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ARTICLE

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Morphological and Agronomic Responses of Hungarian Maize (*Zea mays* L.) Hybrids in Mongolia

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Abstract

Evaluation of exotic germplasm is an important strategy for broadening the genetic base of breeding materials and improving crop adaptation to local environments. This study aimed to assess the morphological and agronomic performance of introduced maize hybrids and identify promising materials for future maize breeding programs in Mongolia. Field experiments were conducted under rain-fed conditions at the Crop Breeding Division of the Plant Science and Agricultural Research Institute during the 2020 and 2021 growing seasons. Fourteen maize hybrids originating from Japan, Canada, Belarus, and Hungary were initially evaluated. Based on their relatively short maturity period, four Hungarian hybrids (TK-178, Bodrog, Aniella, and MV-241) were selected for detailed analysis.

The hybrids were evaluated for germination rate, plant height, ear height, tassel length, ear diameter, ear length, kernel length, ear weight, number of kernels per ear, 1000-kernel weight, biomass yield, days to anthesis, growing period, and grain yield. Two-way analysis of variance (ANOVA) showed that year significantly affected germination rate, tassel length, ear length, kernel length, ear diameter, ear weight, number of kernels per ear, and 1000-kernel weight. Significant genotypic differences were observed for plant height, tassel length, ear diameter, and number of kernels per ear. Principal component analysis based on key agronomic traits indicated that the four hybrids exhibited similar performance in terms of grain yield and biomass production under non-irrigated conditions.

The results suggest that these Hungarian maize hybrids possess favorable adaptation to Mongolian growing conditions and may serve as valuable genetic resources for the development of early-maturing maize varieties suitable for rain-fed production systems in Mongolia.

Keywords: exotic germplasm, maize, genotype, agronomic traits, biomass yield, grain yield

Introduction

Exotic germplasm represents a valuable source of novel alleles that can be introduced, introgressed, or incorporated into locally adapted breeding materials to enhance resistance to biotic and abiotic stresses, improve yield potential, and increase heterosis [1,2]. For maize (*Zea mays* L.), exotic germplasm has played a critical role in broadening the genetic base of breeding populations and developing superior cultivars worldwide.

Mongolia is characterized by a temperate continental climate with a short growing season and frequent environmental constraints. Maize germplasm introduced into Mongolia can be broadly classified into three geographic groups: temperate, lowland tropical, and highland tropical germplasm. The most widely utilized exotic germplasm originates from temperate regions, including Europe, Argentina, and South Africa. Additional germplasm sources include lowland tropical materials such as Cuban Flint and Suwan, as well as highland tropical populations such as Chalqueño, Cuzco, Sabanero, and San Geronimo [3–5]. These genetic resources have been successfully incorporated into breeding programs in many countries to broaden genetic diversity and develop improved hybrids with enhanced heterotic patterns [6–8].

The primary rationale for utilizing exotic germplasm is that greater genetic diversity provides: (i) resilience against unpredictable biological and environmental stresses; (ii) a source of genes for valuable traits such as drought tolerance, disease resistance, and improved agronomic performance; and (iii) a reservoir of favorable alleles that can contribute to higher yield and heterosis [8]. Consequently, exotic germplasm is widely used in crop improvement programs to introduce beneficial traits that may be absent or limited in locally adapted populations. Maize is one of the world's most important cereal crops and serves as both a staple food and a major component of livestock feed. Together with rice and wheat, maize provides at least 30% of the food calories consumed by more than 4.5 billion people in developing countries. In addition, maize grain is a valuable feed source due to its high energy content and digestibility, contributing substantially to livestock nutrition [9]. In Mongolia, the demand for maize as livestock feed has increased considerably over the past decade [10]. Between 2019 and 2022, the area cultivated with maize expanded from 585 ha to 3,237 ha, while grain production increased from 2,076 t to 20,105 t. As climate change continues to affect grassland productivity and pastoral livelihoods, the importance of maize as a reliable feed crop is expected to grow further.

Despite this increasing demand, maize production and breeding efforts in Mongolia remain constrained by several factors, including limited availability of locally adapted hybrids, drought stress, early autumn frost, short growing seasons, and suboptimal agronomic management practices. Therefore, identifying maize germplasm with suitable adaptation to Mongolian environmental conditions is essential for future breeding programs. Exotic maize genotypes, including hybrids, accessions, and inbred lines, particularly those originating from temperate regions, may provide valuable genetic resources for developing improved cultivars adapted to Mongolia. Previous breeding efforts have demonstrated the potential of introduced germplasm; for example, the open-pollinated maize variety MCP was developed using genetic materials originating from Inner Mongolia, the Democratic People's Republic of Korea, Canada, and Russia [11]. Furthermore, Van Inghelandt et al. [12] emphasized that a comprehensive understanding of genetic diversity and population structure is fundamental to the success of breeding programs. Therefore, the objective of this study was to evaluate selected foreign maize hybrids under Mongolian agroecological conditions and identify promising germplasm for future breeding efforts. Specifically, the study aimed to assess the agronomic performance and adaptation of Hungarian maize hybrids under rain-fed conditions and to determine their potential use as breeding materials for the development of early-maturing maize cultivars suitable for Mongolia. Hybrid Bodrog was subsequently registered by the State Variety Council of Mongolia in 2021, demonstrating the potential of introduced germplasm for varietal development under local conditions.

Materials and Methods

Plant Materials and Experimental Site

Fourteen maize (*Zea mays* L.) hybrids originating from temperate regions were evaluated during the 2020 and 2021 growing seasons. The materials consisted of four hybrids from Hungary (Bodrog, TK-178, Aniella, and MV-241), six hybrids from Belarus (Palesskii 101, Palesskii 104, Palesskii 111, Palesskii 175, Palesskii 195, and Palesskii 212), one hybrid from Japan (Fuerla), and three hybrids from Canada (Summer Sweet, Julius, and SH Bicolor). Among these, TK-178, which was registered by the State Variety Council of Mongolia in 2017, was used as the check variety. Field experiments were conducted at the Crop Breeding Division of the Plant Science and Agricultural Research Institute, Darkhan-Uul Province, Mongolia (49°28′ N, 106°00′ E). The experiment was arranged in a randomized complete block design (RCBD) with three replications under rain-fed conditions. Sowing was performed manually on 23 May 2020 and 12 May 2021. Soil samples were collected from the 0–20 cm layer before planting. Soil organic matter content was 2.99% in 2020 and 1.43% in 2021. The concentrations of available $N–NO_3$, P_2O_5, and K_2O were 0.99, 2.8, and 8.0 mg 100 g^{-1} soil in 2020 and 5.43, 2.7, and 9.6 mg 100 g^{-1} soil in 2021, respectively. Each plot consisted of five rows, each 2.5 m long, with 0.75 m spacing between rows and 0.50 m spacing between plants within rows. Two seeds were planted per hill and thinned to one plant at the 3–4 leaf stage. The distance between plots and blocks was maintained at 1.0 m. Fertilizer application, weed management, and pest control were conducted according to local agronomic recommendations.

Weather conditions during the experimental period are presented in Table 1.

Table 1.
Monthly mean air temperature (°C) and total precipitation (mm) during the maize growing seasons (May–September) in 2020 and 2021 at the experimental site, Darkhan-Uul Province, Mongolia

	Temperature, °C						Precipitation, mm					
Year/month	V	VI	VII	VII	IX	Mean	V	VI	VII	VIII	IX	Mean
2020	13.4	19.3	21.2	18.6	12.4	17.0	26.5	22.6	101.9	136.6	85.2	74.6
2021	9.8	16.6	20.1	17.7	10.8	15	32.5	110.1	122.5	118.7	56.6	88.1
Long term average	12.1	18.4	20.8	18.1	11.2		26.5	57.2	70.8	87.9	38.1	

Morphological and Agronomic Traits

Data were collected from plants located in the central rows of each plot. The following traits were evaluated: germination percentage (%), plant height (cm), ear height (cm), tassel length (cm), days to anthesis (50% tasseling), growing period (days), ear length (cm), kernel length (mm), ear diameter (cm), number of kernels per ear, ear weight (g), 1000-kernel weight (g), biomass yield (t ha^{-1}), and grain yield (t ha^{-1}).

Statistical Analysis

Two-way analysis of variance (ANOVA) was performed to evaluate the effects of year, genotype, and their interaction on measured traits. Mean comparisons were conducted using Tukey's Honestly Significant Difference (HSD) test at the 5% significance level. Statistical analyses were carried out using R software.

Relationships among agronomic traits and genotypes were explored using principal component analysis (PCA). Prior to PCA, variables were standardized to zero mean and unit variance. PCA visualization was performed using the facto extra and ggplot2 packages in R.

Results

Adaptation of Exotic Maize Hybrids under Mongolian Conditions

Among the fourteen exotic maize hybrids evaluated during the 2020 and 2021 growing seasons, only four Hungarian hybrids (Bodrog, TK-178, Aniella, and MV-241) reached anthesis within 80 days after sowing. The remaining ten hybrids flowered considerably later and failed to complete their reproductive development within the relatively short growing season of Mongolia. Consequently, these hybrids were excluded from further analyses (data not shown).

Effects of Year and Genotype on Morphological and Agronomic Traits

The results of the two-way analysis of variance (ANOVA) are presented in Table 2. Year significantly affected germination percentage ($p \leq 0.05$), tassel length ($p \leq 0.01$), ear length ($p \leq 0.001$), kernel length ($p \leq 0.001$), ear diameter ($p \leq 0.001$), ear weight ($p \leq 0.001$), number of kernels per ear ($p \leq 0.001$), and 1000-kernel weight ($p \leq 0.001$). In contrast, plant height and ear height were not significantly influenced by year.

Genotype had significant effects on germination percentage ($p \leq 0.05$), plant height ($p \leq 0.01$), tassel length ($p \leq 0.01$), ear length ($p \leq 0.05$), ear diameter ($p \leq 0.001$), and number of kernels per ear ($p \leq 0.001$). However, differences among hybrids were not significant for ear height, kernel length, ear weight, or 1000-kernel weight.

Significant year × genotype interactions were detected for tassel length ($p \leq 0.05$), ear weight ($p \leq 0.05$), number of kernels per ear ($p \leq 0.05$), and 1000-kernel weight ($p \leq 0.05$), indicating that hybrid responses for these traits varied across growing seasons. No significant interactions were observed for germination percentage, plant height, ear height, ear length, kernel length, or ear diameter.

Table 2.
Significance levels from two-way ANOVA for morphological and agronomic traits of four Hungarian maize hybrids evaluated in Mongolia during 2020 and 2021

Source of variation	Germ	PH	EH	TL	EL	KL	ED	Ear wt.	Kernels ear^{-1}	TKW
Year	0.050*	0.059ns	0.520ns	0.005**	0.001***	0.000***	0.000***	0.000***	0.000***	0.000***
Genotype	0.048*	0.004**	0.100ns	0.004**	0.015*	0.980ns	0.000***	0.370ns	0.000***	0.122ns
Year × Genotype	0.100ns	0.188ns	0.970ns	0.027*	0.720ns	0.440ns	0.098ns	0.027*	0.012*	0.027*

p ≤ 0.05, ** p ≤ 0.01, *** p ≤ 0.001; ns = not significant. Germ. = germination percentage; PH = plant height; EH = ear height; TL = tassel length; EL = ear length; KL = kernel length; ED = ear diameter; Ear wt. = ear weight; Kernels ear^{-1} = number of kernels per ear; TKW = 1000-kernel weight

Principal Component Analysis

Principal component analysis (PCA) based on grain yield, biomass yield, anthesis, and growing period revealed that the first two principal components explained 92.7% of the total variation, with PC1 and PC2 accounting for 70.1% and 22.6%, respectively (Figure 1).

The PCA biplot separated observations according to year, indicating a strong environmental influence on hybrid performance. Grain yield and biomass yield were positively associated with the 2020 growing season, whereas longer growing periods and delayed anthesis were associated with the 2021 season. The four Hungarian hybrids clustered relatively closely, suggesting comparable performance for grain yield and biomass production under rain-fed conditions.

Overall, the results indicate that environmental conditions exerted a stronger influence than genotype on several yield-related traits. Nevertheless, the four Hungarian hybrids successfully completed their life cycle under Mongolian conditions and demonstrated sufficient adaptation to short growing seasons, highlighting their potential value as breeding materials for future maize improvement programs.

Principal Component Analysis

Principal component analysis (PCA) was conducted using grain yield, biomass yield, anthesis, and growing period (Figure 1). The first two principal components explained 92.7% of the total variation, with PC1 and PC2 accounting for 70.1% and 22.6%, respectively.

The PCA biplot clearly separated observations according to growing season. Grain yield and biomass production were associated primarily with the 2020 observations, whereas anthesis and growing period were associated with the 2021 observations. Bodrog and TK-178 grown in 2020 were positioned closer to the grain yield and biomass vectors, while the 2021 observations were associated with delayed anthesis and extended growing periods.

These findings indicate that environmental variation between years exerted a stronger influence on grain yield, biomass accumulation, and crop development than genetic differences among the four evaluated hybrids.

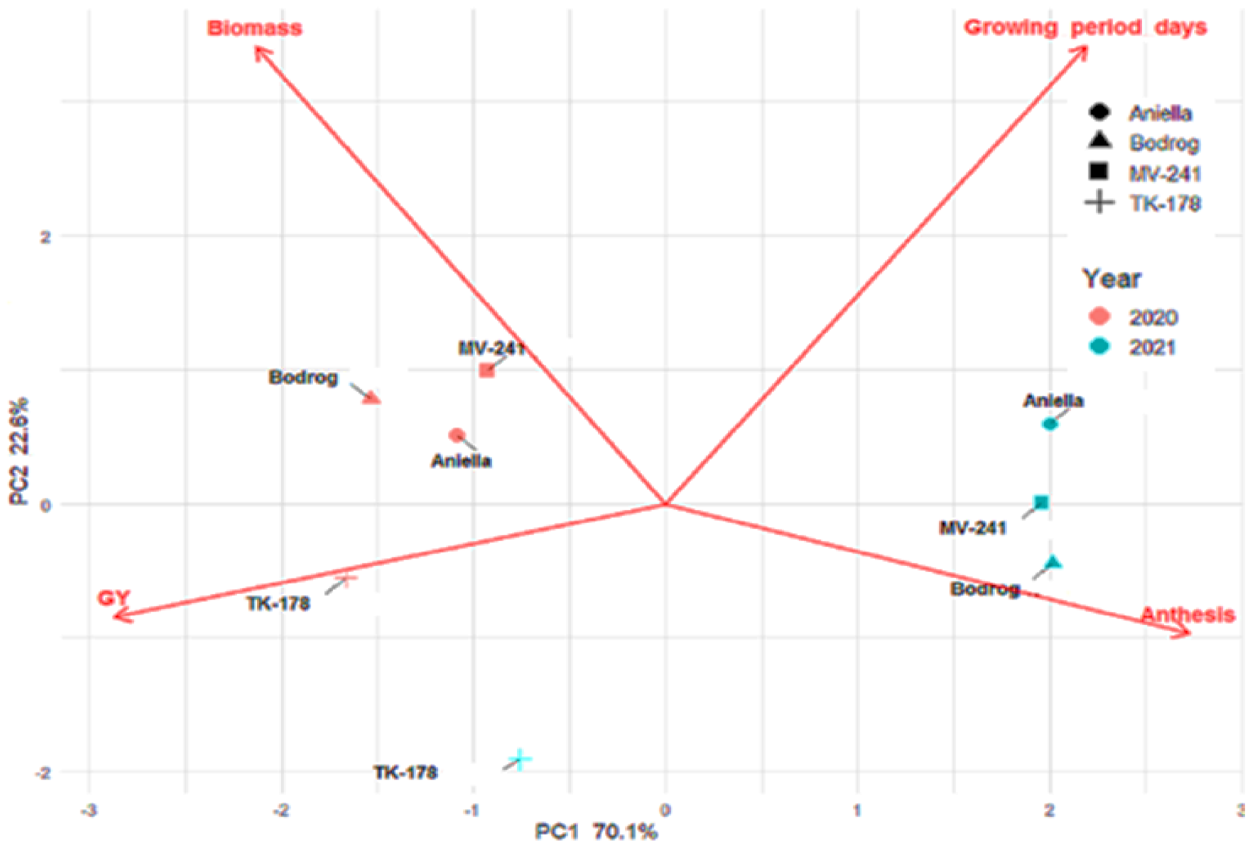

Figure 1. Principal component analysis (PCA) biplot showing the relationships among four Hungarian maize hybrids based on grain yield, biomass yield, anthesis, and growing period during 2020 and 2021

Variation in Morphological and Agronomic Traits Between Years

The distributions of the measured traits are presented in Figure 2. Several agronomic traits exhibited considerable variation between years. Grain yield, biomass production, kernel length, number of kernels per ear, and 1000-kernel weight were generally higher in 2020 than in 2021. In contrast, anthesis and growing period were longer in 2021.

Plant height and ear height showed relatively similar distributions between years, consistent with the ANOVA results indicating non-significant year effects. Conversely, substantial shifts were observed for ear diameter, kernel length, kernels per ear, and 1000-kernel weight, supporting the significant environmental effects detected in Table 2.

The largest differences between years were observed for grain yield and biomass production. Median grain yield exceeded 3 t ha^{-1} in 2020 but declined markedly in 2021. Likewise, biomass production was substantially greater in 2020 than in 2021, suggesting a strong influence of seasonal environmental conditions on crop productivity.

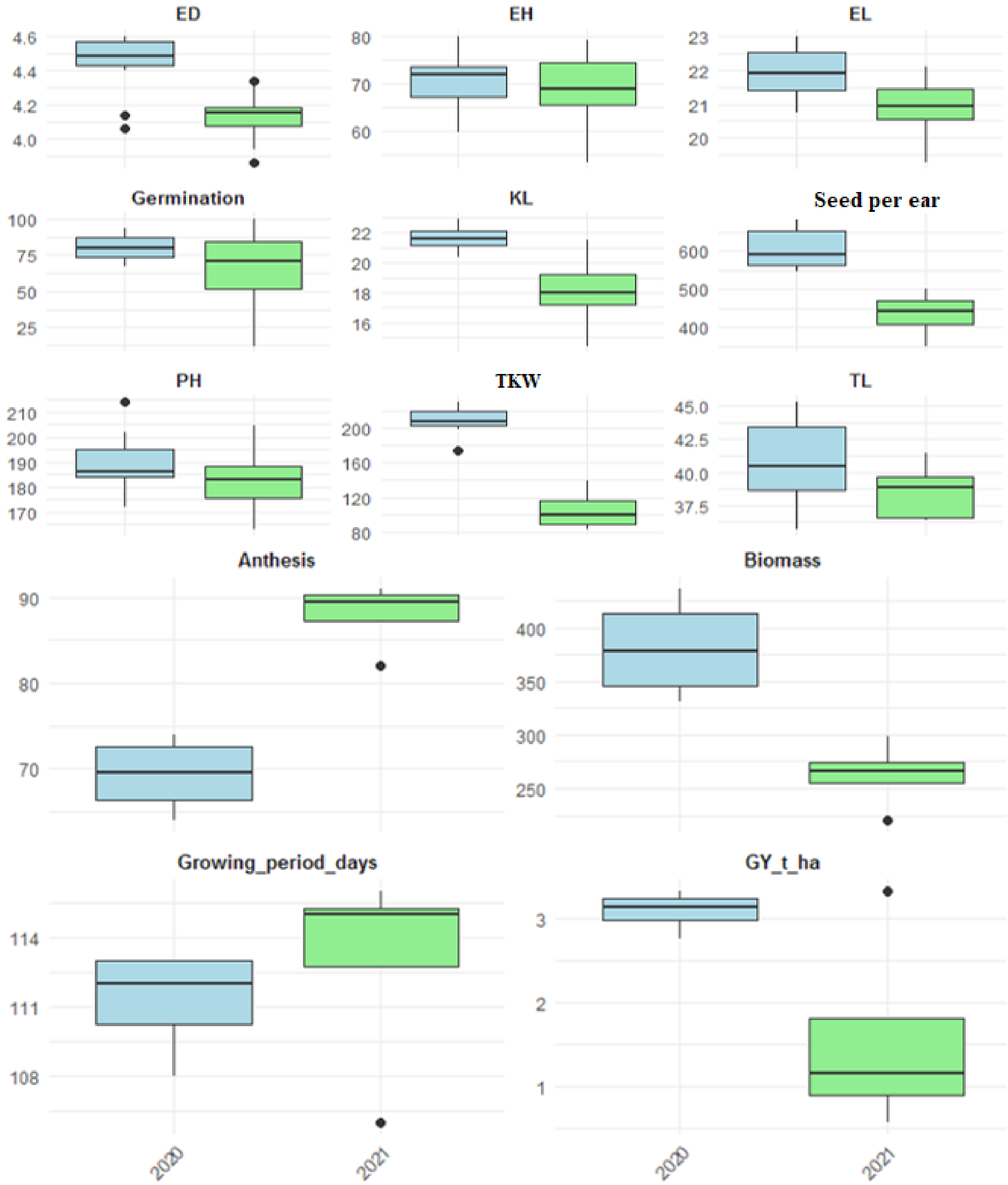

Figure 2. Boxplots showing variation in 13 morphological and agronomic traits of four Hungarian maize hybrids grown under rain-fed conditions in 2020 and 2021.
ED: ear diameter, EH: ear height, EL: ear length, KL: kernel length, PH: plant height, TL: tassel length, GY: grain yield.

Discussion

The successful adaptation of only four Hungarian maize hybrids among the fourteen exotic genotypes evaluated demonstrates the importance of maturity duration for maize production under Mongolian conditions. The ten excluded hybrids failed to reach anthesis within 80 days after sowing, indicating poor adaptation to Mongolia's relatively short growing season and limited heat accumulation. Similar findings have been reported in evaluations of tropical and subtropical maize germplasm under temperate environments, where delayed flowering and maturity often limit grain production potential [16,17]. These results suggest that earliness is a critical prerequisite for maize adaptation and grain production in Mongolia. The significant year effects observed for most morphological and agronomic traits indicate that environmental conditions strongly influenced hybrid performance.

According to the meteorological data, the 2021 growing season was generally cooler than 2020, with a lower mean temperature during the May–September period. Although precipitation was greater in 2021, lower temperatures may have reduced the accumulation of growing degree days required for maize development. This interpretation is supported by the longer anthesis period and extended growing duration observed in 2021. Previous studies have shown that flowering time and physiological maturity in maize are highly dependent on temperature and heat-unit accumulation, and insufficient thermal time can delay reproductive development and reduce productivity [16,17].

The ANOVA results further demonstrated that year had a stronger effect than genotype on several yield-related traits, including ear weight, kernel length, number of kernels per ear, and 1000-kernel weight. This pattern was also evident in the boxplot analysis, where substantial differences between years were observed for grain yield, biomass production, kernels per ear, and 1000-kernel weight. In contrast, plant height and ear height remained relatively stable across years, suggesting that these traits were less sensitive to seasonal environmental variation. Similar responses have been reported in maize, where developmental and yield-related traits are often more affected by environmental conditions than vegetative growth characteristics.

Principal component analysis provided additional evidence of the strong environmental influence on hybrid performance. The clear separation of observations by year indicates that grain yield, biomass production, anthesis, and growing period responded primarily to seasonal conditions rather than to genetic differences among the four hybrids. Grain yield and biomass were associated with the 2020 growing season, whereas delayed anthesis and longer growing periods were associated with 2021. The relatively close clustering of the four hybrids suggests comparable adaptation and performance under rain-fed conditions.

Despite the strong environmental influence, significant genotypic differences were detected for germination percentage, plant height, tassel length, ear length, ear diameter, and number of kernels per ear. These traits may therefore represent useful selection criteria for breeding programs aimed at improving maize adaptation to Mongolian conditions. The ability of Bodrog, TK-178, Aniella, and MV-241 to complete their life cycle within the available growing season demonstrates the value of temperate-origin germplasm for broadening the genetic base of Mongolian maize breeding programs.

Among the evaluated materials, TK-178 and Bodrog appear particularly promising because of their demonstrated adaptation to local conditions and their successful registration by the State Variety Council of Mongolia. Nevertheless, the relatively similar performance of all four Hungarian hybrids suggests that each may contribute useful alleles for future breeding efforts. Further evaluation under multiple environments and growing seasons is required to assess yield stability, drought tolerance, and genotype × environment interactions more comprehensively.

Overall, the present study demonstrates that early-maturing Hungarian maize germplasm is well suited to Mongolia's agroecological conditions and may serve as valuable breeding material for developing maize cultivars adapted to short growing seasons and rain-fed production systems. The results also emphasize the importance of environmental conditions in determining maize productivity and highlight the need for continued evaluation of exotic germplasm under diverse field conditions.

Conclusion

Among the fourteen exotic maize hybrids evaluated, only four Hungarian hybrids (Bodrog, TK-178, Aniella, and MV-241) successfully reached anthesis and completed their life cycle under Mongolian conditions. Year effects significantly influenced most agronomic traits, indicating that environmental conditions played a greater role than genotype in determining performance. The evaluated Hungarian hybrids demonstrated satisfactory adaptation to Mongolia's short growing season and rain-fed environment, with TK-178 and Bodrog showing particular promise as breeding materials. These hybrids may serve as valuable genetic resources for the development of early-maturing maize cultivars adapted to Mongolian agroecological conditions.

Author's contribution

B.B. designed the field experiment, performed initial data formatting. B.B and S.E. carried out the field data collection. T.M. wrote the draft of the manuscript including data analysis and interpretation of the result. B.B. and S.E. contributed the literature review. All authors reviewed and approved the final manuscripts.

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