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Effects of Seed Quality and Hybrid Type on Maize Germination and Yield in Hungary

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Abstract: After wheat and rice, maize is one of the most significant cereal crops worldwide. However, high-quality seed materials are prerequisites for stable yields, and low-quality maize seeds significantly contribute to low yields and deteriorate over time. Therefore, the present investigation aims to investigate the effects of seed quality and hybrid types on maize germination by emphasizing seed viability and vigor and their impact on maize crops' overall performance and productivity. The study was separately conducted in the laboratory and on a field experiment plot under the Department of Crop Production, Hungarian University of Agriculture and Life Sciences, in spring 2022. Nine parental lines, six hybrids, and a controlled hybrid were tested in this study. The studies were laid out using a complete randomization design (CRD) and a randomized complete block design (RCBD) in the laboratory and in the field. The results of the study showed that there was a statistically significant difference between genotypes and number of days and their interaction in seed vigor. The parental lines showed better performance in terms of germination percentage and radicle elongation, whereas single-cross hybrids (SC) produced better plumule length. The radicle and plumule length also expanded significantly as incubation days increased. In field evaluations, as expected, hybrid lines produced better performance than parental lines, and SC hybrids were more prevalent than the other hybrids. In addition, the number of rows per ear, number of kernels per ear, 1000-kernel weight, and ear weight directly affected the final grain yield. However, further research is needed on new approaches that can assist researchers in advancing their work by considering biotic and abiotic factors to address seed-quality issues and enhance yield production.

Keywords: seed quality; *Zea mays*; germination; yield performance

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1. Introduction

Maize, or corn (*Zea mays* L.), is one of the most significant cereal crops cultivated in various regions of the world, after wheat and rice [1]. It is a staple food in many countries, especially in Africa, Latin America, and Asia [2]. Maize is consumed raw and used as food, as starch, as a sweetener, for oil beverages, for non-food products, as a coffee substitute, and as feed grain in livestock industries [3–5]. The wide adaptability of maize due to its versatility and diverse applications makes it the world's largest crop in terms of production volume [6]. This led to intense cultivation, which favored its spread [7,8]. In Hungary, maize is one of the most important crops, accounting for almost 55% of cereal production in 2020 [9]. It has surpassed wheat, barley, and other crops as the main crop grown by farmers. In 2021, the total production was 6,462,205 metric tons, which decreased to 2,803,206 metric tons in 2022 [10] due to heat waves and droughts across the continent [11]. Global climate change is leading to abiotic consequences, including increases in CO_2 concentrations, temperature, rainfall intensity, and the likelihood of extreme weather events [12]. Extreme heat, drought, and intense rainfall significantly reduce the yield of maize production [13].

Therefore, soil temperature affects maize germination and the growth of both the radicle and the shoot [14].

Hybrid maize, first grown commercially in America in the 1930s [15], is higher yielding and more disease resistant than parental lines. Hybrid maize varieties are now grown in over 95% of the world's maize-growing regions [16]. Due to favorable environmental conditions and technical competence, global hybrid maize seed production has expanded rapidly, and China, India, the United States, Brazil, Mexico, and Argentina account for more than 60% of global hybrid maize seed production [17]. In Hungary, the first hybrid was MV 5, which was registered in 1953, and since 1964, 100% of the cultivated area has been planted with hybrid maize [18]. Single crosses (SC), double crosses (DC), and three-way crosses (TC), as well as certain modified forms of these three combinations, are also utilized in commercial production [19,20]. The heterosis effect of F_1 generations is the reason for developing hybrids rather than open-pollinated varieties [21,22]. SC maize hybrids are the most productive, uniform, and expensive because both parents are inbred lines, whereas DC hybrids are more affordable due to both parents being single crosses [20]. SC hybrids are developed by crossing two unrelated parents, whereas TC hybrids involve crossing an inbred line as the male parent with a single cross as the female parent. DC hybrids involve crossing two single crosses in two stages [23].

In maize, low-quality seed has a significant impact on low yields [24]. Various circumstances may lead to a decrease in seed quality, a condition referred to as "seed deterioration." [25]. Seed quality can be determined by evaluating physical and physiological characteristics [26]. Seed quality is an essential quality measure for seed breeders because of the variation among different seed types [27]. Physical quality is determined by seed size, weight, and shape, whereas physiological quality is determined by viability and vigor [28]. Seed germination is also a complex physiological process involving water uptake by dry seeds and the emergence of radicles. Dormancy, an adaptive characteristic, prevents germination under favorable environmental conditions [29]. Temperature, light, and water ability are crucial factors for seed germination, and these elements are closely related to environmental conditions, seed physiology, and the germination process [30]. In artificial conditions, the optimal temperature for gemination is between 20 °C and 25 °C [31]. Meanwhile, water is required to hydrate protoplasmic metabolism, stimulate germination, and minimize water stress in maize seeds [32].

The initial phase of the germination process is known as imbibition, where the seed coat swells and becomes soft due to rapid water absorption [33]. This process triggers internal physiological activity, promotes respiration, and allows for the development of radicles and plumules [33,34]. Germination is defined by several physiological and morphogenetic processes, including seed energy transfer, endosperm nutrient absorption, and metabolic changes [34]. Restoration of essential processes such as transcription, translation, and DNA repair, followed by cell elongation and division, are indicators of germination [35]. Vigorous seeds promote higher germination rates, seedling strength, and germination ability, as well as higher economic yields [36], as shown in hybrid seeds [19]. Furthermore, previous studies have found that seeds of different genotypes respond differently to seed yield and quality [37].

The quality of the seed and its impact on the generation of latent and field performance are mostly determined by the seed's viability and vigor [38]. By assessing seed viability and vigor, an attempt is made to predict the number of seeds needed to avoid later declines in field performance due to a poor correlation with yield. This process is called field germination [39], and uniform and vigorous seedling germination ensures a good plant population and yield [40]. Therefore, seed evaluation and information are a source of great uncertainty for the seed industry [41]. Although many studies have characterized seed-quality parameters separately, a comprehensive study documenting the relationship between seed quality and the yield performance of different maize hybrid types has not yet been completed. This study focused on the intricacies of seed quality and hybrid types on maize germination assessment in the laboratory, with an emphasis on seed viability (germination percentage) and vigor (radicle and plumule length) and their impact on the overall performance and productivity of maize crops. The purpose of this study is to test the hypothesis that different hybrid types do not influence maize germination and yield. By exploring various parameters such as germination rate, radicle and plumule length, number of rows per ear, number of kernels per ear, 1000-kernel weight, and ear weight of different maize hybrid types, we aim to provide valuable insights and recommendations to enhance seed quality by assessing seed viability and vigor and their relationship to yield.

2. Materials and Methods

The experimental method in this research involves two parts, which are laboratory experiments and open-field experiments. Seeds of maize hybrids and lines were obtained from Szeged University, Hungary, and the Centre for Agricultural Research, Martonvásár, Hungary, and commercially available hybrids were used as the control. The seed types used in the study are listed in Table 1.

Table 1. Maize genotypes used in the sample and their descriptions.

Source	Entry	Genotypes	Description
Martonvásár	V1	B1026/17	Parent
	V2	MCS901/19	Parent
	V3	TK/15/DV	Parent
	V4	TK1083/18	Parent
	V5	TK623/18	SC Hybrid [1]
	V6	TK256/17	DC Hybrid [2]
	V7	TK222/17	TC Hybrid [3]
Szeged University	V8	GK131	Parent
	V9	GK144	Parent
	V10	GK150	Parent
	V11	GK154	Parent
	V12	GK155	Parent
	V13	GK144X150	SC Hybrid [1]
	V14	GK154X155	SC Hybrid [1]
	V15	Szegedi 521	SC Hybrid [1]
Commercial	V16	MV277	Control

[1] TC Hybrid = triple-cross hybrid, [2] SC Hybrid = single-cross hybrid, [3] DC Hybrid = double-cross hybrid.

2.1. Laboratory Experiment

A laboratory experiment was carried out at the Laboratory of Agronomy, Hungarian University of Agriculture and Life Sciences (MATE), Gödöllő, Hungary. The selected hybrids, lines, and check variety were allowed to germinate in 13.5 cm Petri dishes lined with a single sheet of Whatman filter paper as part of a standard germination test [42]. Ten millimeters of distilled water were used to moisten the filter paper, and six seeds were placed in each Petri dish, which had four replicates for all genotypes and was laid out in a completely randomized design (CRD). The seeds were then incubated for nine days in a growth chamber at a temperature of 20 °C and a relative humidity (RH) of 70%. The observations and data collection of seed viability and vigor, germination rate (%), radicle length (cm), and plumule length (cm) were conducted on days 3, 5, 7, and 9. All seeds used in this study were treated with fungicide, i.e., 10% sodium hypochlorite.

2.2. Open Field Experiment

The open field experiment was conducted in the spring season of 2022 (May to November) at the Experimental Plot of the Department of Agronomy, Hungarian University of Agriculture and Life Sciences, Hungary (47.5948303′ N, 19.3698959′ E), which is in Gödöllő, to the northeast of Budapest, Hungary. July is the warmest month, with the maximum temperature reaching 32.0 °C (89.6 °F) and the minimum temperature reaching 20.0 °C (68.0 °F). Throughout the research period, the average maximum precipitation was approximately

104.0 mm (4.09 inches), and the minimum precipitation was 24.6 mm (0.97 inches), with the highest peak occurring in September. The soil at the experimental plot consisted of sandy loam and brown forest soil (Chromic Luvisol). The humus content was 1.32%, the pH (H_2O) was 7.08, K_A 40, sand content was 49%, silt content was 25%, and clay content was 26%. The maximum, minimum, and average temperature, precipitation amount, and number of rainy days during the maize growing season are displayed in Figures 1 and 2 [43].

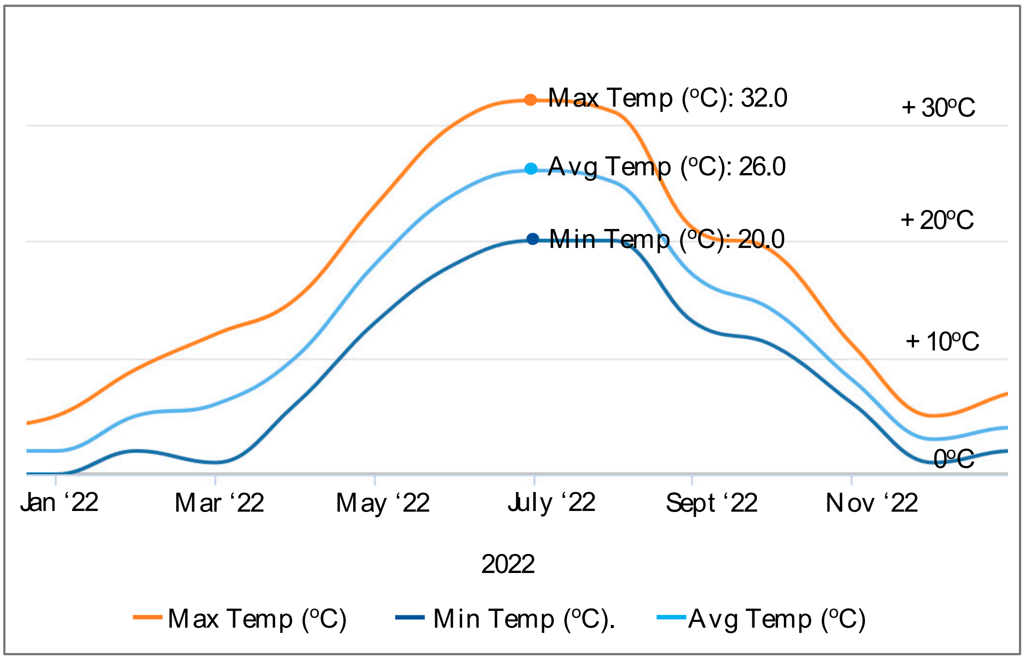

Figure 1. Max, min, and average weather temperature 2022 (Gödöllö, Hungary). https://www.worldweatheronline.com/ (accessed on 7 September 2023).

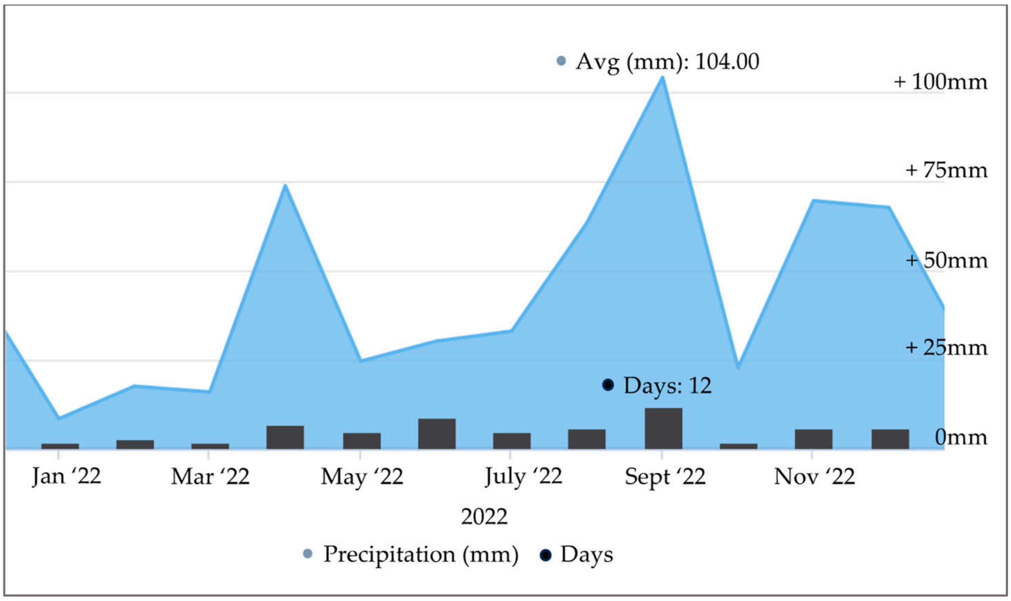

Figure 2. Average precipitation amounts and rainy days in 2022 (Gödöllö, Hungary). https://www.worldweatheronline.com/ (accessed on 7 September 2023).

2.3. Experimental Design

The experiment was laid out in a randomized complete block design (RCBD) with three replications. Each replicate included 10 plants. The maize seeds were sown on 4 May 2022 using a Wintersteiger Plotman planter at a planting density of 75,000 plants per hectare. Standard agronomic practices, such as weeding and manual irrigation to supplement rainfall as needed, were especially important in July, August, and September, when the average afternoon temperatures ranged from 27 °C to 37 °C. In the meantime, the recommended fertilizer application for maize was used [44].

2.4. Data Collection

The maize yield measured in this study was influenced by four important components: number of rows per ear, number of kernels per ear, 1000-kernel weight (g), and ear weight (g). Typically, these components are selected in this order during the growing season.

2.5. Statistical Analysis

The data from the current study were analyzed based on multivariate analysis of variance (MANOVA) using a randomize complete design (CRD) for the laboratory study. On the other hand, the open-field study adopted one-way analysis of variance (ANOVA) with randomized complete block design (CRBD). In addition, Duncan's multiple range test (DMRT) was used to compare the means with a probability of 0.05 using IBM SPSS 21 statistical analysis software and Microsoft Excel version 16.77 for descriptive statistics, including correlation analysis.

3. Results

3.1. Seed Viability and Vigor

The results of the MANOVA show that there were statistically significant differences between the two groups, the genotypes, the number of days, and their interaction on seed viability and vigor viz. germination rate (%), radicle length (cm), and plumule length (cm) for the confidence interval of 0.95 (Table 2).

Table 2. Multivariate analysis of variance (MANOVA) for germination rate (%), radicle length (cm), and plumule length (cm) of various maize genotypes on different incubation days.

Source	Dependent Variables	Sum Square	Df	Mean Square	F
Days	Germination rate (%)	388.953	3	129.651	142.246 **
	Radicle length (cm)	7824.545	3	2608.182	1681.805 **
	Plumule length (cm)	2110.986	3	703.662	1419.352 **
Genotypes	Germination rate (%)	158.109	15	10.541	11.565 **
	Radicle length (cm)	182.861	15	12.191	7.861 **
	Plumule length (cm)	51.976	15	3.465	6.989 **
Days × genotypes	Germination rate (%)	62.422	45	1.387	1.522 *
	Radicle length (cm)	247.334	45	5.496	3.544 **
	Plumule length (cm)	33.788	45	0.751	1.515 *
Error	Germination rate (%)	175.000	192	0.911	
	Radicle length (cm)	297.758	192	1.551	
	Plumule length (cm)	95.186	192	0.496	
Total	Germination rate (%)	3714.000	256		
	Radicle length (cm)	25,731.023	256		
	Plumule length (cm)	5249.053	256		

* = $p < 0.005$; ** = $p < 0.001$.

The results displayed in Table 3 show the mean values of germination rate (%), radicle length (cm), and plumule length (cm) for various maize genotypes. For the total percentage of germination, most genotypes recorded a percentage rate above the grand mean (79.69%) except for V5 (SC hybrid), V7 (TC hybrid), V8 (parent), V12 (parent), V14 (SC hybrid), and V15 (SC hybrid), which recorded a percentage rate of 79.17%, 66.67%, 54.17%, 50.00%, 33.33%, and 75.00%, respectively. Meanwhile, the highest 100% germination rate was observed in V3 (parent) and V6 (DC hybrid), followed by V2 (parent) and V13 (SC hybrid), with 95.83%, whereas V14 (SC hybrid) showed the lowest germination rate (%), which was 33.33%.

Table 3. Mean values of germination rate (%), radicle length (cm), and plumule length (cm) of various maize genotypes.

[1] Genotypes	[2] Germination Rate (%)	[3] Radicle Length (cm)	[4] Plumule Length (cm)
V1 (parent)	83.33 a–d	13.42 fg	8.23 b
V2 (parent)	95.83 ab	18.95 a	7.41 b
V3 (parent)	100 a	18.45 ab	7.54 b
V4 (parent)	87.50 abc	14.60 ef	7.45 b
V5 (SC hybrid)	79.17 bcd	16.92 a–e	7.76 b
V6 (DC hybrid)	100 a	16.37 b–e	7.22 b
V7 (TC hybrid)	66.67 de	15.86 c–f	5.79 c
V8 (parent)	54.17 e	16.78 a–e	7.91 b
V9 (parent)	83.33 a–d	11.41 g	7.42 b
V10 (parent)	91.65 abc	17.70 a–d	8.30 b
V11 (parent)	87.49 abc	13.9 f	7.65 b
V12 (parent)	50.00 ef	18.09 abc	7.75 b
V13 (SC hybrid)	95.83 ab	16.91 a–e	8.04 b
V14 (SC hybrid)	33.33 f	13.68 fg	9.88 a
V15 (SC hybrid)	75.00 cd	15.17 def	7.65 b
V16 (control)	91.67 abc	17.30 a–d	7.78 b
Grand mean	79.69	15.97	7.73
SEM (±)	2.71	0.31	0.14

Different lowercase letters (column) represent significant differences between the means ($p < 0.05$) based on Duncan's multiple range test (DMRT) and starting sequentially, with the letter (a) being the most significant; [1] sixteen genotypes that were used in this study; [2] the percentage of germination of various genotypes (%); [3] the mean length of the radicles of various genotypes (cm); [4] the mean of the length of the of various genotypes (cm).

The greatest radicle length was found in genotypes V2 (parent), V3 (parent), and V12 (parent), with 18.95 cm, 18.45 cm, and 18.09 cm, respectively. However, V9 (parent) produced the shortest radical length throughout the investigation period (11.41 cm). The study, which also focused on plumule length, found a substantial difference between the genotypes with the longest and shortest plumule lengths (V14 (parent), with 9.88 cm, and V7 (TC hybrid), with 5.79 cm), with a grand mean of 7.73 cm.

Based on observation, germination began on the second day after placing the seeds in the incubation chamber. The measurement and data collection started on the third day, once the radicle had reached more than 0.5 cm in length. Figure 3a illustrates a substantial relationship between the number of days and the percentage of germination. The results show that the percentage of germination was relatively slower and that there was no significant difference on days 3 and 5, at 36.61% and 39.62%, respectively. However, there was a significant increase in performance from day 5 to day 9 (76.04%).

The radicle length increased sharply, revealing highly significant differences, with values of 0.88 cm on day 3, 5.92 cm on day 5, 9.92 cm on day 7, and 15.97 cm on day 9 (Figure 3b). Additionally, Figure 3c shows that the length of the plumule expanded significantly as the number of incubation days increased. From 0.15 cm on day 3, the value increased to 1.64 cm on day 5, 4.08 cm on day 7, and 7.73 cm on day 9.

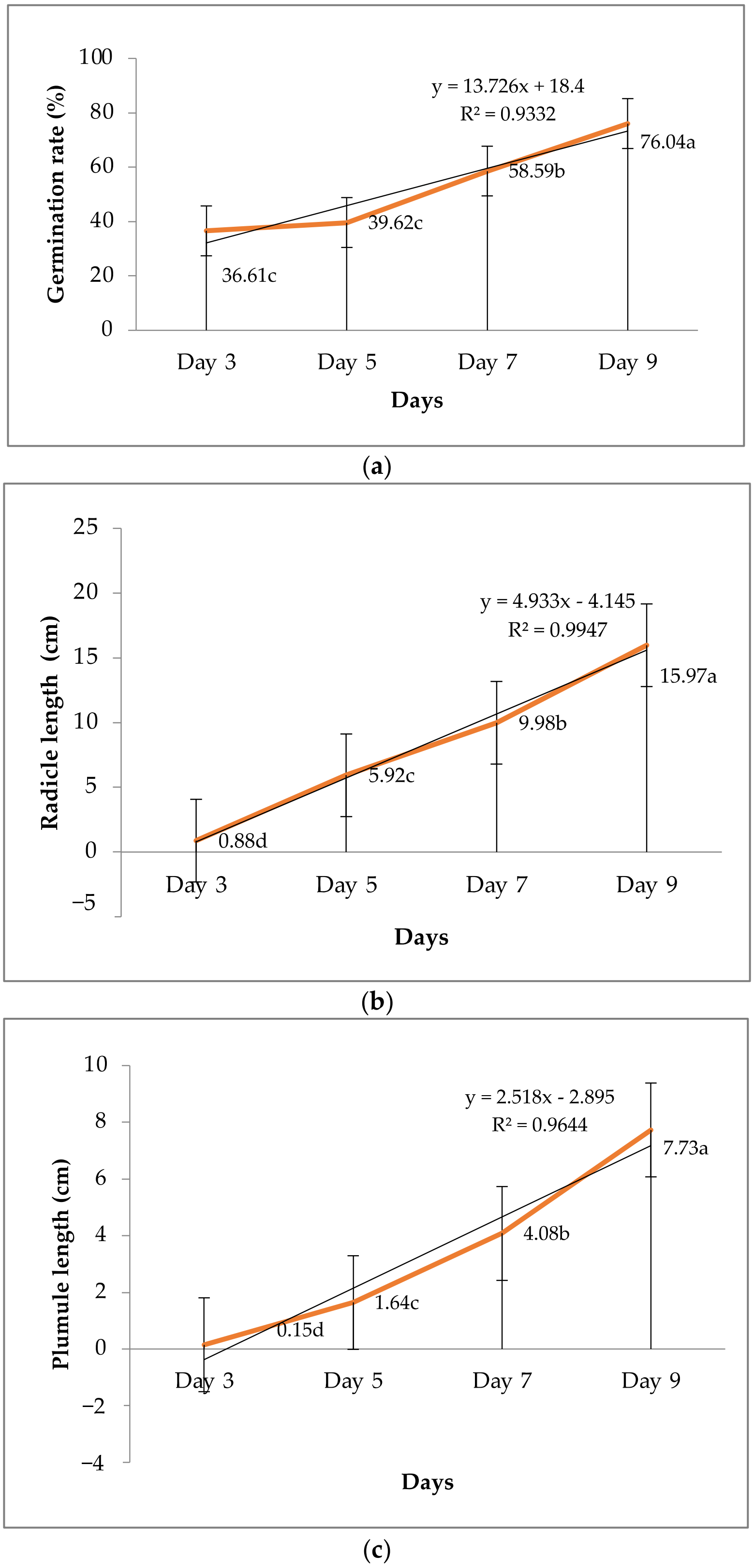

Figure 3. Seed viability and vigor in response to the incubation days. (**a**) Germination rate (%); (**b**) radicle length (cm); (**c**) plumule length (cm). Different lowercase letters represent significant differences between the means (p < 0.05) based on Duncan's multiple range test (DMRT) starting sequentially, with the letter (a) being the most significant.

3.2. Yield Performance

3.2.1. Number of Rows Per Ear

A one-way ANOVA revealed that there was a statistical difference in means between groups (F (15, 224) = [40.48], p = [0.00] (Table 4). Table 5 shows the mean (12.35), minimum (7.00), maximum (18.00), and standard deviation (2.26) of the number of rows per ear for various maize genotypes. Nevertheless, Figure 4 displays the mean value for each genotype. V14 (SC hybrid) had the highest mean (15.07), which was followed by V8 (parent) and V13 (SC hybrid), with 14.53 and 14.27, respectively. V1 (parent) generated the lowest number of rows per ear (7.87), although V16 (check variety) generated a comparable number of rows per ear, which was 13.93.

Table 4. Analysis of variance (ANOVA) for number of rows per ear of various maize genotypes.

Source		Sum of Square	df	Mean Square	F	Sig.
Rows ear^{-1}	Between groups	893.133	15	59.542	40.482	0.00
	Within groups	329.467	224	1.471		
	Total	1222.600	239			

df: Degree of freedom; Sig.: significance; significance level = $p < 0.01$.

Table 5. Mean, minimum, maximum, and standard deviation for the number of rows per ear of various maize genotypes.

Source	No.	Mean	Minimum	Maximum	Std. Deviation
Rows ear^{-1}	240	12.3500	7.00	18.00	2.26174
Valid N (listwise)	240				

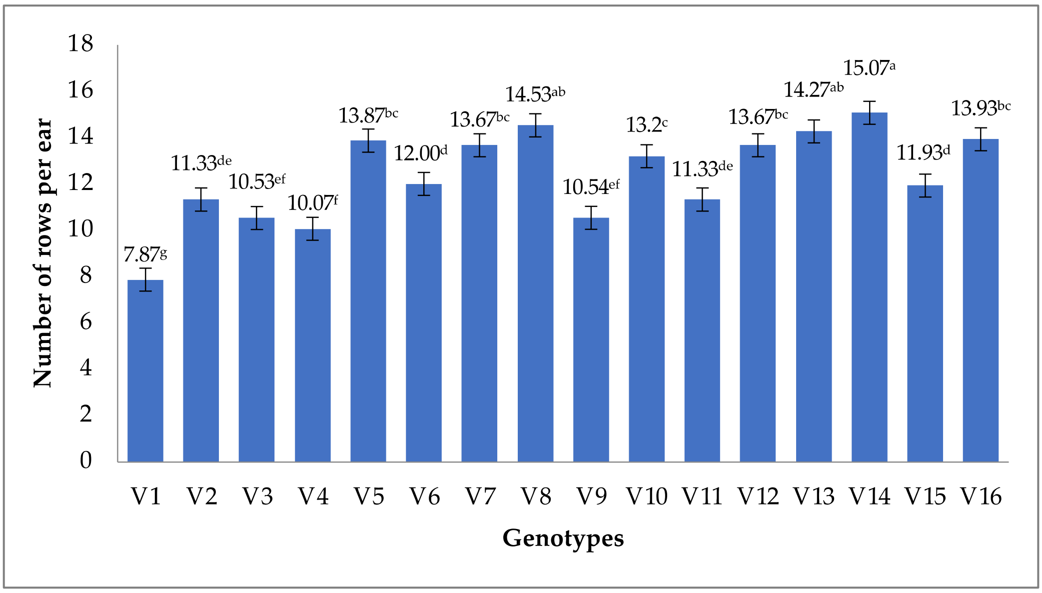

Figure 4. Histograms represent mean values of the number of rows per ear for various maize genotypes. Different lowercase letters represent significant differences between the means ($p < 0.05$) based on Duncan's multiple range test (DMRT) starting sequentially, with the letter (a) being the most significant.

3.2.2. Number of Kernels Per Ear

The results of the ANOVA in Table 6 reveal that there was a statistically significant mean between groups (F (15, 224) = [118.24], p = [0.00]. Although the mean number of kernels per ear was 214.80, the minimum value was 64.00, the maximum value was 538.00, and the standard deviation was 98.64 (Table 7). Nonetheless, Figure 5 displays the mean value for each genotype. The mean for V14 (SC hybrid) was the highest, at 436.27, and showed an astoundingly significant performance compared to other genotypes. V5 (SC hybrid) and V7 (TC hybrid) were next, with means of 329.13 and 325.67, respectively. V1 (parent) produced the lowest number of kernels per ear (74.00).

Table 6. Analysis of variance (ANOVA) for kernels per ear of various maize genotypes.

Source		Sum of Square	df	Mean Square	F	Sig.
No. of kernels per ear^{-1}	Between groups	2,064,762.863	15	137,650.858	118.243	0.000
	Within groups	260,766.993	224	1164.138		
	Total	2,325,529.796	239			

df: degree of freedom; Sig.: significance; significance level = $p < 0.01$.

Table 7. Mean, minimum, maximum, and standard deviation for kernels per ear of various maize genotypes.

Source	No.	Mean	Minimum	Maximum	Std. Deviation
No. of kernels per ear^{-1}	240	214.80	64.00	538.00	98.64203
Valid N (listwise)	240				

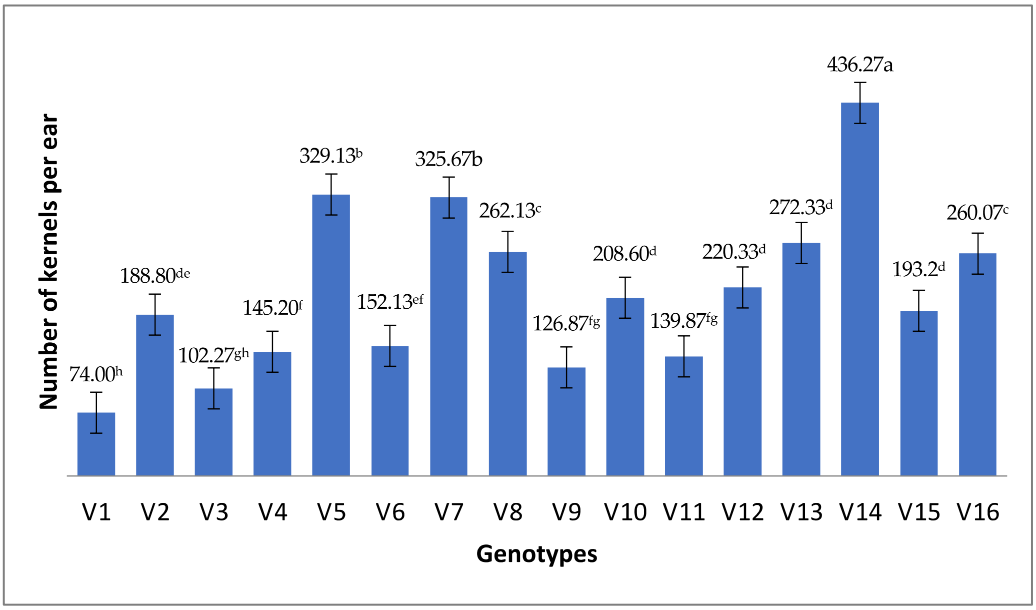

Figure 5. Histograms represent mean values of the number of kernels per ear for various maize genotypes. Different lowercase letters represent significant differences between the means ($p < 0.05$) based on Duncan's multiple range test (DMRT) starting sequentially, with the letter (a) being the most significant.

3.2.2.1. 1000-Kernel Weight (g)

According to the results of the ANOVA in Table 8, the mean difference in 1000-kernel weight between groups was highly significant (F (15, 32) = [9.56], p = [0.00]). The mean, minimum, maximum, and standard deviation values of the 1000-kernel weight for all genotypes were 318.23 g, 209.30 g, 472.20 g, and 60.59 g, respectively (Table 9). Meanwhile, Figure 6 reveals that V15 (SC hybrid) recorded the highest weight (438.87 g), whereas V3 (parent) recorded the lowest (220.33 g).

Table 8. Analysis of variance (ANOVA) for the 1000-kernel weight (g) of various maize genotypes.

Source		Sum of Square	df	Mean Square	F	Sig.
1000-kernel weight (g)	Between groups	141,061.910	15	9404.127	9.561	0.000
	Within groups	31,476.453	32	983.639		
	Total	172,538.363	47			

df: degree of freedom; Sig.: significance; significance level = $p < 0.01$.

Table 9. Mean, minimum, maximum, and standard deviation for the 1000-kernel weight (g) of various maize genotypes.

Source	No.	Mean	Minimum	Maximum	Std. Deviation
1000-kernel weight (g)	48	318.23	209.30	472.20	60.58902
Valid N (listwise)	48				

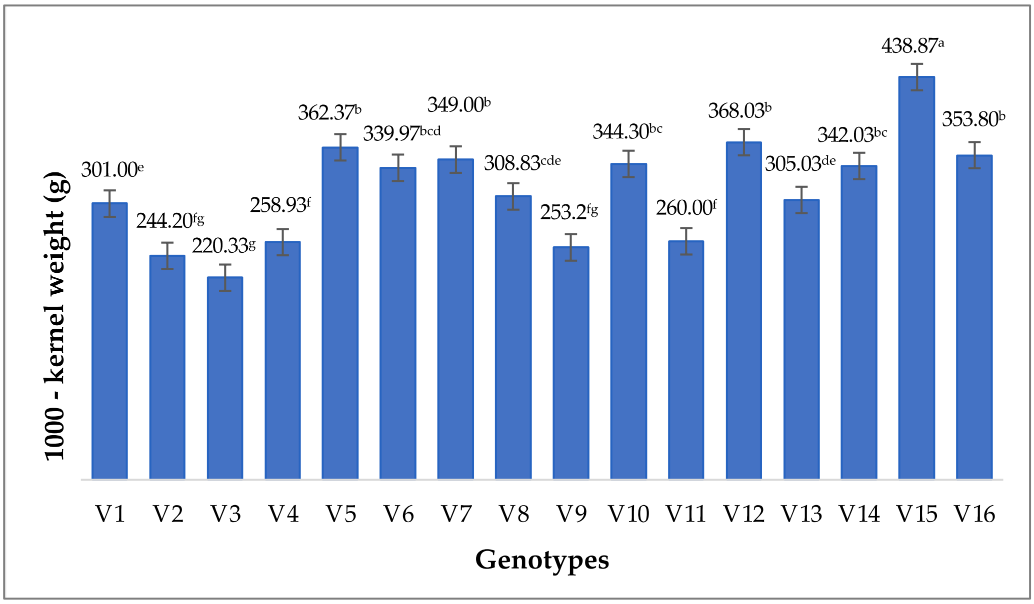

Figure 6. Histograms represent mean values of 1000-kernel weight (g) for various maize genotypes. Different lowercase letters represent significant differences between the means ($p < 0.05$) based on Duncan's multiple range test (DMRT) starting sequentially, with the letter (a) being the most significant.

3.2.3. Ear Weight (g)

Ear weight is a crucial characteristic that greatly influences yield performance. According to the results, each genotype examined in this study demonstrated a significant difference, as shown in the results of the ANOVA in Table 10 ($F (15, 224) = [41.815]$, $p = [0.00]$). On the other hand, Table 11 presents mean, minimum, maximum, and standard deviation values of 318.23 g, 22.20 g, 140.40 g, and 26.15 g, respectively. Overall, the ear weight was dominated by V14 (SC hybrid) at 105.89 g, followed by V7 (TC hybrid) at 100.05 g and V16 (control) at 98.45 g. Additionally, V3 (parent) delivered a less-than-satisfactory performance by only yielding an ear weight of 34.42 g (Figure 7).

Table 10. Analysis of variance (ANOVA) for the ear weight (g) of various maize genotypes.

Source		Sum of Square	df	Mean Square	F	Sig.
Ear weight (g)	Between groups	120,460.654	15	8030.710	41.815	0.000
	Within groups	45,822.069	224	192.054		
	Total	166,282.723	239			

df: Degree of freedom; Sig.: significance; significance level = $p < 0.01$.

Table 11. Mean, minimum, maximum, and standard deviation for the ear weight (g) of various maize genotypes.

Source	No.	Mean	Minimum	Maximum	Std. Deviation
Ear weight	240	318.23	22.20	140.40	26.15377
Valid N (listwise)	240				

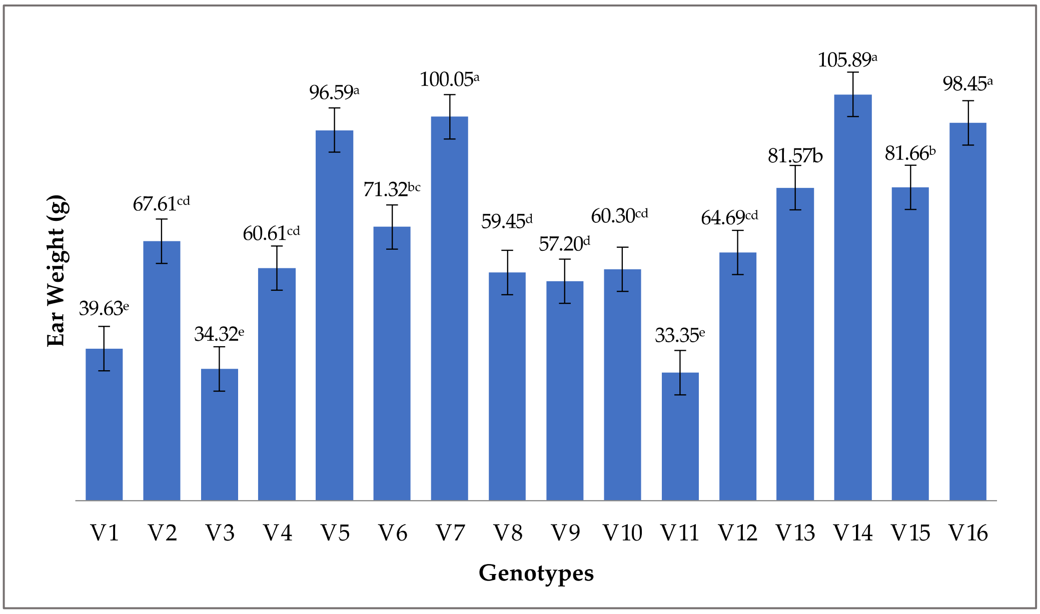

Figure 7. Histograms represent mean values of the ear weight (g) for various maize genotypes. Different lowercase letters represent significant differences between the means ($p < 0.05$) based on Duncan's multiple range test (DMRT) starting sequentially, with the letter (a) being the most significant.

3.3. Relationship between Seed Viability, Vigor, and Yield Traits

The correlation analysis between seed viability, vigor, and yield traits is shown in Table 12. The number of kernels per ear (NKPE) had a significant and positive correlation with the row number per ear (RPE) and 1000-kernel weight (1000 KWT), with values of 0.81, 0.41, and 0.77, respectively. In contrast, germination rate (%) (GR; 0.12) and radicle length (RL; 0.07) were not significant and were negatively correlated with plumule length (PL; −0.17). However, the proportion of ear weight (ER) was significantly and positively correlated with row number per ear (RPE; 0.65), the number of kernels per ear (NKPE; 0.77), and 1000- kernel weight (1000 KWT; 0.49) but not with radicle length (RL; 0.11) and was not significantly and was negatively correlated with germination rate (%) (GR; −0.06) and plumule length (PL; −0.08).

Table 12. Relationship between the seed viability and vigor yield traits (N = 240).

	[1]RPE	[2]NKPE	[3]1000 KWT	[4]EW	[5]GR %	[6]RL	[7]PL
[1]RPE	1						
[2]NKPE	0.81 **	1					
[3]1000 KWT	0.38 **	0.41 **	1				
[4]EW	0.65 **	0.77 **	0.49 **	1			
[5]GR %	−0.04 ns	0.12 ns	−0.004 ns	−0.06 ns	1		
[6]RL	0.15 ns	0.07 ns	0.03 ns	0.11 ns	0.18 *	1	
[7]PL	−0.19 ns	−0.17 *	−0.05 ns	−0.08 ns	−0.20 **	0.09 ns	1

* = $p < 0.005$; ** = $p < 0.001$; ns = not significant (2–tailed). [1]RPE—rows per ear; [2]NKPE—number of kernels per row; [3]1000 KWT—1000-kernel weight (g); [4]EW—ear weight (g); [5]GR %—germination rate (%); [6]RL = radicle length (cm); [7]PL = plumule length (cm).

4. Discussion

Maize is a high-demand crop and is widely used in agriculture for food, animal feed, energy, and industrial materials. This is important to ensuring the survival of global food security. Understanding seed viability, vigor, and yield performance is a valuable method for improving seed quality, breeding high-yielding and disease-resistant maize varieties, and accelerating the development of modern and sustainable agriculture. Since the 1950s, Hungary has produced numerous hybrid varieties that have been widely used until now. Therefore, information on seed-quality testing and its relationship to hybrids and lines is an important indicator in maize production. the seed viability and vigor tests were carried out primarily according to ISTA's international rules for seed testing [42]. Furthermore, field evaluation was carried out using hybrids and lines developed by local research institutes.

4.1. Seed Viability and Vigor

In this study, we found that seed viability and vigor performance were statistically significant between genotypes and the number of days. These significant differences in the characteristics studied appear to be highly dependent on genotypes and less responsive to other factors, as they typically appeared under ideal conditions [45,46]. Our findings revealed that the DC (100%) produced a better germination rate compared to the parent (81.47%), SC hybrid (70.83%), and TC hybrid (66.67%), which contradicted the previous findings [46], which found that single hybrids had the highest germination potential due to heterosis and genetic effects [35,47]. However, numerous factors affect the germination rate, which often varies by orders of magnitude between and within plant species [48,49]. Furthermore, previous studies also found significant paternal effects on seed germination characteristics [50]. In addition, seed size also affects the germination rate of maize, with small seeds being more water permeable, germinating faster, and being more uniform than larger seeds [51]. However, larger seeds retain their cotyledons for a longer amount of time, which is reflected in the strength and vigor of the seed, with a greater store of food, resulting in faster growth and emergence from the soil compared to seeds that store fewer nutrients [38,52]. On the other hand, larger seeds are associated with better performance in the field and more vigorous seedlings [53–55]. Although previous findings suggest that mature male or female plants would produce heavier seeds but are relatively slow to germinate [56], a reduction in seed vigor is a direct consequence of seed aging, which can affect crop performance [57].

The results obtained for radicle length and plumule length show that there were highly significant differences between genotypes. However, the overall results show that the parental lines dominated the development and elongation of the radicles and plumules. However, the radicle elongation rate was lowest in V9 (parent), whereas V7 (TC hybrid) showed the lowest performance in terms of plumule length. The DC hybrid exhibited better vigor potential based on the observed characteristics and possessed a better ability to develop and survive even under stressful conditions [46]. The findings from three separate studies indicated that some DC hybrid tomatoes displayed extreme rooting behavior compared to their parental lines [58], whereas TC hybrids outperformed the other hybrids and their parents because the ratio of chromosome structures increased with the number of parents involved in the crossing procedure [59]. In this laboratory study, it was also shown that V13 and V14 of SC hybrids were significantly different from several other genotypes in terms of plumule length, which is consistent with the results obtained from previous studies [19]. The differences in seed-quality characteristics discovered in hybrid types demonstrates that there were variances because of the genetic composition of the hybrids [46].

4.2. Yield Performance

Yield performance information is essential to ensuring consistency in maize cultivation and production sites. Many traits influence maize yield, including the number of rows per ear, kernels per ear, 1000-kernel weight, and ear weight. In all the genotypes examined in this study, we observed highly significant differences in the number of rows per ear among genotypes, and these results align with a study by [46], indicating that this characteristic contributes most to variation between different maize hybrid types. Our findings also revealed that SC hybrids were more prominent than the DC hybrid, the TC hybrid, and parental lines. This is mostly influenced by heterotic affect, which contributes greatly to hybrid performance in maize, especially for grain yield [60,61]. Additionally, it suggests that, in addition to environmental and nutritional factors, genetic factors also affect this trait [62–64] and that seed size directly affects the number of rows per ear [65].

Similar findings were observed for the number of kernels per ear, which is related to grain yield. Due to heterotic effects, the results show that SC hybrids dominated, followed by the TC hybrid, the DC hybrid, and parents, and, as expected, SC hybrids had the most uniform performance compared to others [66]. On the other hand, increasing the number of rows and kernels per ear directly increases grain yield [62,67]. In addition, environmental factors strongly influence kernel formation, particularly during the flowering stage, when moisture stress reduces the number of kernels by about 15% within two weeks of silking, with a reduction of up to 20% also having been observed [68]. In addition, pollination has a significant impact on grain yield, with 85% of yield being correlated with kernel production per acre and 15% being correlated with individual kernel weight at harvest for a specific hybrid [67]. At the same time, studies show that prolonged exposure to temperatures above 32 degrees Celsius could reduce pollen germination to almost zero for many genotypes [69]. Moreover, a statistically significant difference in the direct effect of temperature on the number of seeds per ear has been demonstrated [65].

The 1000-kernel weight is entirely determined by kernel size, and most of it is influenced by genetic, environmental, and nutrient factors [64,70]. It is also an important factor directly contributing to the final grain yield of the crop [62]. Findings from this trial showed that the performance trend of the 1000-kernel weight was correlated with the number of rows per ear and the number of kernels per ear. This demonstrates a significant difference for all genotypes studied, with hybrid lines predominating and producing heavier 1000-kernel weights than the parental lines. Furthermore, these findings suggest that kernel weight is influenced by size and source [65]. There was also a favorable association with ear weight.

In a way, ear weight is the ultimate objective for maize research, which directly contributes to the grain yield. In this study, we found that the ear weight was related to other traits, such as the number of rows per ear, the number of kernels per ear, and the 1000-kernel weight. These results are consistent with previous reports [62,71], which observed that considerable differences among maize lines, despite an increase or decrease in other traits, affect crop production yield.

In previous research, less emphasis was placed on the comparative benefits of TC hybrids and DC hybrids than SC hybrids. The present investigation supports the idea of previously established information that suggests that SC hybrids have advantages over TC hybrids or DC hybrids; however, this study demonstrates on a prominent level that the presence of TC confers advantages compared to SC and DC hybrids [72,73].

4.3. Relationship between Seed Viability, Vigor, and Yield Traits

The relationship between two variables can be measured quantitatively independent of other factors considered [74]. The relationship between these traits is also important in achieving the objectives of a breeding program. Among many techniques, correlation coefficient analysis is the most frequently utilized [75]. The relationship between seed viability, vigor, and yield traits also varies between hybrids and lines depending on production practices and crop market requirements [76]. This study found that kernel number per ear was significantly and positively correlated with the number of rows per ear and 1000-kernel weight.

However, there was no significant difference between germination rate and radicle length and a negative correlation with plumule length. Hence, an increase in kernel number, rows, kernel weight, and ear weight does not affect the viability and vigor of the seed. Furthermore, the results suggest that seed viability and vigor were most affected by genetic variables [19,47], which do not affect yield performance in the field. Seven key characteristics affect seed germination and vigor, including genetic content, the environment and nutrition of the maternal plant, harvest maturity stage, seed size or weight, mechanical integrity, seed aging, and pathogens [76]. Seed viability, vigor, and size can also directly and indirectly affect crop yield, in addition to seed emergence percentage and time from sowing to emergence [77]. According to earlier studies, seed vigor also influences vegetative growth. It affects yield if plants are harvested at the vegetative or early reproductive stages but not when they are harvested at full reproductive maturity [76,77].

5. Conclusions

Seed viability and vigor are complex traits that are determined at various maternal and seed development stages leading up to seed germination. In addition to genetic factors, environmental factors affect seed germination, emergence, and seedling performance in the field. Therefore, in the current study, we found that seed viability and vigor were statistically significant between genotype and number of days. The DC hybrid (100%) resulted in a better germination rate compared to parents (81.47%), SC hybrids (70.83%), and the TC hybrid (66.67%). These results emphasize that the parental lines showed better performance in terms of germination percentage and radicle elongation, whereas the SC hybrid produced better plumule length. Moreover, the length of the plumule expanded significantly as the number of incubation days increased. In the field evaluation, as expected, the hybrid lines performed better than the parental lines, and the SC hybrids were more dominant than the DC hybrid and the TC hybrid. The results indicate that the number of rows per ear, number of kernels per ear, 1000-kernel weight, and ear weight directly contributed to the final grain yield of the crop. Crop yield is affected whether the other traits increase or decrease. The study also revealed that 1000-kernel weight performance was influenced by the number of rows and kernel number per ear, with hybrid lines being the most dominant and ear weight showing a favorable association.

There are numerous opportunities to improve maize's contribution to global crop production by addressing seed-quality issues and enhancing yield production by considering biotic and abiotic factors. Further research is needed to overcome this problem by increasing the utilization of genetic resources. Moreover, integrated and multidisciplinary approaches should also be implemented to strengthen improvement programs.

Furthermore, intensive research is required to expand the number of genotypes examined across diverse locations and growing seasons by adopting sustainable agriculture practices. That information will assist researchers in conducting research and producing superior varieties while ensuring the sufficiency of food supplies in the near future, thereby benefiting the agriculture and seed industries.

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