

Understanding of some Morphological Parameters, Yield and Seed Quality Indices in Maize by Multivariate Analysis

Alina Laura AGAPIE¹, Marinel Nicolae HORABLAGA^{1,2}, Busuioc VACARIU¹,
Florin SALA^{1,2,*}

¹Agricultural Research and Development Station Lovrin, Lovrin, 307250, Romania

²University of Life Sciences "King Mihai I" from Timisoara, Timisoara, Calea Aradului, 300645, Romania

*Corresponding author: florin_sala@usvt.ro

Abstract. The performance of corn hybrids for efficiency and seed quality indices under specific crop conditions have an interest for improvement programs and agricultural practice. The study analyzed the performance of 20 corn hybrids created within ARDS Suceava, and tests in comparative crop within ARDS Lovrin. Morphological parameters of the ears (ear length - EL, row number - RN, kernel number in row - KNR, ear weight - Ew, grains weight - GW, grains yield in ear - GYE), yield (Y, kg ha⁻¹) and seed quality (thousand kernel weight - TKW, hectoliter weight - HW, protein - PRO, oil - OIL) have been determined. EW, GW and Y parameters had moderate variability, and the other parameters and indexes showed low variability. Variable correlation in intensity was recorded between the analyzed elements, and the yield presented strong correlation with EW, and GW, moderate correlation with KNR, and weak correlation with EL. According to multivariate analysis, four parameters were positioned in PC1 (GW, EW, KNR and Y), two parameters were positioned in PC2 (RN, PRO), two parameters were positioned in PC3 (OIL, TKW), a parameter was positioned in PC4 (GYE), and two parameters were independent positioned (EL, HW). Two parameters presented negative action in relation to the main components (RN in PC2, and TKW in PC3), and the other parameters presented positive action. Based on similarity, cluster analysis grouped corn hybrids in clusters (Coph.Corr. = 0.775). The SV13 hybrid was highlighted in independent position in the C1 cluster, with high performance for yield ($Y_{SV13} = 2756.88 \pm 102.33$ kg ha⁻¹). In descending order, in the ranking of the hybrids were positioned in the first positions (Upper Quartile), the hybrid SV13, followed by the hybrids SV1, SV8, SV7 and SV11.

Keywords: comparative crop, corn hybrids, productivity elements, quality indices, ranking, yield

INTRODUCTION

Morphological parameters of plants, agronomic characters, yield and corn quality indices have been studied for the characterization of genetic resources in germoplasm collections, in corn breedings programs (Bista et al., 2022; Di Pasquale et al., 2024; Chukwu et al., 2025; Hosseini et al., 2025). As a result of the interaction "genotype × medium × crop technology", differentiated variations of plants, yield and quality element in corn have been recorded (Azrai et al., 2022; Kunwar et al., 2024; Yue et al., 2025).

The productivity elements at the level of corn ears are genetically determined, but vary in relation to the hydric factor, the nutrition factor of the plants, with the level of crop technology, but also with stress factors (Jing et al., 2023; Li et al., 2023; Iqbal et al., 2024; Lamlon et al., 2024; Zhou et al., 2025).

The yield to corn is formed on the basis of the elements of productivity at the level of plants, the ears, in the context of environmental conditions and technology practices (Bhat et al., 2024; Mncube et al., 2024; Hammami et al., 2025).

Corn production has a high economic importance, for the food industry, in the feed of animals, in the energy sector, and other areas of the economy, as a result of the quality indices of the grains (Erenstein et al., 2022; Wang et al., 2025). The quality indicators of the corn kernels vary dependent on the genotype, the soil conditions, the fertilization and the nutrition of the plants, the water regime, the technological practices as a whole (Assefa et al., 2021; Abrol et al., 2024; Zou et al., 2024; Liu et al., 2025).

The variability and interdependence of morphological parameters, productivity elements and corn yield have been studied in relation to corn breedings programs and agricultural practices (Omar et al., 2022; Babić et al., 2024; Luz et al., 2024).

Comparative crop in field experiments, with multiple locations, are particularly important to evaluate the potential of corn hybrids for the use of soil conditions, for tolerance to environmental factors, for the use of technological inputs, for efficiency and quality indices (Di Salvo et al., 2021; Ramazan et al., 2023; Ren et al., 2023; Edy et al., 2024; Singh et al., 2025).

The study evaluated a collection of 20 corn hybrids, created within ARDS Suceava, and cultivated in conditions of ARDS Lovrin, in terms of morphological, agronomic parameters and seed quality indices, and explained the position of the parameters considered by multivariate analysis.

MATERIAL AND METHODS

The study was carried out under the pedo-climatic conditions specific to the Western Plain of Romania,

within ARDS Lovrin, the agricultural year 2023-2024. Twenty hybrids created within ARDS Suceava were tested in comparative crop. The field experiment was located within the Corn Breeding Laboratory, on a plane field, chernozem soil, non-irrigated system. The climatic conditions, in terms of the thermal regime and precipitation during the experimental period are preceded in figure 1.

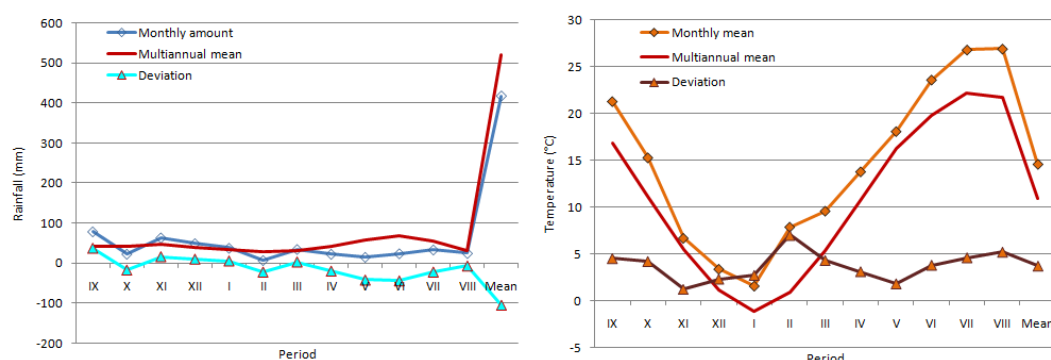


Figure 1. Climatic data

The corn hybrids were noted in the experiment with the SV1 to SV20 codes. Each hybrid has been cultivated in repetitions, randomized. A conventional technology was ensured for the preparation of the land, sown and the maintenance of the crop during the vegetation period. At the harvesting maturity, 99 BBCH Code (Meier, 2001), samples of sciences were collected from each experimental variant.

Based on the experimental protocol, in accordance with the purpose of the study, they were determined: ear length (EL, cm), row number (RN), kernel number in row (KNR), ear weight (EW, KG), grains weight (GW), grains yield in ear (GYE, %), yield (kg ha^{-1}), thousand kernel weight (TKW, g), hectoliter weight (HW, kg hl^{-1}), protein content (PRO, %), and oil content (OIL, %).

Experimental data, mean values, were evaluated by descriptive statistical analysis, ANOVA test, correlation analysis, multivariate analysis, cluster analysis, ranking analysis, in order to understand the position and the interaction of the parameters, to evaluate the degree of similarity of the hybrids, and the performance of the hybrids. Past's software (Hammer et al., 2001), JASP (2022) and the calculation module in Excel were used to analyze the experimental data.

RESULTS AND DISCUSSIONS

The study did a synthetic analysis of the morphological, agronomic and quality parameters for corn hybrids within the collection provided by ARDS Suceava. Based on the descriptive statistical analysis, the values in Table 1 resulted. According to ANOVA Test, the experimental data presented the statistical safety ($\alpha = 0.05$), Table 2.

Table 1. Results of descriptive statistical analysis

Parameters	EL	RN	KNR	EW	GW	GYE	Y	TKW	HW	PRO	OIL
N	20	20	20	20	20	20	20	20	20	20	20
Min	16.00	12.00	23.50	0.54	0.41	70.60	1023.34	136.00	71.55	9.45	5.15
Max	20.30	17.00	46.00	1.30	1.04	86.00	2756.88	229.00	83.70	12.40	6.05
Mean	17.44	14.55	36.90	0.91	0.74	80.27	1815.39	195.95	77.45	10.69	5.65
Std. error	0.29	0.29	1.09	0.05	0.04	0.85	102.33	4.85	0.68	0.18	0.06
Stand. dev	1.32	1.32	4.87	0.22	0.17	3.81	457.65	21.67	3.04	0.79	0.27
Median	17.15	14.50	36.25	0.96	0.78	80.95	1750.35	199.00	76.95	10.60	5.70
25 prentil	16.50	14.00	34.63	0.76	0.63	79.20	1485.87	183.50	75.71	10.19	5.46
75 prentil	18.00	15.75	40.13	1.07	0.83	83.05	2256.51	208.00	78.76	11.23	5.80
Geom. mean	17.39	14.49	36.57	0.89	0.72	80.18	1759.64	194.71	77.39	10.67	5.65
Coeff. var	7.55	9.05	13.21	23.60	23.11	4.74	25.21	11.06	3.93	7.39	4.78

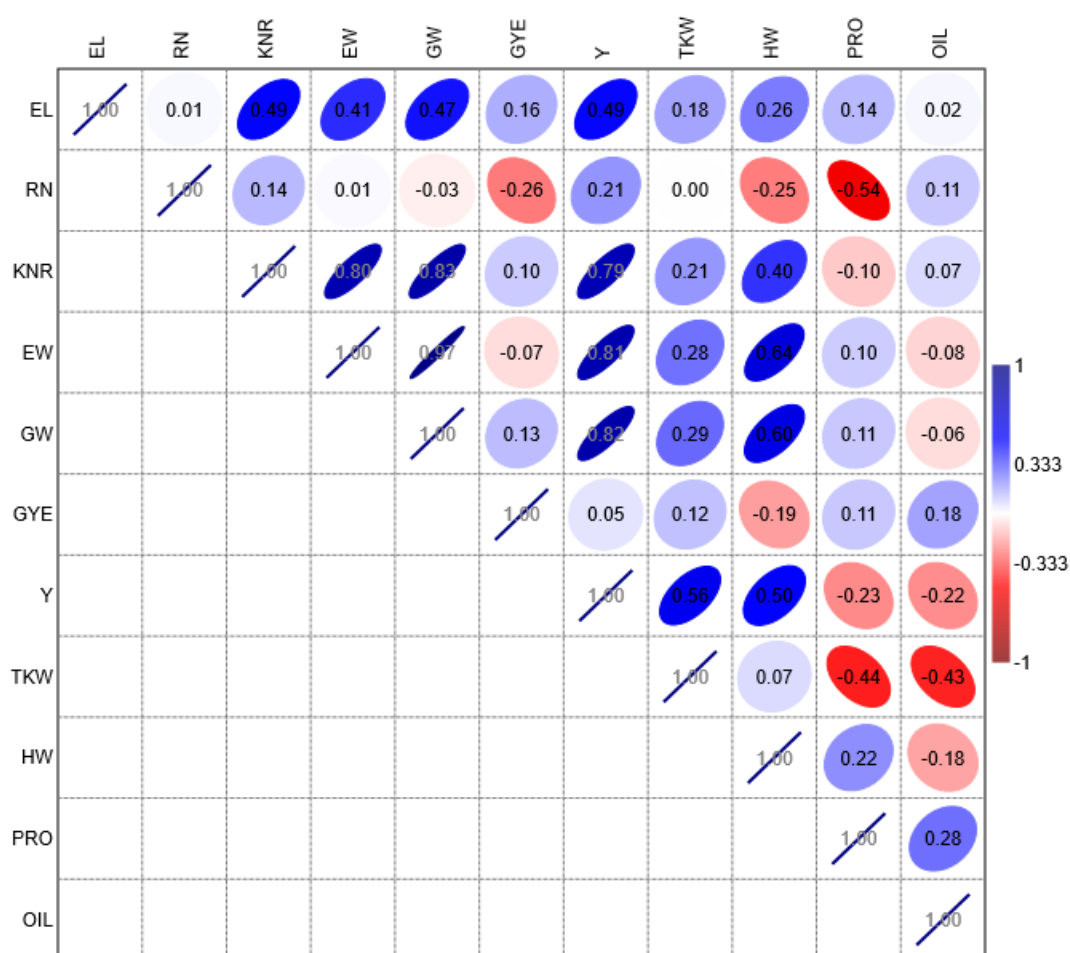
Table 2. ANOVA Test

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	57717242	10	5771724	302.3866	2.1E-118	1.876216
Within Groups	3989232	209	19087.24			
Total	61706474	219				

Alpha = 0.05

In the conditions of the study, in the comparative crop of the 20 corn hybrids, moderate variability was registered in the case of the EW parameter, with CV = 23.60, in the case of the GW parameter, with CV = 23.11, and in the case of the yield (Y), with CV = 25.21. In the case of the other morphological parameters (EL, RN, KNR, Gye), and parameters and quality indices in seeds (TKW, HW, PRO, OIL), low variability were registered, table 1.

Positive and negative correlation, of different levels of intensity was recorded between morphological parameters, yield, parameters and quality indices in corn seeds, figure 2. The yield presented strong correlation with the EW parameter ($r = 0.81$), and with the GW parameter ($r = 0.82$). Moderate correlation was registered between the yield and the KNR parameter ($r = 0.79$), and the weak correlation was recorded with EL parameter ($r = 0.49$).

**Figure 2.** Correlations at the level of the elements analyzed

In order to understand the positioning of the parameters and indices analyzed for corn hybrids in relation to the main components, multivariate analysis has been applied. The data from table 3 resulted, with the characteristics of the components in table 4, in Chi-Squared Test conditions, Value model = 38.773, DF = 17, $p = 0.002$.

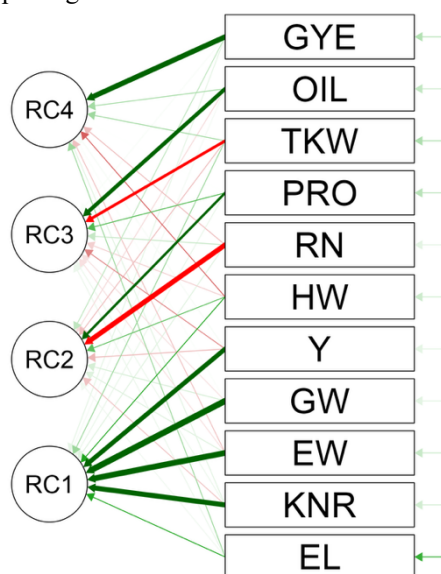
Table 3. Component loadings

	PC1	PC2	PC3	PC4	Uniqueness
GW	0.954				0.070
EW	0.938				0.077
KNR	0.902				0.150
Y	0.880				0.073
RN		-0.900			0.123
PRO		0.779			0.163
OIL			0.848		0.207
TKW			-0.796		0.190
GYE				0.910	0.137
EL					0.547
HW					0.221

Table 4. Component characteristics

	Unrotated solution			Rotated solution		
	Eigenvalue	Proportion var.	Cumulative	SumSq. Loadings	Proportion var.	Cumulative
Component 1	4.366	0.397	0.397	4.224	0.384	0.384
Component 2	2.003	0.182	0.579	1.772	0.161	0.545
Component 3	1.392	0.127	0.706	1.753	0.159	0.704
Component 4	1.28	0.116	0.822	1.292	0.117	0.822

According to the data in table 3, four parameters with positive action, GW with $r = 0.954$, EW with $r = 0.938$, KNR with $r = 0.902$, and Y with $r = 0.889$ were included in the PC1. In PC2, RN with very strong negative action $r = -0.900$, and PRO with moderate positive action, $R = 0.779$ were included. In PC3 the OIL quality index, with strong positive action, $r = 0.848$ and the TKW parameter with moderate negative action, $r = -0.796$ were included. In PC4 the GYE parameter, with very strong positive action, $r = 0.910$ has been included. Parameters EL and HW have positioned themselves independently of the main components. The graphic representation of the parameters as a classification on the main components is presented in figure 3, and the Component – Eigenvalue relationship in figure 4.

**Figure 3.** Framing the parameters on the main components

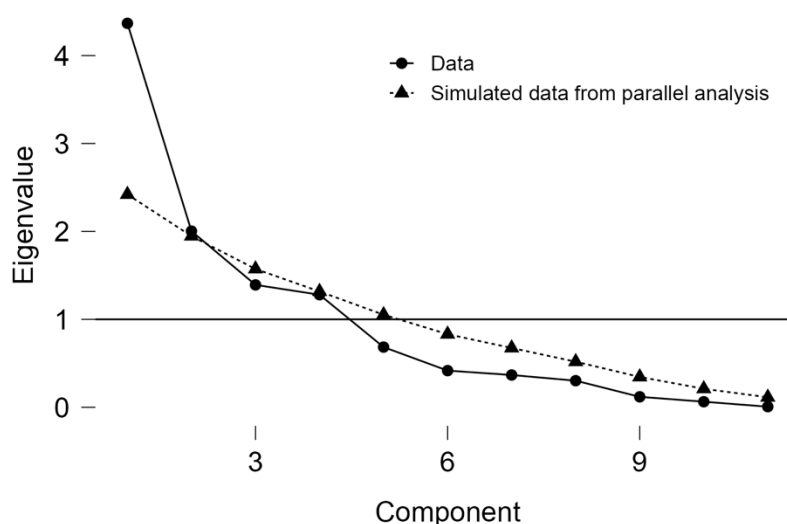


Figure 4. Graphic distribution of Eigenvalue-Component relationship

Based on the 11 parameters considered in the characterization of corn hybrids, the cluster analysis generated the cluster diagram in figure 5 (Coph.Corr. = 0.775). The corn hybrids were grouped in two clusters, in conditions of similarity. The highest level of similarity was recorded between the SV3 and SV4 hybrids, with SDI = 13.84. The full set of SDI values is presented in table 5.

Independent position in the C1 cluster occupied the SV13 hybrid, with the maximum value of the yields in the series of tested hybrids ($Y_{SV13} = 2756.88 \pm 102.33 \text{ kg ha}^{-1}$). In the same cluster, five other hybrids were positioned, in two sub-clusters, with high performances for one or more parameters (SV7, SV1), (SV15), (SV8, SV20) respectively.

In the C2 cluster, to the right of the dendrogram, five hybrids with lower performances were positioned as a whole, respectively (SV14, (SV5, (SV2, SV6), SV19). The other hybrids were positioned in the sub-clusters in the center of the dendrogram, with mean values of the elements of productivity, yield and determined quality indices.

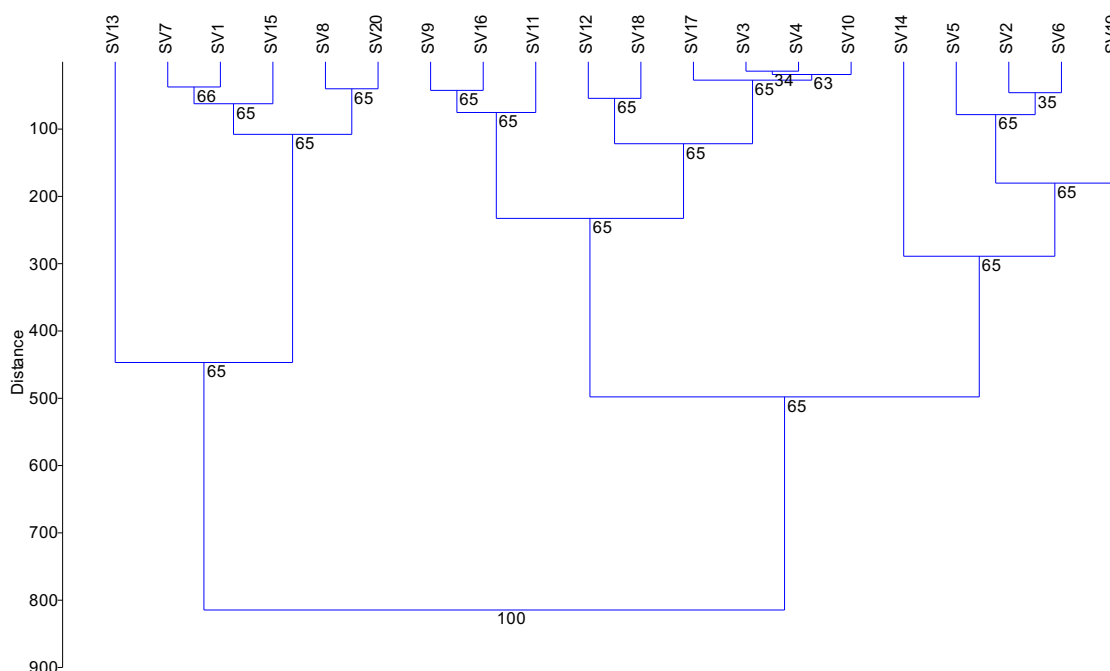
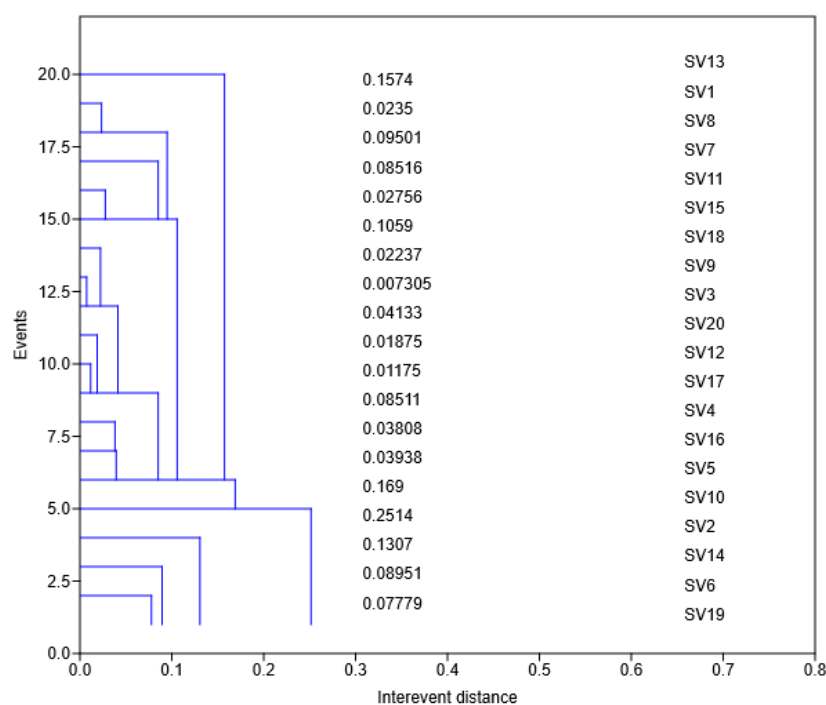


Figure 5. Cluster diagram with the degree of association of genotypes based on similarity

Table 5. SDI values for corn genotypes based on registered items

	SV1	SV2	SV3	SV4	SV5	SV6	SV7	SV8	SV9	SV10	SV11	SV12	SV13	SV14	SV15	SV16	SV17	SV18	SV19	SV20
SV1		1116.30	765.29	771.89	1113.60	1151.20	37.37	126.02	496.40	759.83	439.77	666.96	366.16	1368.80	79.96	530.65	742.47	615.35	950.66	163.57
SV2	1116.30		351.38	345.23	60.50	45.91	1081.10	991.18	621.38	356.57	676.74	450.03	1482.20	253.88	1037.30	585.81	374.60	501.27	167.38	952.98
SV3	765.29	351.38		13.84	350.26	387.76	729.86	640.40	270.14	15.12	325.57	102.86	1131.30	603.57	686.20	234.80	24.87	150.94	186.03	601.98
SV4	771.89	345.23	13.84		343.41	381.63	736.36	647.13	276.54	22.68	332.23	110.62	1137.90	596.96	692.74	241.39	30.41	157.86	178.88	608.64
SV5	1113.60	60.50	350.26	343.41		96.46	1077.90	989.42	617.20	357.61	674.28	452.11	1479.70	258.54	1034.30	584.05	372.24	500.95	168.04	950.60
SV6	1151.20	45.91	387.76	381.63	96.46		1116.00	1025.70	657.60	391.92	712.12	484.32	1516.60	224.91	1072.30	621.14	411.06	536.17	205.32	987.78
SV7	37.37	1081.10	729.86	736.36	1077.90	1116.00		92.77	460.71	724.55	404.38	631.93	402.00	1333.20	44.72	495.28	706.95	580.01	915.18	128.81
SV8	126.02	991.18	640.40	647.13	989.42	1025.70	92.77		372.62	634.66	315.17	541.46	491.00	1243.90	51.08	405.79	617.77	490.16	825.83	40.14
SV9	496.40	621.38	270.14	276.54	617.20	657.60	460.71	372.62		265.90	59.33	177.19	862.49	872.87	417.10	42.49	246.92	124.11	455.20	333.56
SV10	759.83	356.57	15.12	22.68	357.61	391.92	724.55	634.66	265.90		320.34	94.53	1125.60	609.44	680.84	229.38	26.59	144.85	191.88	596.44
SV11	439.77	676.74	325.57	332.23	674.28	712.12	404.38	315.17	59.33	320.34		228.58	805.79	929.02	360.69	91.25	302.74	176.30	511.00	276.54
SV12	666.96	450.03	102.86	110.62	452.11	484.32	631.93	541.46	177.19	94.53	228.58		1032.40	703.35	588.21	138.14	83.64	54.33	286.11	503.59
SV13	366.16	1482.20	1131.30	1137.90	1479.70	1516.60	402.00	491.00	862.49	1125.60	805.79	1032.40		1734.80	445.53	896.62	1108.50	981.10	1316.70	529.36
SV14	1368.80	253.88	603.57	596.96	258.54	224.91	1333.20	1243.90	872.87	609.44	929.02	703.35	1734.80		1289.60	838.22	626.32	753.95	418.33	1205.50
SV15	79.96	1037.30	686.20	692.74	1034.30	1072.30	44.72	51.08	417.10	680.84	360.69	588.21	445.53	1289.60		451.66	663.28	536.38	871.53	84.89
SV16	530.65	585.81	234.80	241.39	584.05	621.14	495.28	405.79	42.49	229.38	91.25	138.14	896.62	838.22	451.66		212.15	85.62	420.11	367.39
SV17	742.47	374.60	24.87	30.41	372.24	411.06	706.95	617.77	246.92	26.59	302.74	83.64	1108.50	626.32	663.28	212.15		128.99	208.51	579.21
SV18	615.35	501.27	150.94	157.86	500.95	536.17	580.01	490.16	124.11	144.85	176.30	54.33	981.10	753.95	536.38	85.62	128.99		336.13	451.98
SV19	950.66	167.38	186.03	178.88	168.04	205.32	915.18	825.83	455.20	191.88	511.00	286.11	1316.70	418.33	871.53	420.11	208.51	336.13		787.40
SV20	163.57	952.98	601.98	608.64	950.60	987.78	128.81	40.14	333.56	596.44	276.54	503.59	529.36	1205.50	84.89	367.39	579.21	451.98	787.40	

Based on all the parameters considered, the ranking of corn hybrids was made, figure 6. The SV13 hybrid ranked first, followed by the SV1, SV8, SV7 and SV11 hybrids. The distribution of hybrids in the confidence range, based on the yield (Y , kg ha^{-1}) is presented in figure 7.

**Figure 6.** Ranking of corn hybrids based on determined parameters

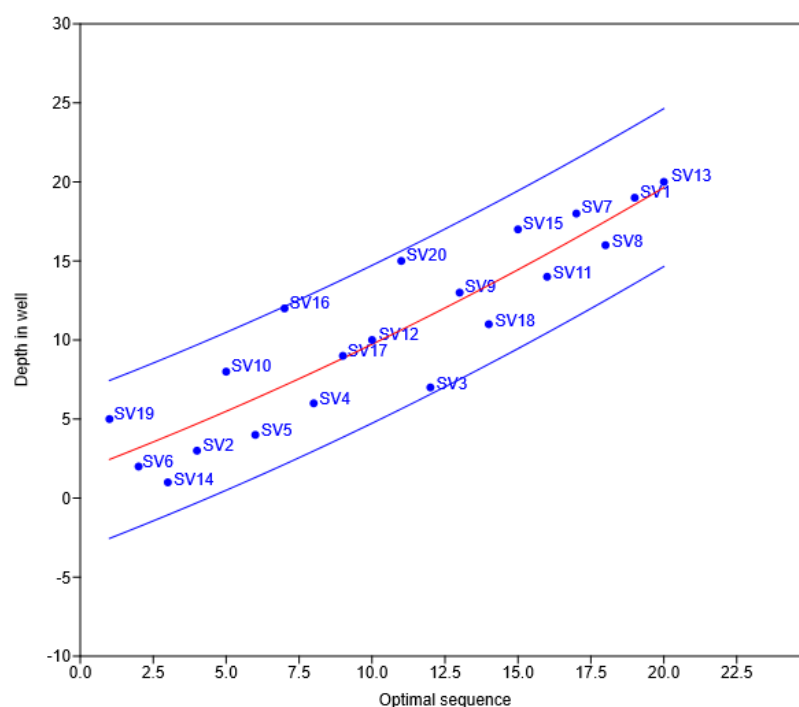


Figure 7. Distribution of corn hybrids based on yield values

The productivity elements at the level of corn ears were analyzed in relation to the potential of some genotypes, with the density of plants, with technology elements, especially fertilization and irrigation, but also in relation to environmental factors (Ezin et al. 2022; Wang et al., 2023; Wang et al., 2025; Zhou et al., 2025). Six parameters at the level of corn ears, and yields were evaluated in this study at 20 corn hybrids, in comparative crop, non-irrigated system. Moderate variability has been recorded in the case of EW and GW parameters, respectively within the yield (Y).

The content of protein and oil in corn kernels have been reported in relation to various corn genotypes, with environmental conditions, fertilization rate, different technology elements (Agapie and Sala, 2022; Lu et al., 2022; Katral et al., 2024). In relation to fertilization, the protein content was reported in an experiment with 25 variants (NP fertilizer) between $5.5 \pm 0.62\%$ and $9.5 \pm 0.73\%$ (Agapie and Sala, 2022). Boldea and the Sala (2010) communicated models for optimizing fertilizers in relation to the yield and economic indicators. Genome-wide association with corn kernel protein content was reported with a variation ranged from 4.09 to 16.15%, according to Yang et al. (2024). In the case of this study, the protein varied between 9.45% (SV13) and 12.40% (SV17), and the oil content varied between 5.15% (SV6) and 6.05% (SV9 and SV17). Quality indices (PRO, and OIL) presented low variability.

The variable correlation rate was communicated at the level of plant traits and corn cob parameters (Magar et al., 2021; Wang et al., 2023). In the context of the present study, the quality indices (PRO, OIL) showed low, insignificant correlation values with the other parameters studied. TKW and HW parameters showed weak correlation with yield and with certain morphological parameters of the ears. Yield showed positive, strong and moderate correlation with certain morphological parameters of the ears (e.g. $r = 0.82$ between Y and GW, $r = 0.81$ between Y and EW, $r = 0.79$ between Y and KNR). Among the morphological parameters of the ears, a very strong correlation was recorded ($r = 0.97$ between GW and EW, $r = 0.83$ between GW and KNR, respectively $r = 0.80$ between EW and KNR).

Agronomic parameters, quality indices and efficiency were studied by multivariate analysis with corn genotypes, practice differentiated by crop and environmental factors (Yadav and Shukla, 2022; Chaves et al., 2023; Guo et al., 2024). The association of the morphological parameters, the yield and the quality indicillo of the seeds with the main components was obtained in this study based on PCA. The multivariate analysis showed the grouping of parameters, the mode and intensity of action in relation to the main components.

The cluster grouping of the corn hybrids based on similarity, and the value hierarchy of hybrids also resulted by specific statistical analyzes, information that contributes to an assembly painting for understanding the morphological parameters, of the efficiency, and the quality elements of the seeds within the collection of studied hybrids.

CONCLUSIONS

The corn hybrids created at ARDS Suceava, and tested under the specific conditions of the Western Plain of Romania, ARDS Lovrin, expressed differentiated the genetic potential for the formation of the morphological parameters of the ears, the yield, and of some seed quality indices.

Ear weight (EW), grains weight (GW) parameters, and yield (Y), presented moderate variability, and the other quality parameters and indices presented low variability.

The efficiency presented a strong correlation with the EW parameter ($r = 0.81$), and with the GW parameter ($r = 0.82$), moderate correlation with the KNR parameter ($r = 0.79$), and poor correlation with EL parameter ($r = 0.49$).

The multivariate analysis explained the positioning of the parameters in relation to the main components: four parameters in PC1 (GW, EW, KNR, and Y), two parameters in PC2 (RN, Pro), two parameters in PC3 (OIL, TKW), one parameter in PC4 (GYE), and two parameters with independent position (EL, HW). Two parameters have presupposed negative action (RN, TKW), and the other parameters have presupposed positive action.

Cluster analysis has grouped corn hybrids for similarity, in relation to all parameters considered in the characterization of hybrids. Independent position in the C1 cluster occupied the SV13 hybrid, with the maximum value of the yields in the series of tested hybrids ($Y_{SV13} = 2756.88 \pm 102.33 \text{ kg ha}^{-1}$).

The ranking of the hybrids, by simultaneous analysis of the parameters, has ranked the first five positions (Upper Quartile) the hybrids SV13, SV1, SV8, SV7, SV11.

The information provided by this study is useful for understanding the mode of grouping and action of the parameters considered in relation to the main components, with utility for the corn breeding program, but also for the adjustment of agricultural technologies.

ACKNOWLEDGMENTS

The authors thank SCDA Lovrin for facilitating this study. The present data were generated following the implementation of the ADER 2.1.2 project.

REFERENCES

1. Abrol V., Sharma P., Chary G.R., Srinivasarao Ch., Sankar G.R.M., Singh B., Kumar A., Hashem A., Ibrahimova U., Abd-allah E.F., Kumar M. Integrated organic and mineral fertilizer strategies for achieving sustainable maize yield and soil quality in dry sub-humid inceptisols. *Scientific Reports*, 2024, 14, 27227. <https://doi.org/10.1038/s41598-024-74727-4>
2. Agapie A.L., Sala F. The variation of protein content in maize grains in relation to the fertilization level. *Scientific Papers Series Management, Economic Engineering in Agriculture & Rural Development*, 2022, 22(4), 31-38.
3. Assefa B.T., Chamberlin J., van Ittersum M.K., Reidsma P. Usage and impacts of technologies and management practices in Ethiopian smallholder maize production. *Agriculture*, 2021, 11(10), 938. <https://doi.org/10.3390/agriculture11100938>
4. Azrai M., Efendi R., Muliadi A., Aqil M., Suwarti, Zainuddin B., Syam A., Junaedi, Syah U.T., Dermail A., Marwiyah S., Suwarno W.B. Genotype by environment interaction on tropical maize hybrids under normal irrigation and waterlogging conditions. *Frontiers in Sustainable Food Systems* (2022, 6, 913211. doi: 10.3389/fsufs.2022.913211
5. Babić V., Nikolić V., Babić M., Kravić N., Pavlov J., Žilić S., Camdžija Z., Filipović M. Elite maize lines having variability in quality parameters – A valuable starting material for grain quality-oriented breeding programs. *Agriculture*, 2024, 14(12), 2122. <https://doi.org/10.3390/agriculture14122122>
6. Bhat S.A., Qadri S.A.A., Dubbey V., Sofi I.B., Huang N.-F. Impact of crop management practices on maize yield: Insights from farming in tropical regions and predictive modeling using machine learning. *Journal of Agriculture and Food Research*, 2024, 18, 101392. <https://doi.org/10.1016/j.jafr.2024.101392>
7. Bista P., Thapa S., Rawal S., Dhakal D., Joshi D. Agro-morphological characterization and estimation of genetic parameters of spring maize hybrids in the inner plains of Far-West Nepal. *International Journal of Agronomy*, 2022(1), 4806266. <https://doi.org/10.1155/2022/4806266>
8. Boldea M., Sala F. Optimizing economic indicators in the case of using two types of state-subsidized chemical fertilizers for agricultural production. *AIP Conference Proceedings*, 2010, 1281, 1390-1393. <https://doi.org/10.1063/1.3497988>
9. Chaves A.R.D., Moraes L.G., Montañó A.S., da Cunha F.F., de Faria Theodoro G. Analysis of principal components for the assessment of silage corn hybrid performance under water deficit. *Agriculture* 2023, 13(7), 1335. <https://doi.org/10.3390/agriculture13071335>
10. Chukwu S.C., Okporie E.O., Chukwu G.C., Anyanwu C.C., Teresia K.N., Awala S.K., Rafii M.Y., Oladosu Y.A., Olalekan K.K. Assessment of agro-morphological performance, genetic parameters and clustering

- pattern of early maturing high yielding maize (*Zea mays* L.) genotypes developed through NC II. Discover Plants, 2025, 2, 109. <https://doi.org/10.1007/s44372-025-00201-8>
11. Di Pasquale G.M., Stagnati L., Lezzi A., Lanubile A., Marocco A., Rossi G., Busconi M. Morphological and genetic characterization of maize landraces adapted to marginal hills in North-West Italy. Plants, 2024, 13(7), 1030. <https://doi.org/10.3390/plants13071030>
 12. Di Salvo J.I., Lee C., Salmerón M. Regional multi-environment analysis of corn productivity and yield stability as impacted by hybrid maturity. Field Crops Research, 2021, 262, 108025. <https://doi.org/10.1016/j.fcr.2020.108025>
 13. Edy, Makkulawu A.T., Aminah, Subaedah St. Multilocation test of prospective composite sticky corn varieties with high production in Indonesia. International Journal of Agronomy, 2024, 2024, 5511045. <https://doi.org/10.1155/ijoa/5511045>
 14. Erenstein O., Jaleta M., Sonder K., Mottaleb K., Prasanna B.M. Global maize production, consumption and trade: Trends and R&D implications. Food Security, 2022, 14, 1295-1319. <https://doi.org/10.1007/s12571-022-01288-7>
 15. Ezin V., Kpanougo C.M.I., Ahanchede A. Genetic diversity and environmental influence on morphological and yield parameters of maize in Benin. Heliyon, 2022, 8(6), e09670. <https://doi.org/10.1016/j.heliyon.2022.e09670>
 16. Guo Z., Han J., Zhang Y., Zhuang H. The impact of high-temperature treatments on maize growth parameters and soil nutrients: A comprehensive evaluation through principal component analysis. PLoS One, 2024, 19(8), e0309070. <https://doi.org/10.1371/journal.pone.0309070>
 17. Hammami M.D.E., Lasram A., Kthiri Z., Boukef S., Hamada W., Revilla p., Karmous C. Assessing yield and productivity gaps in Tunisian maize cropping system. Agronomy, 2025, 15(2), 331. <https://doi.org/10.3390/agronomy15020331>
 18. Hammer Ø., Harper D.A.T., Ryan P.D. PAST: Paleontological Statistics software package for education and data analysis. Palaeontologia Electronica, 2001, 4(1), 1-9.
 19. Hosseini S.M.S., Shiri M., Mostafavi K., Mohammadi A., Miri S.M. Genetic analysis and association detection of agronomic traits in maize genotypes. Scientific Reports, 2025, 15, 399. <https://doi.org/10.1038/s41598-024-84471-4>
 20. Iqbal W., Khan A., Jamal A., Radicetti E., Elsadek M.F., Ali M.A., Mancinelli R. Optimizing maize productivity and soil fertility: Insights from tillage, nitrogen management, and hydrochar applications. Land, 2024, 13(8), 1329. <https://doi.org/10.3390/land13081329>
 21. JASP Team (2022). JASP (Version 0.16.2) [Computer software].
 22. Jing L., Weng B., Yan D., Zhang S., Bi W., Yan S. The persistent impact of drought stress on the resilience of summer maize. Frontiers in Plant Science, 2023, 14, 1016993. <https://doi.org/10.3389/fpls.2023.1016993>
 23. Katral A., Hossain F., Zunjare R.U., Ragi S., Kasana R.K., Duo H., Gopinath I., Mehta B.K., Guleria S.K., Thimmegowda V., Vasudev S., Kumar B., Karjagi C.G., Pandey S., Neeraja C.N., Yadava D.K., Muthusamy V. Maize genotypes with favourable *dgat1-2* and *fatb* alleles possess stable high kernel oil and better fatty acid health and nutritive indices. International Journal of Biological Macromolecules, 2024, 278(Pt 3), 134848. <https://doi.org/10.1016/j.ijbiomac.2024.134848>
 24. Kunwar C.B., Basnet B., Sunuwar S., Mahato D.N., Chaudhari R., Upadhyia J., Pokhrel P. Unraveling genotype-by-environment interaction in maize using cutting edge statistical tools: Innovative empirical selection for increased yield stability. Ecological Genetics and Genomics, 2024, 32, 100249. <https://doi.org/10.1016/j.egg.2024.100249>
 25. Lamlon S.F., Abdelghany A.M., Ren H., Ali H.M., Usman M., Shaghalen H., Hamoud Y.A., El-Sorady G.A. Revitalizing maize growth and yield in water-limited environments through silicon and zinc foliar applications. Heliyon, 2024, 10(15), e35118. <https://doi.org/10.1016/j.heliyon.2024.e35118>
 26. Li Y., Zhang P., Sheng W., Zhang Z., Rose R.J., Song Y. Securing maize reproductive success under drought stress by harnessing CO₂ fertilization for greater productivity. Frontiers in Plant Science, 2023, 14, 1221095. <https://doi.org/10.3389/fpls.2023.1221095>
 27. Liu C., Si B., Zhao Y., Wu Z., Lu X., Chen X., Han X., Zhu Y., Zou W. Drivers of soil quality and maize yield under long-term tillage and straw incorporation in Mollisols. Soil and Tillage Research, 2025, 246, 106360. <https://doi.org/10.1016/j.still.2024.106360>
 28. Lu X., Zhou Z., Wang Y., Wang R., Hao Z., Li M., Zhang D., Yong H., Han J., Wang Z., Weng J., Zhou Y., Li X. Genetic basis of maize kernel protein content revealed by high-density bin mapping using recombinant inbred lines. Frontiers in Plant Science, 2022, 13, 1045854. <https://doi.org/10.3389/fpls.2022.1045854>
 29. Luz L.S., Reis H.M.D., de Leon da Costa N.M.E.P., Carvalho F.R., Caixeta D.G., DeLima R.O. Combining ability for agronomic traits among commercial maize hybrids under low and high nitrogen inputs targeting the development of breeding populations. PLoS One, 2024, 19(10), e0309296. <https://doi.org/10.1371/journal.pone.0309296>

30. Magar B.T., Acharya S., Gyawali B., Timilsena K., Upadhayaya J., Shrestha J. Genetic variability and trait association in maize (*Zea mays* L.) varieties for growth and yield traits. *Heliyon*, 2021, 7(9), e07939. <https://doi.org/10.1016/j.heliyon.2021.e07939>
31. Meier U. Growth stages of mono-and dicotyledonous plants e BBCH monograph. Federal Biological Research Centre for Agriculture and Forestry, 2001, 158 pp.
32. Mncube T.L., Phiri E.E., Mothapo P.N., Rugare J.T., Pieterse P.J., Mloza-Banda H.R. Characterising productivity factors affecting maize (*Zea mays*) production in a smallholder crop-livestock system. *Agricultural Research*, 2024, 13, 124-136. <https://doi.org/10.1007/s40003-023-00674-7>
33. Omar M., Rabie H.A., Mowafi S.A., Othman H.T., El-Moneim D.A., Alharbi K., Mansour E., Ali M.M.A. Multivariate analysis of agronomic traits in newly developed maize hybrids grown under different agro-environments. *Plants (Basel)*, 2022, 11(9), 1187. <https://doi.org/10.3390/plants11091187>
34. Ramazan S., Jan N., John R. Comparative protein analysis of two maize genotypes with contrasting tolerance to low temperature. *BMC Plant Biology*, 2023, 23(1), 183. <https://doi.org/10.1186/s12870-023-04198-8>
35. Ren Y., Li Q., Du X., Zhang Y., Wang H., Shi G., Wei M. Analysis of corn yield prediction potential at various growth phases using a process-based model and deep learning. *Plants*, 2023, 12(3), 446. <https://doi.org/10.3390/plants12030446>
36. Singh A.K., Elango D., Raigne J., der Laan L.V., Rairdin A., Soregaon C., Singh A. Plant-based protein crops and their improvement: Current status and future perspectives. *Crop Science*, 2025, 65(1), e21389. <https://doi.org/10.1002/csc2.21389>
37. Wang J., Zhao S., Zhang Y., Lu X., Du J., Wang C., Wen W., Guo X., Zhao C. Investigating the genetic basis of maize ear characteristics: a comprehensive genome-wide study utilizing high-throughput phenotypic measurement method and system. *Frontiers in Plant Science*, 2023, 14, 1248446. <https://doi.org/10.3389/fpls.2023.1248446>
38. Wang Z., Guo Y., Xie R., Wang K., Zhang G., Hou P., Xue J., Gao S., Shen D., Fang L., Zhou L., Sun L., Bao S., Huo Z., Ming B., Li S. Optimizing maize production: Balancing yield, quality, and economic benefits through planting density - Driven nutrient analysis. *Journal of Agriculture and Food Research*, 2025, 21, 101943. <https://doi.org/10.1016/j.jafr.2025.101943>
39. Wang Z., Wang K., Liu X., Zhu W., Deng X., Zhao Y. Effects of different base fertilizers on water use efficiency and growth of maize during growth period. *Agronomy*, 2025, 15(2), 491; <https://doi.org/10.3390/agronomy15020491>
40. Yadav A., Shukla A. Prediction of maize crop yield using principal component analysis of weather parameters. *International Journal of Environment and Climate Change*, 2024, 14(10), 189-195. <https://doi.org/10.9734/ijecc/2024/v14i104479>
41. Yang X., Shaw R.K., Li L., Jiang F., Sun J., Fan X. Discovery of candidate genes enhancing kernel protein content in tropical maize introgression lines. *BMC Plant Biology*, 2024, 24, 1110. <https://doi.org/10.1186/s12870-024-05836-5>
42. Yue H., Olivoto T., Bu J., Wei J., Liu P., Wu W., Nardino M., Jiang X. Assessing the role of genotype by environment interaction as determinants of maize grain yield and lodging resistance. *BMC Plant Biology*, 2025, 25, 120. <https://doi.org/10.1186/s12870-025-06158-w>
43. Zhou D., Hou P., Zhang J., Yu C., Liu D., Huang Z., Zhang C., Wang Z., Lin Z., Chen T. Mechanism of low damage rate maize ear pre-threshing based on cob internal expansion cracking. *Biosystems Engineering*, 2025, 255, 104157. <https://doi.org/10.1016/j.biosystemseng.2025.104157>
44. Zou Y., Li L., Wang Y., Duan R., Dong H., Zhang Y., Du Z., Chen F. Growth and yield of maize in response to reduced fertilizer application and its impacts on population dynamics and community biodiversity of insects and soil microbes. *Frontiers in Plant Science*, 2024, 15, 1362905. <https://doi.org/10.3389/fpls.2024.1362905>
45. Zhou L., Shen D., Wang K., Ming B., Fang L., Wang Z., Sun L., Liu J., Zhang G., Li S. Impact of planting density and nitrogen application on maize source-sink relationships and yield under drip irrigation. *Journal of Agriculture and Food Research*, 2025, 21, 102000. <https://doi.org/10.1016/j.jafr.2025.102000>