2,675.9
LINPG66	1.1	2.6	3.9	3.0	787.0	3,565.8(2)	2,953.5	1,972.5
LINPG70	1.8	2.6	4.7	4.0	1,105.5	2,588.5	3,085.3	2,761.8(2)
LINPG76	1.8	2.0	4.6	3.6	1,036.4	2,802.4	2,833.9	2,401.8
LINPG87	1.2	2.7	5.7	2.2	1,077.2	2,956.9	3,364.3	2,480.6
LINPG88	2.3(2)	2.4	4.4	2.2	1,286.4	3,144.8	3,474.3	2,340.2
LINPG89	1.5	2.1	4.7	2.9	1,564.1	3,052.2	2,951.2	2,239.6
LINPG95	1.6	2.9	2.7	1.8	1,454.4	2,993.5	2,272.2	2,124.9
LINPG96	2.1	2.3	2.9	2.2	1,696.0(2)	2,834.3	3,058.8	2,281.0
LINPG100	1.1	2.0	4.9	2.0	949.3	2,635.1	2,455.3	2,229.6
LINPG102	1.4	2.3	2.5	2.4	895.4	3,001.8	2,981.0	2,347.5
LINPG109	1.8	2.2	3.5	2.5	1,571.9	2,450.7	2,610.6	2,014.1
LINPG111	1.4	2.1	4.2	3.7	778.7	2,684.3	2,984.5	2,529.0
LINPG113	1.6	2.3	2.7	2.7	836.0	2,696.4	2,345.1	2,104.5
Mean	1.5	2.4	4.0	2.7	1,074.0	2,874.7	2,901.6	2,326.9

(1)A local variety. (2)The best performance.

Table 4. Sowing density and final stand of 20 genotypes of yellow flax (*Linum usitatissimum*) in four environments (municipalities), in the state of Santa Catarina, Brazil.

Environment/ Year	Sowing density (seeds m^{-2})	Final stand (plants m^{-2})		
		Minimum	Average	Maximum
Curitibanos/ 2018	147	52	75	98
Curitibanos/ 2019	294	81	126	171
Curitibanos/ 2020	294	55	88	120
Campos Novos/ 2020	294	61	106	151

In general, studies on flax use plant densities of 100 to 2,000 plants per square meter (Casa et al., 1999; Arslanoglu et al., 2022). Depending on the environment, plant density affects growth and yield differently. In systems with a low plant density, Casa et al. (1999), for example, found more pronounced environmental effects. Combined with well-distributed rainfall and maximum temperatures of 20 to 26°C, low sowing densities lead to: an increase in stem diameter and number; an indirect increase in yield capacity due to a reduced competition between plants for water, radiation, and nutrients; and a reduction in the probability of lodging (Sangiovo et al., 2022). Sangiovo et al. (2022) highlighted the importance of optimizing both sowing density and row spacing, as lower sowing densities allow of a better distribution of plants in the row, minimizing the effects of intraspecific competition, which explains the higher agronomic performance of flax crops subjected to a low sowing density and small row spacing.

The results of the correlation analysis indicate that the effect of final plant stand on yield components can be altered by environmental conditions (Casa et al., 1999). In all environments, plant stand was negatively correlated with number of capsules per plant, suggesting a compensation strategy, as observed by Sangiovo et al. (2022). The correlation between stand and plant yield was also negative, except in Curitibanos, in 2018, whereas that between number of capsules per plant and plant yield was positive, being higher in Curitibanos, in 2019 and 2020, and in Campos Novos in 2020 (Table 5). These findings are in agreement with those of Dash et al. (2016).

There was a positive correlation between yield per plant and yield per area, except in Curitibanos, in 2019. Plant stand was correlated positively with yield per area in Curitibanos, in 2018 and 2019, despite the different sowing densities. The joint correlation analysis revealed that larger stands resulted in a lower capsule number and yield per plant, but yield per area was not affected (Table 6). The analysis of correlation between traits is crucial for evaluating genotypes in different environments, whether alone or combined, aiming selection for superior agronomic performance.

For the selection of superior genotypes, it is important to investigate genotype performance in different environments via the joint analysis of variance, since the genotype × environment interactions ultimately reduce the usefulness of genotypes due to the fluctuation in productive performance. Therefore, evaluating genotypes in different harvest cycles facilitates selecting genotypes with yield or agronomic stability, that is, with a high productive performance over crop seasons. When analyzing variation in the response of genotypes to different sites, Adugna & Labuschagne (2013) observed that the effects of environments were masked, confirming that stability and adaptability parameters are essential for identifying genotypes with a predictable behavior and that are responsive to specific or broad environmental variations, so selection can be conducted with scientific rigor and a lower error probability (Cruz et al., 2012).

Regarding the stability and adaptability parameters of yellow flax genotypes (Table 7), P_i represents the parameters in all four environments, whereas P_{i+} and P_{i-} represent parameter P_i in "favorable" and "unfavorable"

Table 5. Phenotypic correlations between number of capsules per plant (NCP), plant yield (PY), grain yield (GY), and final stand (FS) of 20 genotypes of yellow flax (*Linum usitatissimum*) per square meter per environment (municipality), in the state of Santa Catarina, Brazil.

Environment/ Year		Phenotypic correlation		
		NCP	PY	GY
Curitibanos 2018	FS	-0.61*	-0.20^{ns}	0.58*
	NCP		0.58*	0.01^{ns}
	PY			0.58*
		NCP	PY	GY
Curitibanos 2019	FS	-0.74*	0.78*	0.68*
	NCP		0.96*	-0.11^{ns}
	PY			-0.15^{ns}
		NCP	PY	GY
Curitibanos 2020	FS	-0.87*	-0.87*	-0.28^{ns}
	NCP		0.99*	0.63*
	PY			0.65*
		NCP	PY	GY
Campos Novos 2020	FS	-0.84*	-0.87*	-0.16^{ns}
	NCP		0.98*	0.44*
	PY			0.45*

*Significant by the t-test at 5% probability. ^{ns}Nonsignificant.

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environments, respectively. According to the criteria of Lin & Binns (1988), LINPG88, LINPG87, LINPG49, LINPG89, and LINPG96 had low P_i values and high mean yields, with LINPG88 and LINPG87 being little affected by the genotype × environment interaction. This finding is explained by the used P_i estimation method, in which low P_i values indicate a higher adaptability and stability when yields are close to the maximum for each environment (Cruz & Carneiro, 2003). Moreover, LINPG113, LINPG42, LINPG100, LINPG109, and LINPG95 had the highest P_i values and low mean yields, exhibiting a poor (or inferior) performance for overall adaptability. Considering P_{i+} and P_{i-}, LINPG88, LINPG49, and LINPG87 showed responsiveness to favorable environmental conditions, while LINPG96, LINPG109, and LINPG89 had a good performance in unfavorable ones. When evaluating adaptability and stability, it is important to consider the P_i value, the contribution to the interaction, and the mean yield of the genotypes. Using the method of Lin & Binns (1988), Adugna & Labuschagne (2013) identified three stable genotypes.

Given that differences from the maximum are squared, the P_i statistic has a variance property of stability or predictability of behavior, as shown by genotypes with P_i values with small variations in relation to the hypothetical genotype. In general, plant breeders agree on the importance of high yield stability but do not agree on the definition of stability, which is a theoretical concept that is difficult to apply. Furthermore, given that P_i represents the difference

Table 6. Results of the joint correlation analysis for number of capsules per plant (NCP), plant yield (PY), grain yield (GY), and final stand (FS) of 20 genotypes of yellow flax (*Linum usitatissimum*) in four environments, in the state of Santa Catarina, Brazil.

	NCP	PY	GY
FS	-0.79**	-0.75**	0.13^{ns}
NCP		0.95**	0.41*
PY			0.46**

* and **Significant by the t-test at 5 and 1% probability, respectively. ^{ns}Nonsignificant.

Table 7. Estimates of the stability and adaptability parameters for all environments (P_i) for grain yield (GY) of 20 genotypes (G) of yellow flax (*Linum usitatissimum*) in four environments (E), classified by GY and ranked as superior genotypes in unfavorable (P_{i-}) and favorable environments (P_{i+}) in the state of Santa Catarina, Brazil.

Genotype	GY (kg ha^{-1})	P_i	P_{i+}	P_{i-}	G (%)	G × E (%)
LINPG88	2563.7	86721	First	-	99.9	0.0
LINPG87	2463.9	142986	Third	-	93.2	6.8
LINPG49	2488.9	169899	Second	-	71.0	29.0
LINPG89	2451.1	180892	-	Third	77.3	22.7
LINPG96	2465.5	184763	-	First	71.7	28.3
LINPG57	2369.5	234012	-	-	79.7	20.3
LINPG102	2306.4	245006	-	-	92.6	7.4
LINPG70	2384.8	245796	-	-	72.1	27.9
LINPG10	2389.8	266002	-	-	65.5	34.5
LINPG76	2259.1	292512	-	-	88.9	11.1
LINPG66	2317.8	294182	-	-	74.6	25.4
LINPG111	2246.9	310610	-	-	86.5	13.5
LINPG50	2279.7	342007	-	-	71.7	28.3
LINPG35	2129.9	376588	-	-	96.0	4.0
Common yellow	2137.1	379150	-	-	93.7	6.3
LINPG95	2217.9	415645	-	-	69.9	30.1
LINPG109	2158.0	438920	-	Second	77.0	23.0
LINPG100	2088.9	449167	-	-	88.4	11.6
LINPG42	2011.1	492542	-	-	95.3	4.7
LINPG113	2000.5	532918	-	-	90.0	10.0

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between the yield of the evaluated genotype and the hypothetical genotype, this statistic also takes into account cultivar adaptation.

It is important to highlight that obtaining a high grain yield and agronomic performance under a wide range of environmental conditions is fundamental for cultivar development. One of the main objectives of flax breeding programs is to increase grain and fiber yields. However, according to Sigh (2016), the development of dual-purpose cultivars is not possible since flax plants cultivated for grain and oil production should have short stems with many branches and those for fiber production, long stems with few branches. Therefore, there is a wide variability in the productive performance among flax genotypes. The productive performance observed for the lines evaluated in the present study was quite favorable, given that the mean yield obtained was higher than the Brazilian average and similar to that of countries with successful breeding programs, such as Canada. However, the presence of interaction effects indicated differences in performance according to the environment, representing a challenge for the selection and recommendation of genotypes with high mean yields and productive stability. According to the obtained results, the effect of factors as soil, climate, and population density on the yield components of flax (number of capsules and grain weight) must be considered as they directly affect the productive performance of the genotypes.

Conclusions

1. The genotype × environment interaction greatly affects the evaluated flax (*Linum usitatissimum*) traits, as do heritability coefficients, favoring selection.
2. Final plant stand influences flax yield components due to different environments.
3. In general, the studied genotypes present higher yields than the Brazilian average, with values similar to those of foreign cultivars.
4. LINPG87 and LINPG88 are considered promising candidates for breeding given their high performance and yield stability.

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