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Path analysis of yield and yield components in super-sweet maize (*Zea mays* L. var. Saccarata) inbred lines at drought-stress and normal conditions

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Abstract
To identify the most effective characteristics on grain yield, 24 super-sweet maize inbred lines were investigated under two moisture conditions (normal and drought stress) during the 2017 growing season. The experiment was carried out as a randomized complete block design with four replications. Analysis of variance for grain yield and eight agronomic characteristics showed significant differences among investigated inbred lines. Phenotypic correlations indicated that grain yield had a significant relationship with kernel number per row, ear diameter, row number per ear, and stem diameter under normal conditions, and with kernel number per row and plant height under drought-stress conditions. Stepwise multiple linear regression showed that kernel number per row, ear diameter, and stem diameter explained 72% of the variation for grain yield at normal conditions. On the other hand, cob present, plant height, ear diameter, and ear length governed 60% of the grain yield variation under drought-stress conditions. Path analysis under normal conditions revealed that kernel number per row had the highest positive direct effect (0.717) on the grain yield followed by the stem diameter (0.292) and ear diameter (0.273). In the drought stress conditions, ear diameter (0.455) and plant height (0.436) showed the highest positive direct effects on grain yield.

Keywords: Drought; Maize; Multiple linear regression; Path coefficient; Phenotypic correlation

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Introduction

Maize (*Zea mays* L.) is considered one of the valuable energy sources for humans and animals and ranks as the most important grain crop because its production exceeds 1.2 billion metric tons (FAO 2020). The name of super-sweet or shrunken-2 corn, which contains around twice the sugar of the the standard varieties, originated from its wrinkled dry grains.

Characterization of genotypes, determining the genetic diversity, and studying the genetic association among traits are essential in breeding crop plants. The immediate purpose of maize breeding is to enhance grain yield, which is considered a complex quantitative characteristic that relies on various factors such as different growth and physiological processes of the crop and also on environmental conditions. Knowing about existing relationships between yield and its related components can enhance the efficiency of the breeding programs by providing appropriate selection criteria (Pavlov *et al.* 2015). Correlation coefficients demonstrate the degree of the relationships among traits. Path analysis is widely used to determine the direct and indirect effects of the causal components on the dependent variable. It is useful to identify those components with a significant impact on yield. The decomposition of the correlation coefficient into direct and indirect effects is one of the advantages of using path analysis (Rafiq *et al*. 2010). The path coefficient in the path analysis indicates the direct effect of an independent variable upon the dependent variable. An independent variable also has an indirect effect(s) on the dependent variable through other independent variables (Dewey and Lu 1959). Dividing total correlation into direct and indirect effects using path analysis helps to identify useful traits as selection criteria for improving the yield of crop plants (Milligan *et al.* 1990).

The present research was designed to determine the direct and indirect effects of eight agronomic characteristics on grain yield of super-sweet maize inbred lines using different methods, such as path coefficient analysis.

Materials and Methods

Genetic material evaluated in this research included 24 super-sweet maize inbred lines (at S6 and S7 selfing generations) derived from the F2 generation of commercial super-sweet maize single cross hybrids (Table 1) developed by Khorasan Razavi Agricultural and Natural Resources Research and Education Institute Center, Mashhad, Iran. The inbred lines were evaluated under two moisture levels (normal irrigation and drought stress). The experimental design in each condition was a randomized complete block design with four replications, which was conducted in 2017. Each plot consisted of four 3 m-length rows with a between-row spacing of 0.75 m. Regular agronomic practices for the maize crop were performed. The plant density was 70000 plant/ha. Irrigation was applied based on 50 and 80 percent water depletion, respectively, for the normal and drought stress conditions. GY was considered as the response (dependent) variable, and cob percent (CP), kernel number per row (KN), row number per ear (RN), ear length (EL), stem diameter (SD), ear diameter (ED), plant height (PH), and 300-seed weight (SW) as independent variables. These traits were measured on 10 random competitive plants in each plot. After analysis of variance, the means were computed by the least significant difference test at the 0.05 level of probability. The multiple linear regression method was used separately in each condition to develop regression models relating the GY with other measured agronomic characteristics. Also, the correlation coefficients between the variables were calculated. To partition the correlation coefficients of the grain yield with other agronomic characteristics into direct and indirect effects, a path analysis ((Dewey and Lu 1959) was performed in each environment. Data were analyzed by the Minitab 18 and IBM SPSS Amos 22 software.

Descriptive statistics

The results of the phenotypic statistics, including minimum, maximum, mean, standard error, and standard deviation concerning the super-sweet inbred lines of maize under normal and drought-stress conditions are shown in Table 2. The mean values of the measured traits under normal conditions were higher than those from the drought-stress conditions except for the CP, which

Table 1. List of the 24 super-sweet maize inbred lines under study

Entry Code	Name	SG	Entry Code	Name	SG
1	MBA87001/ 3-2	S7	13	MPA90001/ 48-1	S6
2	MBA87003/ 4-1	S7	14	MPA90004/ 49-2	S6
3	MBA87001/ 18-1	S7	15	MPA90010/ 51-1	S6
4	MCH87002/ 19- 1	S7	16	MSH9001/ 76-1	S6
5	MCH87001/ 22-1	S7	17	MSH9006/ 76-5	S6
6	MCH87004/ 23-1	S7	18	MSH90011/ 82-1	S6
7	MCH87001/ 23-3	S7	19	MSH90015/ 87-1	S6
8	MCH87011/ 25-1	S7	20	MSH90019/ 89	S6
9	MCH87017/26-3	S7	21	MSG9002/ 96-1	S6
10	MCH87022/ 28-3	S7	22	MSG9008/118-1	S6
11	MCH87025/ 29-3	S7	23	MSG90012/ 124-1	S6
12	MOB87002/ 37-1	S7	24	MSG90017/ 124-2	S6

SG: selfing generation

Table 2. Some descriptive statistics of super-sweet maize inbred lines at normal and drought-stress conditions

Trait	Minimum		Maximum		Mean		Standard error		Std. Deviation	
	Normal	Stress	Normal	Stress	Normal	Stress	Normal	Stress	Normal	Stress
GY	973	915	4106	3624	2333	1944	154	147	753	722
CP	13.45	24.18	46.22	64.42	32.60	44.24	1.80	2.30	8.84	11.27
SW	7.63	13.557	37.18	28.318	24.60	21.735	1.41	0.970	6.91	4.750
KN	12.333	12.000	18.250	15.233	14.432	13.481	0.330	0.198	1.618	0.972
RN	91.92	78.11	157.15	145.42	120.80	108.38	3.12	3.49	15.30	17.08
EL	2.9417	2.6644	4.1552	3.7250	3.5189	3.3417	0.0677	0.0534	0.3316	0.2615
ED	1.7437	1.3150	2.7667	2.7000	2.1715	2.0878	0.0549	0.0589	0.2689	0.2884
SD	10.353	8.708	15.904	14.500	13.020	12.016	0.297	0.269	1.454	1.318
PH	42.00	57.50	135.00	130.00	97.48	91.67	4.74	4.95	23.20	24.26

GY: grain yield, CP: cob percent, KN: kernel number per row, RN: row number per ear, EL: ear length, SD: stem diameter, ED: ear diameter, PH: plant height, SW: 300-seed weight

was higher under the drought-stress environment.

Multiple linear regression

Results of the stepwise multiple regression analysis showed the relative contribution of each trait to the GY (Table 3). Under normal conditions, the traits KN, ED, and SD, and under drought stress conditions, CP, PH, ED, and EL had a significant relationship with the super-sweet corn GY. The coefficient of determination of the model showed proper goodness of fit of the model in both conditions (R^2 in normal and drought-stress were 0.73 and 0.60, respectively). The final models based on the standardized data are as follows:

GY= 0.512 KN** + 0.353 ED* + 0.268 SD* (normal)

Table 3. Final models derived using the stepwise multiple linear regression in super-sweet maize under normal and drought stress conditions

Normal			
Variable	Regression coefficient	VIF	R^2
Kernel number per row	0.512	1.52	
Ear diameter	0.353	1.62	0.73
Stem diameter	0.268	1.1	
Regression equation: 0.512 KN + 0.353 ED + 0.268 SD			

Drought stress			
Variable	Regression coefficient	VIF	R^2
Cob percent	-0.307	1.12	
Plant height	0.504	1.23	0.60
Ear diameter	0.503	1.15	
Ear length	0.352	1.2	
Regression equation: - 0.307 CP + 0.504 PH + 0.503 ED + 0.352 EL			

GY= - 0.307 CP* + 0.504 PH** + 0.503 ED** + 0.352 EL* (drought stress)

where * and ** indicate significance at $p \leq 0.05$ and $p \leq 0.01$, respectively

Correlation and path analysis

Knowledge of the relationship among the traits such as yield and yield-related traits is essential in plant improvement (Priya and Joel 2009; Snowdon *et al.* 2021). Path analysis separates direct and indirect effects of the independent variables on the response variables, such as yield, by partitioning the correlation coefficients (Priya and Joel 2009). Correlation measures the mutual relationship between two variables without concerning the causal effects. Also, the correlation between two traits may be the result of their association with another trait. However, path analysis evaluates causal models.

The correlation coefficients between the studied traits under normal and drought-stress conditions are presented in Table 4. At the normal condition, the highest correlation coefficients were observed between GY and KN (0.76**), followed by those of GY with RN (0.76**), ED (0.73**), and SD (0.45*). The lowest insignificant correlation coefficient was observed between SW and GY (0.13). The highest significant correlation coefficient among the yield related-traits was found between KN and RN (0.65**), followed by the correlation of KN with EL (0.60**). Under drought stress conditions KN (0.61**) and SD (0.19) had the highest and lowest associations with the GY, respectively. The highest correlation coefficient among yield-related characteristics was observed between SW and ED (0.67**). Teodoro et al. (2014) also reported a significantly positive correlation of the GY with KN, and 100-grain

Table 4. Matrix of correlation coefficients of grain yield and agronomic traits in super-sweet maize inbred lines

	GY	CP	KN	RN	PH	ED	SD	EL	SW
GY	-	-0.153	0.760**	0.422*	0.305	0.729**	0.452*	0.389	0.134
CP	-0.31	-	0.089	-0.181	0.365	-0.273	0.122	0.365	-0.442*
KN	0.61**	-0.51*	-	0.651**	0.486*	0.581**	0.157	0.602**	-0.159
RN	0.37	-0.28	0.39	-	0.480*	0.422*	0.080	0.474*	-0.182
PH	0.46*	0.12	0.40	0.41*	-	0.007	0.377	0.524**	-0.514*
ED	0.40	-0.27	0.35	0.09	-0.27	-	0.295	0.231	0.460*
SD	0.19	0.11	0.15	0.09	0.49*	-0.26	-	0.246	0.024
EL	0.40	0.22	0.14	0.13	0.37	-0.14	0.10	-	-0.432*
SW	0.29	-0.57**	0.25	0.25	-0.31	0.67**	-0.23	-0.21	-

Upper-right: correlation coefficients at normal conditions; Lower-left: correlation coefficients at drought-stress conditions; *,**significant at $p \leq 0.05$ and $p \leq 0.01$, respectively; GY: grain yield, CP: cob percent, KN: kernel number per row, RN: row number per ear, EL: ear length, SD: stem diameter, ED: ear diameter, PH: plant height, SW: 300-seed weight

weight in two classes of maize hybrids (single crosses and three-way crosses). According to Pavan *et al*. (2011), EL, KN, RN, PH, ear circumference, shelling percent, and 100-grain weight showed a significant and positive correlation with the GY of maize.

The coefficient of determination (R^2) obtained from the path analysis was equal to 0.82 and 0.68 for the normal and drought stress conditions, respectively, characterizing that 82% and 68% of the variation in the GY was explained by the variables used in the path analysis. The path diagram is shown in Figure 1. Under normal conditions, KN had the highest direct effect on grain yield (0.717) followed by SD (0.292), and ED (0.273). This implies that higher KN, SD, and ED lead to increased GY. The phenotypic correlation between KN and GY (0.76) was predominately attributed to the direct effect of KN on GY (Table 5). The positive significant correlation between ED and GY (0.729) was largely due to the indirect effect of ED on GY through KN (0.417). RN showed the highest negative direct effect on GY (-0.255) followed by CP (-0.249). The negative direct influence of RN on GY was nullified by the higher magnitude of its positive indirect effects via other studied traits, especially through KN (0.467) and, therefore, this trait showed a significant positive correlation with GY (0.42). Likewise, EL and PH showed the highest positive indirect effects on GY through KN (0.432, and 0.348, respectively). The indirect contribution of any agronomic trait through SW, EL, and PH was very small. So, SW, EL, and PH were not proper traits for indirect selection, since they have low direct effects on GY (-0.016, 0.002, and 0.049, respectively) and also a non-significant phenotypic correlation with grain yield (0.134, 0.389, and 0.305, respectively). CP revealed both a negative direct effect and a negative correlation coefficient with GY. Almost similar results were obtained by other researchers in maize. Pavan *et al.* (2011) conducted a path analysis on the data obtained from evaluating 87 F_1 genotypes developed by the line × tester method. PH, KN, RN, SW, and shelling percent had the highest direct effect on GY. Singh et al. (2011) studied the relationships of GY with yield-contributing traits in quality protein maize (QPM) through the path coefficient analysis. The highest positive direct effects on GY belonged to EL, ear height, ear girth, days to 75% tasselling, and days to 75% brown husk. Therefore, they

Table 5. Path-coefficient analysis showing the direct and indirect effects of agronomic traits on grain yield in super-sweet maize inbred lines at normal conditions

	SW	EL	SD	ED	PH	RN	CP	KN	Correlation coefficient with GY
SW	-0.016	-0.001	0.007	0.126	-0.025	0.046	0.110	-0.114	0.13
EL	0.007	0.002	0.072	0.063	0.026	-0.121	-0.091	0.432	0.39
SD	0.000	0.000	0.292	0.081	0.018	-0.020	-0.030	0.113	0.45*
ED	-0.007	0.000	0.086	0.273	0.000	-0.108	0.068	0.417	0.73**
PH	0.008	0.001	0.110	0.002	0.049	-0.122	-0.091	0.348	0.30
RN	0.003	0.001	0.023	0.115	0.024	-0.255	0.045	0.467	0.42*
CP	0.007	0.001	0.036	-0.075	0.018	0.046	-0.249	0.064	-0.15
KN	0.003	0.001	0.046	0.159	0.024	-0.166	-0.022	0.717	0.76**

GY: grain yield, CP: cob percent, KN: kernel number per row, RN: row number per ear, EL: ear length, SD: stem diameter, ED: ear diameter, PH: plant height, SW: 300-seed weight; *,**significant at $p \leq 0.05$ and $p \leq 0.01$, respectively

concluded that a reliable selection of parental lines based on these traits can be achieved to develop high-yielding cultivars of QPM maize. Kinfe *et al*. (2015) also reported the positive direct effects of EL, ED, and PH on the GY of maize hybrids.

Path coefficient analysis in drought stress conditions (Table 6) revealed that ED had a maximum direct effect on grain yield (0.455) followed by PH (0.436), and EL (0.353). As mentioned before, there was also a positive correlation between ED and GY (0.40). The direct negative effect on GY was attributed mainly to the CP (-0.256). CP also revealed a negative correlation with GY (-0.31). Under the drought stress conditions, KN showed the highest phenotypic correlation between GY (0.61). This may be attributed to the direct effect of KN and its indirect effects on GY through ED, PH, and CP (0.158, 0.174, and 0.13, respectively). The significant phenotypic correlation between PH and GY (0.46) can be predominately due to the direct effect of PH on GY. RN mainly contributed indirectly to GY through PH (0.181), followed by CP, EL, and KN. It was revealed that under drought-stress conditions, selection for KN, PH, EL, and ED can be effective in improving the GY in maize. Khalili *et al.* (2013) used path analysis to partition the genetic correlations between GY and related characteristics in maize cultivars under drought stress conditions and suggested that 100-grains weight and the total number of grains per ear can be used to improve GY in maize under drought stress.

Conclusion

Path analysis under normal conditions showed that ED, KN, and SD were the most significant characters directly contributing to the GY of super-sweet maize inbred lines. So, improvement in super-sweet maize yield would be best accomplished by emphasizing these traits compared to other agronomic traits. In the drought-

Table 6. Path-coefficient analysis showing the direct and indirect effects of agronomic traits on grain yield in super-sweet maize inbred lines at drought stress conditions

	SW	EL	SD	ED	PH	RN	CP	KN	Correlation coefficient with GY
SW	0.053	-0.073	-0.019	0.306	-0.133	-0.005	0.145	0.020	0.29
EL	-0.011	0.353	0.008	-0.062	0.161	-0.003	-0.058	0.012	0.40
SD	-0.012	0.036	0.084	-0.117	0.214	-0.002	-0.027	0.012	0.19
ED	0.036	-0.048	-0.022	0.455	-0.118	-0.002	0.069	0.029	0.40
PH	-0.016	0.130	0.041	-0.123	0.436	-0.008	-0.030	0.033	0.46*
RN	0.013	0.045	0.008	0.041	0.181	-0.020	0.073	0.032	0.37
CP	-0.030	0.079	0.009	-0.122	0.051	0.006	-0.256	-0.041	-0.31
KN	0.013	0.050	0.013	0.158	0.174	-0.008	0.130	0.082	0.61**

GY: grain yield, CP: cob percent, KN: kernel number per row, RN: row number per ear, EL: ear length, SD: stem diameter, ED: ear diameter, PH: plant height, SW: 300-seed weight; *significant at $p \leq 0.05$

stress conditions, PH, ED, and EL, and to a lower extent, KN affected directly the GY based on standardized multiple linear regression and path analysis. KN mainly contributed indirectly to GY via other traits such as PH and ED. This study indicated that environmental conditions can change the relative magnitude of agronomic traits in governing maize GY. However, to confirm the results obtained in this study, the inbred lines should be evaluated at several locations and over years.

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Conflict of Interest

The authors declare that they have no conflict of interest with any organization in relation to the subject of the manuscript.

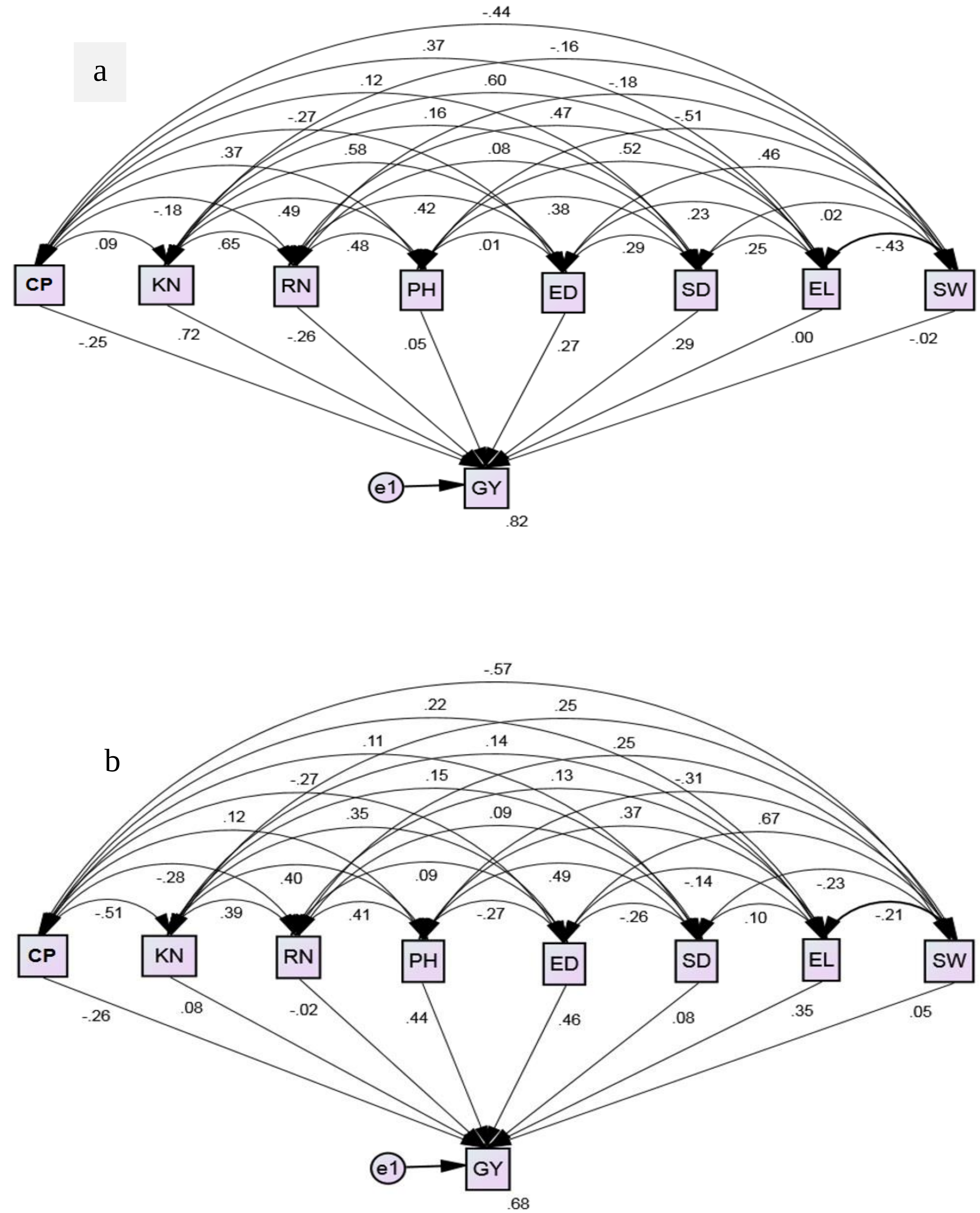

Figure 1. Sequential path model illustrating interrelationships among various characters contributing to grain yield; a) at normal conditions, b) at drought stress conditions); GY: grain yield, CP: Cob percent, KN: kernel number per row, RN: row number per ear, EL: ear length, SD: stem diameter, ED: ear diameter, PH: plant height, SW: 300-seed weight

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تجزیه علیت عملکرد و اجزای عملکرد در لاین‌های اینبرد ذرت فوق شیرین (Zea mays L. var. Saccarata) تحت شرایط نرمال و تنش خشکی

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چکیده

برای شناسایی موثرترین صفات بر عملکرد دانه ، ۲۴ لاین اینبرد ذرت فوق شیرین تحت دو شرایط رطوبتی (نرمال و تنش خشکی) در طول سال زراعی ۲۰۱۷ مورد بررسی قرار گرفتند. این آزمایش به صورت طرح بلوک‌های کامل تصادفی با چهار تکرار در هر دو شرایط انجام شد. تجزیه واریانس عملکرد دانه و هشت صفت مورد مطالعه اختلاف معنی داری را بین لاین‌های مورد بررسی نشان داد. محاسبه همبستگی‌های فنوتیپی نشان داد که عملکرد دانه با تعداد دانه در ردیف، قطر بلال، تعداد ردیف بلال و قطر ساقه در شرایط نرمال و با تعداد دانه در ردیف و ارتفاع بوته در شرایط تنش خشکی همبستگی معنی داری داشتند. رگرسیون خطی چندگانه گام به گام نشان داد که تعداد دانه در ردیف، قطر بلال و قطر ساقه ۷۲٪ از تغییرات عملکرد دانه را در شرایط نرمال و درصد چوب بلال، ارتفاع بوته، قطر بلال و طول بلال ۶۰٪ از تغییرات عملکرد دانه را در شرایط تنش خشکی توضیح دادند. تجزیه علیت در شرایط نرمال نشان داد که تعداد دانه در ردیف بالاترین اثر مستقیم مثبت (۰,۷۱۷) را روی عملکرد دانه ذرت فوق شیرین و به دنبال آن قطر ساقه (۰,۲۹۲) و قطر بلال (۰,۲۷۳) داشتند. در شرایط تنش خشکی، بیشترین اثر مستقیم مثبت روی عملکرد دانه ذرت فوق شیرین به صفات قطر بلال (۰,۴۵۵) و ارتفاع بوته (۰,۴۳۶) تعلق داشت.

واژه‌های کلیدی: تجزیه علیت؛ خشکی؛ ذرت؛ رگرسیون خطی چندگانه؛ همبستگی فنوتیپی