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STUDY ON GENETIC VARIABILITY AND HETEROSIS OF DIFFERENT AGRONOMIC CHARACTERISTICS, YIELD COMPONENTS AND GRAIN QUALITY IN MAIZE (*ZEA MAYS* L.)

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LIST OF ABBREVIATIONS

%	:	Percent
^0F	:	Degree Fahrenheit
AA	:	Accelerated Ageing
ANOVA	:	Analysis of variance
AOSA	:	Association of Official Seed Analysts
cm	:	Centimeter
cm^2	:	Square centimeter
CO_2	:	Carbon Dioxide
CRD	:	Completely randomized design
CIMMYT	:	The International Maize and Wheat Improvement Institute
DC	:	Double cross
DF	:	Days to flower
df	:	Degree of Freedom
DMRT	:	Duncan's Multiple Range Test
DNA	:	Deoxyribonucleic Acid
F	:	F statistic
F_1	:	First Generation of Hybrid
FAO	:	Food and Agriculture Organization
GA	:	Genetic advance
GCV	:	Genotypic Coefficient Variation
h^2b	:	broad sense heritability
H_2O	:	Chemical Symbol of Water
HP	:	High Parent
ISTA	:	International Seed Testing Association
KA	:	Coefficient of active lateral earth pressure.
KCI	:	Neutral compound (salt)
LSD	:	Least Significant Difference
MANOVA	:	Multivariate Analysis of Variance
ml	:	Milliliter
mm	:	Millimeter
MP	:	Mid Parent
^OC	:	Degree Celsius

p-value	:	The Probability under the Assumption of No Effect or No Difference (null hypothesis)
PCV	:	Phenotypic coefficient of variation
pH	:	Potential of Hydrogen
RCBD	:	Randomized Complete Block Design
RH	:	Relative Humidity
SC	:	Single cross
Sig.	:	Significance
SPAD	:	Chlorophyll meter
SPSS	:	Statistical Package for the Social Sciences
TC	:	Three-way cross
UN	:	United Nations
σ^2g	:	Genotypic Variances
σ^2p	:	Phenotypic Variances

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1. INTRODUCTION

1.1. Background of Study

Maize, or corn (*Zea mays* L., 2n = 20), is one of the most important cereal crops grown worldwide, together with wheat (*Triticum aestivum* L.) and rice (*Oryza sativa* L.) (GOLOB et al. 2004). Maize is a staple crop in many countries and provides sustenance to millions of people around the world (HOSSAIN et al. 2021), particularly in Africa, Latin America, and Asia (SULEIMAN et al. 2013). Maize is consumed both raw and cooked for various purposes, including food products (starch, sweetener, oil beverage, and coffee substitute), as a non-food product (cosmetics, adhesives, paints, varnishes, industrial alcohols, and ethanol fuels), and as a feed grain in the livestock industry (BREADLEY 1992, KUMAR AND NARAYAN 2013, RANUM et al. 2014). Maize is rich in carbohydrates, nutrients, and phytochemical compounds (SHAH et al. 2016). Maize has become the most versatile and diverse application crop in the world due to its high adaptability to the environment and productivity (KOUTSIKA-SOTIRIOU 1999, PRUITT 2016, CONABIO 2017). It resulted in intense cultivation, which prompted it to spread (HAKE AND ROSS-IBARRA 2015, INDIAN COUNCIL OF AGRICULTURAL RESEARCH 2010).

Maize has major economic importance with the widest distribution, exceedingly more than 30% of the world's total cultivation area, and is grown in 166 countries, 49 more than rice and 44 more than wheat. Its production has expanded globally, surpassing other grain crops, and making it the most valuable staple food (FORTUNA et al. 2020, SHAH et al. 2016). According to data from the United Nations (UN) Food and Agriculture Organisation (FAO), global maize production in 2021 exceeded 1,210.2 million metric tonnes, with the United States, China, and Brazil leading the way. The global maize area covered 205.8 million hectares, with European countries accounting for approximately 9.25 million hectares, or 4.49% of the global maize area, with 72.99 million metric tonnes of production (FAO et al. 2022).

In Hungary, maize is one of the important agricultural crops, accounting for almost 55% of the 6.42 million metric tonnes of cereal production in 2021 (FAOSTAT 2022). It plays an essential role in cereal, which has a surplus and is in high demand in various markets and has surpassed wheat, barley, and other crops as the main crop cultivated by farmers. This is because maize is an important agricultural export crop due to its various applications, as well as being directly consumed as food and, on a large scale, in the livestock industries, in the production of fructose and glucose, flour, oil, ethanol, and distillers with soluble by-products (MIZIK AND RÁDAI 2021).

1.2. Problem Statement

Accurate and comprehensive knowledge regarding genetic variability, heterosis, agronomic characteristics, and grain quality, as well as adequate fertiliser application, is imperative for the successful development of maize crops. In order to meet the increasing demand for maize due to the expanding human population, it is crucial to have a well-rounded information package that can guide the design of research programmes. However, there are significant challenges that hinder the augmentation or sustenance of maize production. These challenges include various factors such as global climate change, infertility, and unfavourable soil conditions. Climate change has led to abiotic consequences, including elevated levels of CO_2, temperature, rainfall intensity, and an increased likelihood of extreme weather events. These factors have resulted in reduced maize yields and heightened susceptibility to pest infestations and diseases (LI et al. 2019, XIAO et al. 2022). This predicament arises from the lack of superior maize varieties that can withstand harsh environmental conditions, as well as the existence of technological gaps, particularly prevalent in the least-developed countries or rural areas.

According to the research conducted by ANDORF et al. (2019), there is a growing demand for maize in developing countries for various purposes such as food, animal feed, fuel (ethanol), and other raw materials for industry. This demand is expected to align with the projected growth in the global population, which is estimated to reach 10 billion by 2050 (ROSEGRANT et al. 2009). In order to meet this increasing demand, it will be necessary to achieve an annual yield increase of approximately 2.4%. The issue of food security is of utmost importance, as hunger has become a significant challenge faced by humanity today, and its magnitude is expected to be even greater in the future. Since 2014, there has been a steady rise in the number of people affected by hunger globally, reaching 690 million individuals, which accounts for nearly 9 percent of the world population in 2019 (FAO et al. 2020). These trends will inevitably drive demand in the agricultural industry as it strives to ensure food and nutrient security for staple crops (POOLE et al. 2020). Furthermore, the increasing awareness of health and nutrition is leading to a shift in societal preferences towards higher consumption of meat, fruits, vegetables, and grains. This transition necessitates a transformation in production methods and puts additional pressure on natural resources. Therefore, it is crucial to establish a sustainable agricultural industry that can enhance the quality of agricultural products and food. This can be achieved through the development of superior plant varieties or hybrids that possess high adaptability to global environmental changes.

The cultivation of maize has been a long-standing and deeply ingrained traditional practice for thousands of years. It is noteworthy that hybrid maize yields have consistently increased since the

1930s, with half of the increase attributed to field management and the other half to breeding technology (ANDORF et al. 2019). The most significant trait changes are those that enhance resistance to biotic and abiotic stress. However, morphological, and physiological changes also contribute to the improvement of efficiency in growth, development, and division. Consequently, the capacity of maize plants to withstand all stresses that arise drives growth and yield potential.

Moreover, the focus on enhancing agronomic traits plays a crucial role in ensuring that the physical and biological attributes necessary for growth, development and productivity are present. These traits include plant height, leaf area, root system architecture, blooming period, seed size, and others. They are vital in determining a plant's suitability for growth in a specific environment and its ability to withstand both biotic and abiotic stresses. It is imperative for plant breeders and farmers to have a comprehensive understanding of agronomic characteristics in order to develop new varieties with improved performance and yield potential. This is exemplified by the development of drought-resistant maize varieties that can thrive in regions with limited water resources. Furthermore, knowledge of agronomic traits can assist in the selection of appropriate fertilizer and pest management strategies to optimize crop growth and minimize losses.

Maize breeding work mainly aims at the development of new or improved varieties or cultivars with higher yields, good quality or appearance, and resistance to pests and diseases. This is a crucial requirement for release or creates a genetic variation for desired characteristics or traits (MUNTEAN et al. 2022). In addition, the current global situation has made the objectives of maize breeding work more focused on improving stability in stress-prone environments (drought, heat, and less fertile soil) and enhancing nutritional quality (provitamin A, high-kernel zinc, and quality protein in maize) or fibre quality (green forage). However, achieving successful results also requires a comprehensive understanding of the complex biology of quantitative traits as well as an extensive assessment of the broad genetic basis of maize (WALLACE et al. 2014).

Over the course of several decades, numerous studies have been conducted to exploit the potential of inbred lines to produce economically viable hybrids that possess desirable traits, such as high seed yield, yield stability, and quality. Subsequently, hybrid maize varieties are now used worldwide to achieve higher grain yields (MAKORE et al. 2022). Maize was the first crop to benefit from heterosis through the breeding of F_1 hybrids, although the underlying mechanisms behind this phenomenon remain unknown (SCHNABLE AND SPRINGER. 2013). The use of heterosis as a means to enhance genetic characteristics and estimate genetic variability is a fundamental tool for increasing productivity in offspring (FLINT-GARCIA et al. 2009). Consequently, the widespread adoption of heterosis in plant breeding for important agricultural species is considered a significant accomplishment in maize breeding. A thorough understanding of heterosis is crucial for comprehending the genetic expression of a hybrid in relation to its parent plants. Typically, the effect of heterobeltiosis leads to improved hybrid performance compared to the better parent (FONSECA AND PATTERSON 1968).

1.3. Justification of the Study

Genetic variability holds significant importance in cross-pollinated crops such as maize, as it confers a population advantage by enabling certain individuals to adapt to the environment while ensuring the survival of the population. The primary objective of maize breeding programs is to enhance maize yield characteristics in order to meet future demand. This is achieved by producing inbred varieties that are well-suited for this purpose. Consequently, plant breeding entails the evaluation of desirable characteristics and the examination of superior genotypes. The effectiveness of selection is contingent upon the nature and extent of the relationship between yield and yield components, which is heavily reliant on the study of genetic variability and diversity in maize (*Zea mays* L.) inbred lines. Furthermore, traits such as days to 50% silking, plant height, ear height, and cob play a crucial role in determining the ideal plant architecture and indirectly selecting high-yielding maize cultivars (BHADRU et al. 2020). These characteristics heavily rely on genetic parameter estimates, which allow for greater control over quantitative traits. Despite the existence of various methods for improving maize crops, breeding remains the most sustainable and financially viable approach for addressing the combined challenges posed by increasing demand, global environmental impacts, population growth, and nutritional disruption.

Through a study of genetic variability and heterosis, this research aims to identify diverse genetic groups with higher heterotic effects for various agronomic traits, yield components, and grain quality in maize, providing valuable tools for successful breeding programmes. This study will be supported by data analysis and assessment of genetic diversity while acknowledging potential limitations related to environmental factors and practical implementation challenges. The development of high-yielding maize varieties necessitates the identification of diverse genetic groups with higher heterotic effects. Moreover, an understanding of the nature and magnitude of genetic variability can aid in predicting hybrid performance, while evaluation of agronomic traits, yield components, and grain quality will provide a comprehensive understanding of hybrid performance. This study will contribute to the conservation and utilization of diverse genetic resources.

1.4. Objectives of the Study

The objectives of this study are as followed:

i. To determine the germination potential of variations in the performance of various hybridization pathways.
ii. To evaluate the impact of seed quality and hybrid types on maize germination, emphasising seed viability and vigour and their influence on maize crops the yield and productivity.
iii. To quantify the effect of N fertilization on grain yield and its components, and grain quality parameters (moisture, oil, protein, and starch contents) for maize crops, and
iv. To investigate the various genetic mechanisms that contribute to genetic variability and heterosis for yield and yield components in maize (inbred parents, single cross, three-way cross, and double cross hybrids).

2. LITERATURE REVIEW

2.1 Origin and Scientific Classification

Maize, or corn (*Zea mays* L., 2n = 20) is one of the most important cereal crops cultivated in many parts of the world. It serves as a primary source of carbohydrates and essential nutrients, and phytochemical compounds. The term “Zea” originates from the ancient Greek language meaning "sustaining life," and “Mays” is derived from the “Taino” word, which means "giver of life" (SHAH et al. 2016). It is also known as corn (American English) and other synonyms such as maïs (French), blé d’Inde (Canadian French), maíz (Spanish), milho (Portuguese), mais (Italian, German, Tagalog), majs (Danish, Swedish), kukorica (Hungarian), mielie (Africans), mhindi (Kiswahili), mısır (Turk), jagung (Malaysia, Indonesia, and Brunei) etc.

According to archaeological histories, maize arose from a single plant domesticated by indigenous people in Southern Mexico 10,000 years ago. It was diversified from highland areas before spreading to the lowland regions (MATSUOKA et al. 2002). Initial studies suggested maize first spread into South America through the Andes and Brazil’s east coast (MCCLINTOCK et al. 1981). The analysis of isozyme and chloroplast DNA diversity provides strong evidence supporting the theory that maize was not domesticated multiple times independently. This is not surprising when one assumes that converting teosinte into maize is highly improbable, making it unlikely that it happens several times (DOEBLEY 1990). Teosinte and maize have 10 pairs of chromosomes (RONEY 2009), and isozymes have been used to distinguish between maize grown at different elevations in Mexico (DOEBLEY et al. 1985) and Guatemala (BRETTING et al. 1990).

Maize was brought to Europe by Columbus in 1493 from the Caribbean and quickly spread to the Vatican (BRANDOLINI 2009). Early representations of maize in Europe can be seen in frescoes near Rome dating back to 1517 (JANICK AND CANEVA 2005). Maize was also reported in northern European regions since 1539 in Germany and was well established in the Alpine regions of Italy by 1570 (MATTHIOLE 1572). This suggests a rapid expansion from southern Europe with adaptation to low temperatures or a second distinct introduction of maize pre-adapted to temperate climates. Maize became popular during the 17th century in northern Spain (REVILLA et al. 2003) and southwestern France (CARRARETTO 2005). After the Second World War, traditional European varieties were utilised to create hybrid varieties that were well-suited for northern European conditions. These hybrids proved to be more successful than local open-pollinated varieties, and the importance of genetic complementarities in hybrid breeding programmes remains significant (VAN DE WOUW et al. 2010).

Table 1 illustrates the scientific classification of maize, an annual grass that belongs to the Poaceae family. This family also encompasses other crops such as wheat, rye, barley, rice, sorghum, and sugarcane. Within the genus *Zea,* there are five distinct species, with *Zea mays* L. (maize) being the most economically viable. The other *Zea* species are *Zea diploperennis* L. (diploperennial teosinte, grass species, and wild relative of maize or corn), *Zea luxurians* L. (flowering plant, true grass, and a teosinte), *Zea nicaraguensis* L. (annual and true grass species), and *Zea perennis* L. (perennial, true grass, and a teosinte). *Zea mays* L. is further classified into four subspecies: *Zea mays* spp. *huehuetenangensis*, *Zea mays* spp. *mexicana*, *Zea mays* spp. *parviglumis*, and *Zea mays* spp. *mays*. The first three subspecies are teosintes, while the last is maize, or corn, the only domesticated taxon in the genus *Zea* (OGTR 2008). However, the annual teosinte variety, *Zea mays* spp. *mexicana*, is the closest botanical relative to maize and is found growing as a wild grass in Mexico and Central America (SHAH et al. 2016).

Table 1. Scientific classification of maize.

	Scientific classification	**Description**
Kingdom	Plantea	Plants
Subkingdom	Tracheabionta	Vascular plant
Superdivision	Spermatophyta	Seed Plant
Division	Magnoliophyta	Flowering plants
Class	Liliopsida	Monocotyledons
Subclass	Commelinidae	
Order	Cyperales	
Family	Poaceae	Grass family
Genus	*Zea* L.	Maize
Species	*Zea mays* L.	Maize
Subspecies	*Zea mays* L. *ssp. parviglumis Iltis & Doebley*	Maize
Variety	*Zea mays* L. *ssp. parviglumis Iltis & Doebley var. huehuetenangensis Iltis & Doebley*	

Source: USDA 2020.

The number of chromosomes in *Zea mays* is 2n = 20, including the wild *Zea mays* ssp. *parviglumis, Zea mays* ssp. *mexicana* and *Zea mays* ssp. *mays*. The highly domesticated and variable derivative subspecies, *Zea mays* ssp. *mays*, is the result of selective breeding by humans (DOEBLEY et al. 1980). The Andropogoneae tribe comprises seven genera, which are categorised into old and new world groups. The old world includes *Coix* (2n = 10/20), *Chionachne* (2n = 20), *Sclerachne* (2n = 20), *Trilobachne* (2n = 20), and *Polytoca* (2n = 20). On the other hand, the new world group has *Zea* and *Tripsacum* (YAN AND TAN 2019).

2.2 Uses

Maize is a highly versatile crop that plays a significant role in the global food and industrial sectors. It is consumed and processed in various ways across different cultures and regions, making it a staple in many diets worldwide. There are six main types of maize, including dent corn, flint corn, pod corn, popcorn, flour corn, and sweet corn (BRAD 2021). Sweet corn which rich in sugar content, making is a popular choice for fresh consumption, as well in canned and frozen forms. It is often boiled, grilled, or steamed and enjoyed as a side dish, added to salads, or used as an ingredient in various dishes. Maize is a valuable source of carbohydrates, providing energy and essential nutrients. It can be consumed raw, such as in salads or salsas, or cooked in a variety of ways, including boiling, baking, or frying. In many cultures, maize is a staple food and forms the basis of traditional dishes like tortillas, polenta, and cornbread.

Beyond its role as a food crop, maize is extensively used in the production industry. It is processed to create a wide range of products, including starches, sweeteners, oils, beverages, and non-food products such as cosmetics, adhesives, paints, varnishes, industrial alcohols, ethanol, and other biofuels (RANUM et al. 2014). Furthermore, maize plays a crucial role in the livestock industry as a feed grain. Its high energy content makes it an ideal source of nutrition for animals, particularly poultry, cattle, and pigs. Maize is often processed into animal feed pellets or included in mixed feed formulations to provide essential nutrients and promote healthy growth (KUMAR AND NARAYAN 2013, RANUM et al. 2014). Interestingly, roasted maize kernels can even be used as a substitute for coffee or included in coffee mixtures. This alternative is particularly popular in regions where coffee is scarce or expensive, offering a similar flavour profile and aroma (BREADLEY 1992). The various uses of maize are shown in Figure 1.

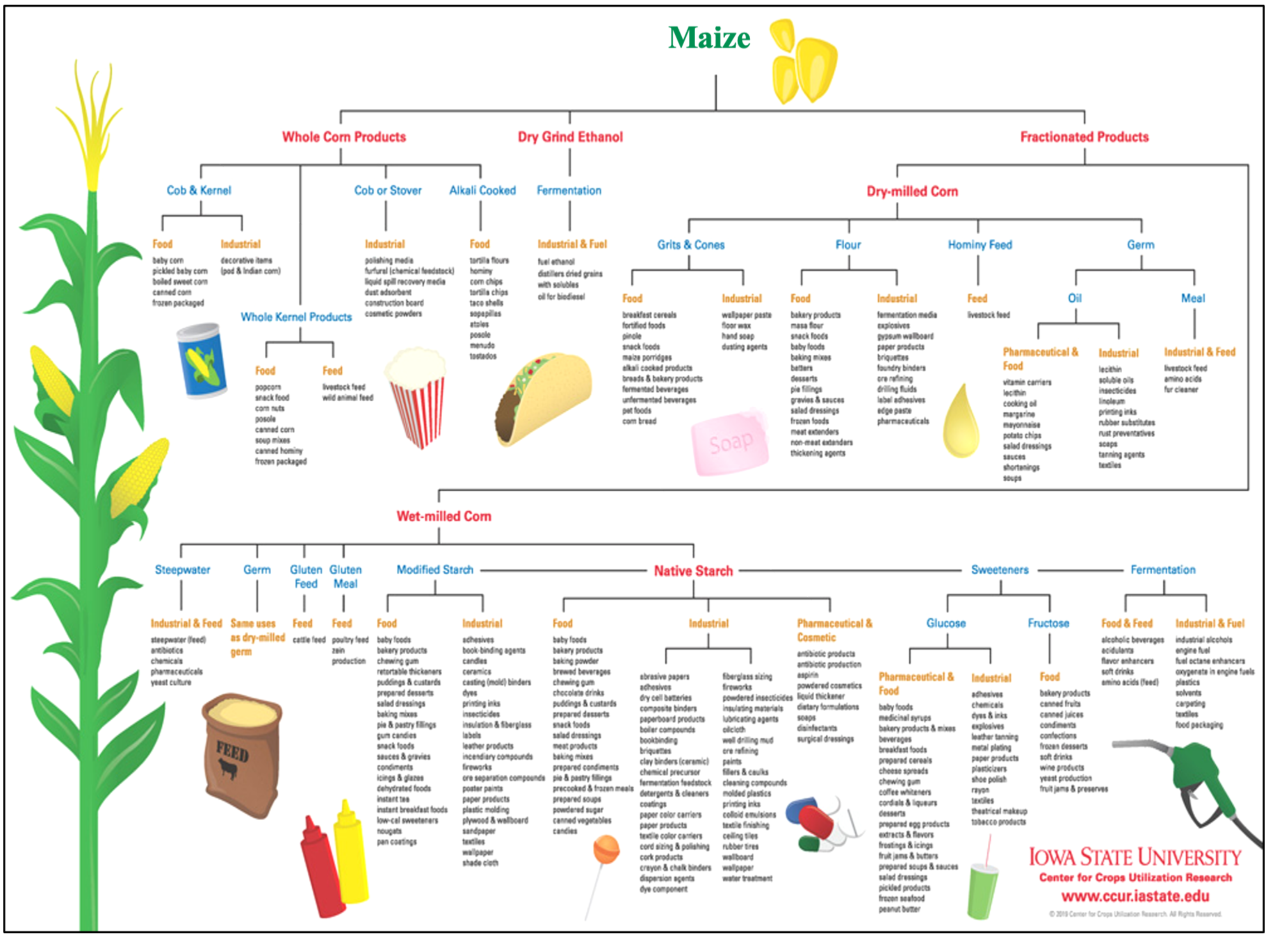


Figure 1. The overall use of maize flowchart.

Source: CENTRE FOR CROPS UTILIZATION RESEARCH, IOWA STATE UNIVERSITY 2009.

2.3 Nutritional Value

The three primary global cereal crops, i.e., wheat, rice, and maize, constitute a significant component of the human diet, accounting for 48 percent of the world's food calories and 42 percent of protein intake (MACNEIL 2021). Maize, as a staple food, contributes 30 percent of their food calories. In addition to its caloric, maize is a rich source of protein, micronutrients, and phytochemicals, all of which are beneficial to human health (SHAH et al. 2016). Maize is particularly abundant in vitamin B-complex, including thiamine (B1), niacin (B2), riboflavin, pantothenic acid (B5), and pyridoxine (B6), which are essential for energy metabolism, skin health, digestion, the nervous system, the brain, cell creation, red blood cells, and DNA formation, as presented in Table 2 (SHAH et al. 2015). Furthermore, maize contains significant amounts of vitamins C, A, and K, as well as a substantial quantity of beta-carotene and a fair amount of selenium, which can benefit the thyroid gland and play a crucial role in the immune system. The protein and fat content of maize are higher than those of other cereals (KUMAR AND NARAYAN 2013).

According to ORTHOEFER et al. (2003), maize germ contains approximately 45–50% of the oil obtained from wet milling processes. However, it is important to note that maize germ oil consists of a significantly high proportion of unsaturated and low-saturated fatty acids. The primary fatty acids found in maize germ oil, namely palmitic, stearic (saturated fatty acids), oleic, and linoleic (unsaturated fatty acids), make up more than 96% of the total oil content. This component makes the maize germ a valuable resource in the oil industry for human consumption, rather than as a component in animal feed, as highlighted by JOVANOVIC et al. (2005).

Table 2. Composition per 100 g of edible portion of maize**.**

Source	**Per 100 g**
Carbohydrate	71.88 g
Protein	8.84 g
Fat	4.57 g
Fibre	2.15 g
Ash	2.33 g
Moisture	10.23 g
Phosphorus	348 mg
Sodium	15.9 mg
Sulphur	114 mg
Riboflavin	0.10 mg
Amino acids	1.78 mg
Mineral	1.5 g
Calcium	10 mg
Iron	2.3 mg
Potassium	286 mg
Thiamine	0.42 mg
Vitamin C	0.12 mg
Magnesium	139 mg
Copper	0.14 mg

Source: SHAH et al. 2015.

2.4 Global Maize Production, Consumption and Trends

Based on the data presented in Table 3, global maize production has experienced a significant increase, surpassing that of other cereal crops (KOLVER et al. 2001, THORNE et al. 2002, CHAUDHARY et al. 2012, KUMAR AND NARAYAN 2013, RANUM et al. 2014, SHAH et al. 2016, FORTUNA et al. 2020, MESTERHÁZY et al. 2020). Maize is currently the third most consumed cereal worldwide, with its primary consumption taking place in Southern and Eastern Africa, Central America, and Mexico (RANUM et al. 2014). The global harvested area for maize has increased from 191.0 million ha in 2015 to 205.8 million ha in 2021, resulting in a corresponding rise in maize production yield from 1,053.9 million metric tonnes in 2015 to 1,210.2 million metric tonnes in 2021 (FAOSTAT 2022). The world's leading maize producers in 2021 were the United States of America, followed by China, Brazil, the European Union, and Argentina, with total production exceeding 383.9 million metric tonnes, 272.8 million metric tonnes, 88.4 million metric tonnes, 73.0 million metric tonnes, and 60.5 million metric tonnes, respectively (FAOSTAT 2022). These figures are presented in Table 4. Furthermore, the production of various industrial products also contributes to the overall increase in global maize production. Additionally, maize cultivation is relatively cost-effective compared to other grain crops.

Table 3. Global cereal production statistics for 2015, 2020 and 2021 (Estimated).

		2015	**2020**	**2021 (Estimated)**
Maize	Area (Million ha, M ha)	191.0	199.99	205.8
	Production (Million tonnes, Mt)	1,053.9	1,163.0	1,210.2
	Yield (hg/ha)	55.1	58.1	58.8
Wheat	Area (Million ha, M ha)	233.3	217.9	220.8
	Production (Million tonnes, Mt)	741.8	756.9	770.9
	Yield (hg/ha)	33.2	34.7	34.9
Rice	Area (Million ha, M ha)	160.5	163.0	165.2
	Production (Million tonnes, Mt)	732.9	769.2	787.3
	Yield	45.6	47.1	47.6

Source: FAOSTAT 2022.

Table 4. Global maize production statistics for 2015, 2020 and 2021, by country.

Country	2015	2020	2021
United States	345.5	358.4	383.9
China	265.2	260.9	272.8
Brazil	85.3	104	88.4
European Union	59.3	67.0	73.0
Argentina	33.8	58.4	60.5
Ukraine	23.3	30.3	42.1
India	24.2	28.8	31.7
Mexico	24.7	27.4	27.5
South Africa	10.6	15.8	16.9
Other	182.0	212.0	213.4

Source: FAOSTAT 2022.

2.5 Maize Production in Hungary

Maize is a prominent cereal crop cultivated in Hungary (NAGY 2008), occupies the largest cultivated area of 1 million hectares, and plays a significant role in driving economic growth in the country's agricultural sector (HORVÁTH ET AL. 2021). According to the Hungarian Central Statistical Office (HCSO 2021), maize production constituted around 55% of the total grain production in 2020. It has surpassed other crops such as wheat and barley to become the primary crop cultivated by farmers (Figure 2). The introduction of first maize hybrid, Mv5, was introduced in Hungary in 1953. However, starting in 1964, hybrid maize occupied 100% of the maize-growing area in the country (MARTON 2013). To meet the increasing demand for maize cultivation, twelve seed processing plants were established between 1956 and 1964. Since the 1980s, Hungary has increasingly relied on foreign hybrid varieties, which has directly impacted the distribution of planting areas. Consequently, Hungary became one of the world's largest exporters of maize seed during the 1980s. Currently, maize breeding is being conducted in five research units in Hungary (MARTON et al. 2003).

The production of maize has experienced fluctuations over the years, serving as a crucial indicator of its market competitiveness. These fluctuations are primarily influenced by environmental factors. The adoption of more resilient maize cultivars, along with the appropriate application of fertilizers, particularly nitrogen and potassium, can enhance yield (MIZIK AND RÁDAI 2021). However, efficient allocation and economic returns are also vital in terms of optimizing input consumption. Farmers should ensure reasonable compensation for each unit of input (NAGY 2006). Similarly, in Hungary, achieving high yield required fertile land, favourable weather conditions, knowledge and skills, maize hybrid selection, as well as research and development (BOJTOR et al. 2021).

In 2021, Hungary produced roughly 8.80% of the EU's maize production, with an average yield of 6.09 metric tonnes per hectare, placing in the middle of the rankings. According to the Hungarian Central Statistical Office (HCSO, 2023), as shown in Table 5, the total harvested area of maize production in Hungary in 2015 was 1,146,127 hectares, which decreased to 1,054.566 hectares in 2021 and 819,356 hectares in 2022. Consequently, the total harvested production was 6,632,783 metric tonnes (2015), 6,462,205 metric tonnes (2021), and 2,803,206 metric tonnes (2022), with an average yield of 5,790 grams per hectare (2015), 6,130 grams per hectare (2021), and 3,420 grams per hectare (2022). According to data from the Hungarian Meteorological Service, there have been recurring droughts in the spring in recent years, and April 2020 ranked as the third driest since 1901 (HCSO 2021). Given that the global climate change scenario becomes a major factor in maize fluctuation, greater emphasis should be placed on improving the adaptability and stability of hybrid yields for different agroecological conditions (MARTON et al. 2003).

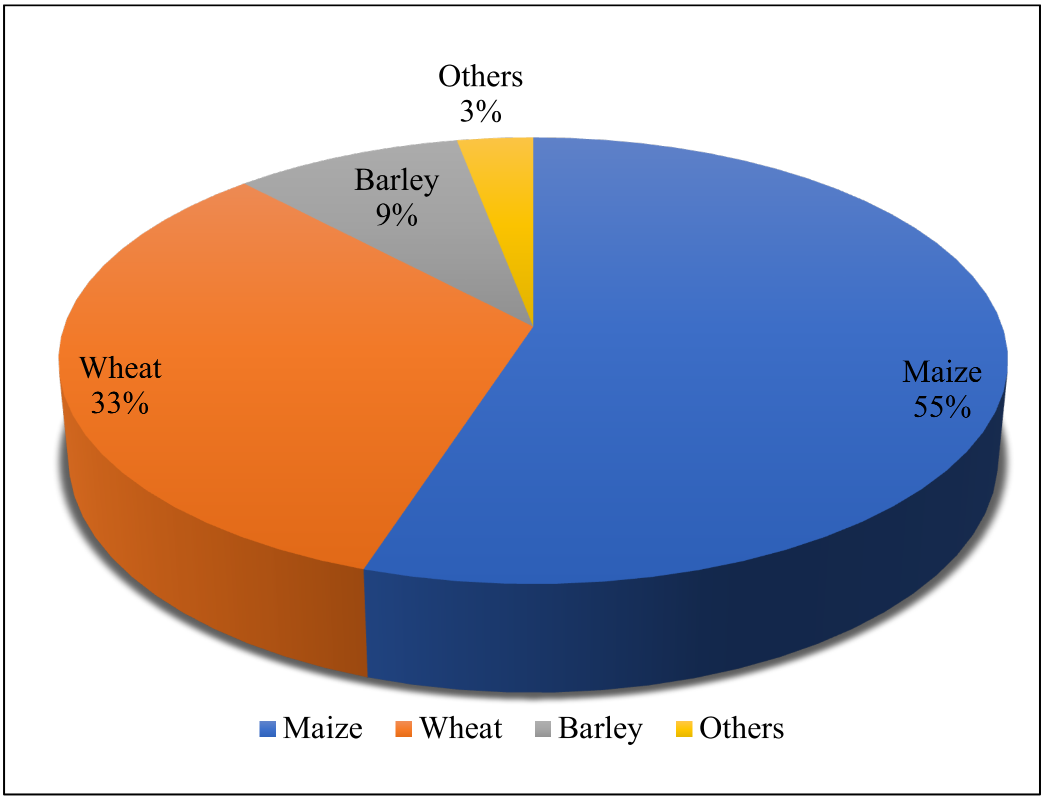


Figure 2. Distribution of production of major cereals, 2020 in Hungary

Source: HCSO 2021.

Table 5. Maize production statistics in Hungary for 2015, 2020 and 2021, by region.

Name of Territorial units	Level Territorial units	2015	2021	2022*
		Harvested area, hectare		
Budapest	Capital, region	7,630	290	78
Pest	Country, region	58,578	55,034	34,009
Central Hungary	Large region	66,208	55,324	34,087
Central Transdanubia	Region	153,613	131,103	120,835
Western Transdanubia	Region	119,129	97,860	84,189
Southern Transdanubia	Region	246,414	198,495	177,089
Transdanubia	Large region	519,156	427,458	382,113
Northern Hungary	Region	60,369	70,079	54,425
Northern Great Plain	Region	250,770	259,641	180,885
Southern Great Plain	region	249,624	242,064	167,845
Great Plain and North	Large region	560,763	571,784	403,155
Total	Country	1,146,127	1,054,566	819,356
		Total harvested production, tonnes		
Budapest	Capital, region	42,055	1,885	113
Pest	Country, region	321,929	334,889	43,047
Central Hungary	Large region	363,984	336,774	43,161
Central Transdanubia	Region	923,062	821,823	335,930
Western Transdanubia	Region	709,621	749,429	510,584
Southern Transdanubia	Region	1,717,774	1,166,998	856,648
Transdanubia	Large region	3,350,458	2,738,250	1,703,162
Northern Hungary	Region	276,643	484,481	155,175
Northern Great Plain	Region	1,194,443	1,690,656	483,519
Southern Great Plain	region	1,447,255	1,212,044	418,190
Great Plain and North	Large region	2,918,341	3,387,181	1,056,884
Total	Country	6,632,783	6,462,205	2,803,206
		Average yield, kg/hectare		
Budapest	Capital, region	5,510	6,500	1,440
Pest	Country, region	5,500	6,090	1,270
Central Hungary	Large region	5,500	6,090	1,270
Central Transdanubia	Region	6,010	6,270	2,780

Western Transdanubia	Region	5,960	7,660	6,060
Southern Transdanubia	Region	6,970	5,880	4,840
Transdanubia	Large region	6,450	6,410	4,460
Northern Hungary	Region	4,580	6,910	2,850
Northern Great Plain	Region	4,760	6,510	2,670
Southern Great Plain	region	5,800	5,010	2,490
Great Plain and North	Large region	5,200	5,920	2,620
Total	Country	5,790	6,130	3,420

* Preliminary data

Source: HCSO 2023

2.5.1 Cultivated Varieties in Hungary

The cultivation of maize in Hungary has a rich and extensive history that can be traced back to the late 19th century. During this time, Italian varieties such as Cinquantino and Pignoletto were the preferred choice for maize cultivation (HADI 2006). However, these varieties had relatively low yields, averaging less than one tonne per hectare. Consequently, the introduction of American varieties increased the National yield to 1.5 tonnes per hectare, and breeding for adaptable varieties resulted in an additional yield of up to 2 t/ha. The period after the Second World War saw a significant boost in maize yield in Hungary. The average yield tripled during this time with farmers regularly achieving yields of more than 6 tonnes per hectare. Nevertheless, in 1985, there was a sudden and unexplained reduction in maize yield (MARTON et al. 2003). This posed a significant challenge to farmers and researchers alike. To address this issue, the Martonvásár Institute introduced the Martonvásári 5 (Mv5) hybrid, which was the first hybrid maize variety developed in Hungary and Europe (KOVÁCS 2003, MARTON 2003). This hybrid played a crucial role in revitalizing maize cultivation and restoring yields to previous levels.

The Maize Breeding Department of the Centre for Agricultural Research, Hungarian Academy of Sciences (MTA MGI, 2019) has been actively involved for over 60 years in maize breeding work activities and has made significant contributions to the development of maize hybrids in Hungary. The department has registered more than 250 maize hybrids, with 80 of them still listed on the European Union variety list. Additionally, the hybrids grown in Martonvásár have been registered in several non-EU countries, including Ukraine, Russia, Kazakhstan, Iran, and Turkey. The current most popular varieties are listed in Table 6. In addition to hybrids, the department has also been granted patents or plant breeder’s rights for approximately 60 parent materials. Furthermore, the staff of the department has registered five patents (MTA MGI, 2019).

Table 6. Currently most popular maize varieties in Hungary.

Characteristics	Variety
Early grain hybrids	Mv170, Masuk, Mv270, Mv251, Bodrog, Mv255, Amanita, Mv277, Lenacorn, Ivola
Mid-season grain hybrids	Hunor, Mv350, Mv343, Mv Tarján, Mv Koppány, Gazda, Miranda, Danietta
Late grain hybrids	Mv500, Maros, Maxima
Silage hybrids	Megasil, Lactosil, Classil, Siloking, Massil
Sweetcorn hybrid	Mv Július.

Source: MTA MGI 2019.

2.6 Germination Characteristics

Germination is the transformative process of converting a seed into a new plant, involving the activation of the embryo and the emergence of the shoot from the seed coat. It is also associated with the metabolic potential of seed vigour, which is evident throughout germination and seedling growth. It is also interpreted as the metabolic potential of seed vigour, which is manifested throughout germination and seedling growth. Initially, the germination process was known as the imbibition phase. Germination involves the expansion and softening of the seed coat due to water absorption (MASUBELELE et al. 2005). This process stimulates inner physiological activity, promotes respiration, and facilitates the development of the shoot and root (MASUBELELE et al. 2005, ITROUTWAR ET AL. 2020). The most common form of germination is seen in the emergence of seedlings from angiosperm or gymnosperm seeds (MIRANSARI AND SMITH 2014).

Germination is a complex process involving various physiological and morphogenetic processes, including seed energy transfer, endospermic nutrient absorption, and metabolic changes (LTROUTWAR et al. 2020). It is influenced by environmental conditions such as water, temperature, and sunlight. Water is particularly crucial for seed germination as it facilitates the transition from imbibition to active root growth, and germination is completed when the radical emerges from the covering structures (BEWLEY 1997). Other elements that affected the germination include phytohormones, sugar, nutrients, and even magnetic attraction (CASAL AND

SÁNCHEZ 1998). The restoration of essential processes like transcription, translation, and DNA repair, followed by cell elongation and division, indicates successful germination (VISHAL AND KUMAR 2018). The vigorous seed promotes greater germination rates, seedling vigour, and germination ability, as well as higher economic yields (CLOR et al. 1976), as demonstrated by hybrid seeds (OMAR et al. 2022a). Additionally, different genotypes can react differently in terms of seed yield and quality (KRISHNAN AND RAO 2005). The germination percentage is also influenced by genetics, and OMAR et al. (2022a) discovered that hybrids had a greater germination rate and more vigorous seedlings compared to their parents. The germination process is illustrated in Figure 3.

According to BYRUM AND COPELAND (1995), seed vigour testing has become more essential in the seed industry for quality control and marketing since both producers and farmers require repeatable testing to appropriately represent the growing potential of seed companies. It is necessary to ensure that the seeds produced will successfully germinate under the right conditions. Besides, the main purpose of germination testing is to figure out the percentage of seeds alive in any seed lot. It also demonstrates that germination is related to seed vigour and provides an estimate of field performance. A standard germination test takes 7–10 days, with the seed absorbing moisture in two days and producing the first roots and leaves in four days. At this point, the seeds are considered germinating seedlings.

In 1876 Fedrich Nobbe was the first to separate seed vigour from germination (COPELAND AND MCDONALD 1999), while FRANCK (1950) proposed the term "vigour" to describe seed lot farms' ability to generate plants. Seed quality is a measure of seed viability and vigour, which determine the ability of normal seedlings to emerge in various field conditions. The seed count (SC) test, the accelerated ageing (AA) test, and the soak test are used to assess seed quality (GOGGI et al. 2008). Furthermore, germination is an important indicator of viability, which is the characteristic of the seeds that allows them to germinate under ideal conditions. BERZY et al. (2020) emphasised the relevance of maternal cross-combination effects, and there is a link between seed vigour, fresh shoot weight, fresh root weight, and kernel yield in most maize hybrids.

Germination is related to field emergence performance, seedling establishment, and the subsequent performance of the plant produced. The quality of the seed and its impact on the generation of latent and field performance are mostly determined by the viability and vigour of the seed (LAFTA AND CHILAB 2019). By assessing seed viability and vigour, one attempt is made to predict the number of seeds needed to avoid the poor field performance that appears later due to its low correlation with yield. This process is known as field emergence (HAMZA 2006), and uniform and vigorous seedling emergence will ensure a good plant population and yield (SHIRIN et al. 2008). Consequently, seed evaluation and information are significant sources of uncertainty for the seed industry (MARCOS 2015).

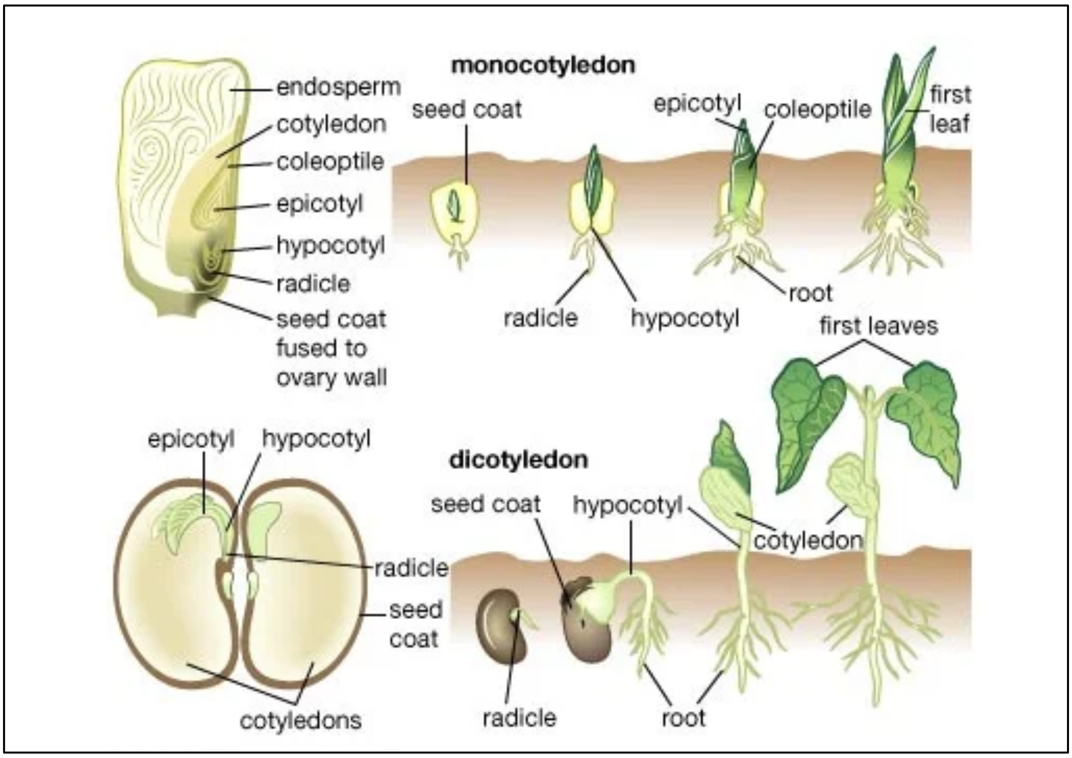


Figure 3. Seed Germination Process.
Source: HESLOP-HARRISON 1999.

2.7 Agronomic Characteristics

The most important agronomic characteristic of maize is the combination of all factors that contribute to increased yield. It can be evaluated through plant growth characteristics such as earliness characteristics, yield attributes, yield and yield components, and grain quality characteristics. These characteristics are determined at different growth and development stages of the maize plant (Figure 4). Furthermore, many studies have been conducted to evaluate maize performance in the field, with the most important parameters measured including days to anthesis and silking, anthesis-silking interval, plant and ear heights, number of ears per plant, leaf area, ear weight, and grain yield (OGUNNIYAN AND OLAKOJO 2014). Then, MALIK et al. (2005) also stated that the most important characteristics in maize were grain yield, days to tasselling, days to silking, tassel branches, plant height, ear height, leaf length, leaf width, leaf area, ear weight, grain moisture, kernel rows, and 1000 kernel weight. In accordance with KASSAI et al. (2020), yield and grain quality can also be affected by agronomic practices. In addition to genetic factors, the environment and agronomic practices also influence maize production, and understanding the factors that drive increased yield has become a priority in research and development (RIZZO et al. 2022).

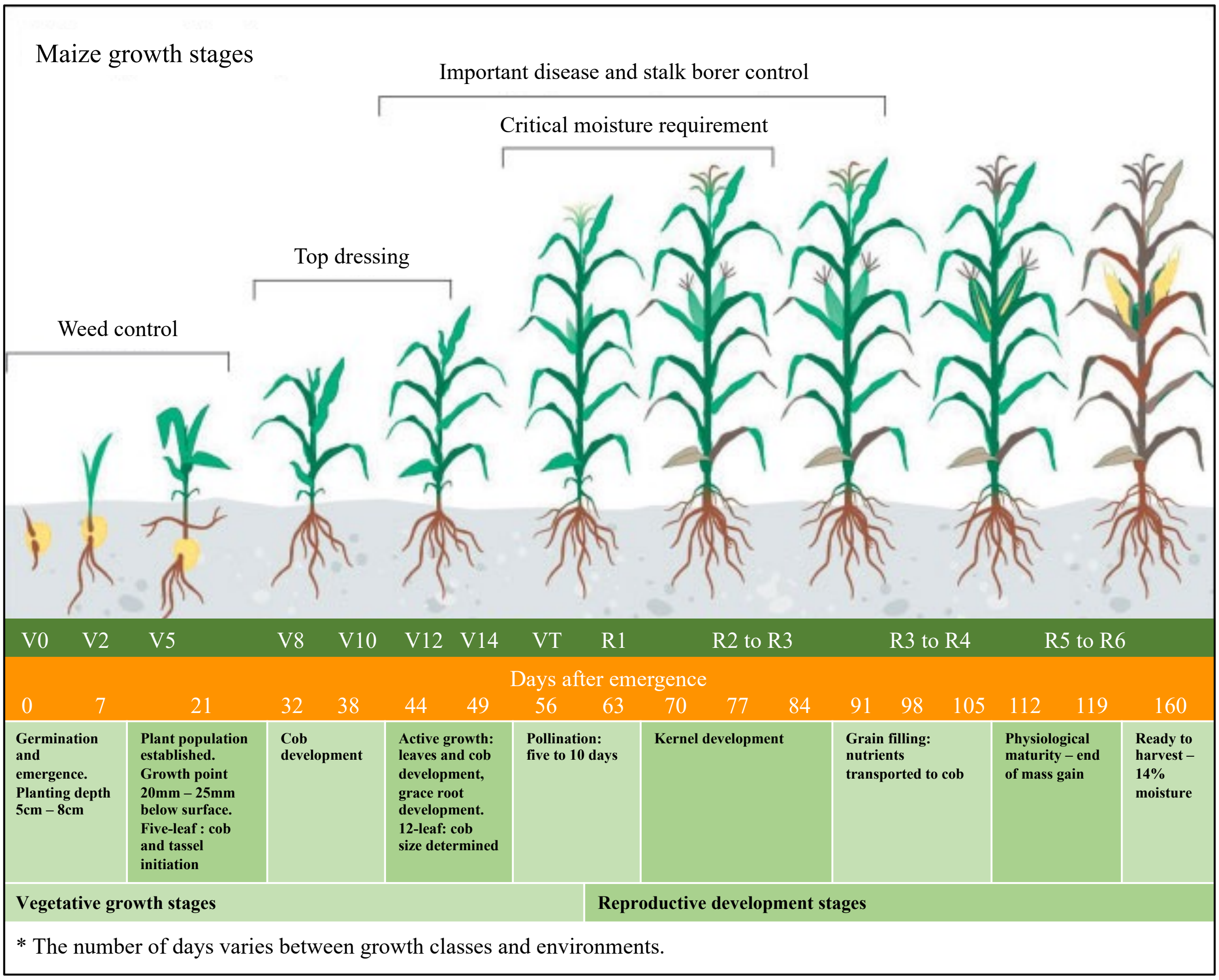


Figure 4. The different growth and development stages of the maize plant.
Source: MAGAZINES 2020.

2.7.1 Earliness Characteristics

Earliness, or early maturity, plays a vital role in the profitable cultivation of maize and affects the relationship between yield, grain moisture, and plant density. This was highlighted in a recent study by BABIC et al. (2022). It is an essential characteristic that plays a central role in the adaptation of genotypes to different environments and cropping systems, as well as overall yield and stability (KUMAR AND ABBO 2001). Furthermore, early maturity can provide protection against various biotic and abiotic stresses, including diseases, heat, and drought (BA AND DHAMELIYA 2013).

Flowering time is a complex characteristic correlated with maize adaptability in various climatic zones (HOSSAIN et al. 2022). Anthesis, silking, maturity, and the number of leaves are examples of earliness characteristics. Anthesis occurs when pollen is shed, while silking occurs when silk emerges from the ear. Grain maturity is achieved when the migration processes are completed, and at high temperatures, it is associated with the development of the black point (GAY 1984). The milked line in maize grain and dried husks are also used to estimate maturity. The anthesis, silking, and maturity of maize are typically expressed in days after planting and are rather complicated since they also depend on environmental conditions. However, the adoption of thermal units will eliminate these issues (BONHOMME et al. 1994). KIM AND HALLAUER (1989) discovered a significant correlation between anthesis and silking days, while REDDY et al. (1986) found a high correlation in inbred lines compared to hybrids for days between days of silking and days of 50% dried husk.

The number of leaves is also related to earliness characteristics, which can be evaluated by counting the number of leaves at a certain period and determining the maize cycle's reliability (SALAMINI 1985). SALAMINI (1985) also noted that the number of leaves depends on two physiological parameters: leaf production rate and panicle initiation time. The difference in leaf count between short and long days is used to measure a plant's susceptibility to photoperiod (STEVENSON AND GOODMAN 1972, BREWBAKER 1981). Understanding the timing of maturity is a critical aspect of maize research and development, as it has a significant influence on grain yield (FONSECA AND PATTERSON 1968, GOLAM et al. 2011, ALI et al. 2017, RAUT et al. 2017, ALI et al. 2018). Additionally, understanding the genetic behaviour related to early maturity provides an extra advantage in predicting its usefulness in plant breeding. These will provide preliminary information as well as an understanding of the potential advantages of specific genotypes for early maturity and higher grain yield (BA AND DHAMELIYA 2013).

2.7.2 Grain Yield and Its Components

Grain yield is a complex characteristic that is determined by several yield components, including the number of ears per plant, rows per ear, kernels per row, number of seeds per ear, kernel weight, ear diameter, and ear length. The most important characteristics of grain yield are the combination of three yield components: the number of ears per unit area, the number of grains per ear, and the unit grain weight (GARDNER et al. 1987). Grain yield is greatly influenced by genotypes with desirable characteristics and is significantly correlated to the kernel set (CIRILO AND ANDRADE 1994). However, it is highly sensitive to environmental changes, particularly when tasselling and silking (CIRILO AND ANDRADE 1994), indicating that it is impacted by the environment (ALI et al. 2017). Grain yield is also affected by physiological and biochemical interaction processes, controlled by genes, and influenced by the environment (ZSOLT et al.

2005). SALASYA et al. (1998) identified multiple factors that contribute to low grain yield, including biotic stress (viz., pests and diseases and a lack of superior varieties) and abiotic stress (viz., low soil fertility, nutrient deficiency, and inefficient field management). In addition, the kernel number is related to the interception of light and varies across low- and intermediate-latitude environments (KINIRY AND KNIEVEL 1995). Also, ARHA et al. (1990) stated that the yield depends on the type of material and the environment, which was added by ABRAHA AND SAVAGE (2006), who found that grain yield varied greatly from one place to another due to yield changes that affected the characteristics. Furthermore, there are many other factors that affect maize grain yield, including the application of a tillage system, where an inefficient tillage system will reduce yield between 8 and 33 percent (RÁTONYI et al. 2005).

GOODMAN (1965), LONNQUIST et al. (1966), and MONTEAGUDO (1971) discovered a positive correlation between the mean number of ears per plant and grain yield or prolificacy. Prolificacy refers to the ratio of harvested ears to the number of plants recorded at harvest. Additionally, AGBAJE et al. (2000) also found that grain yield and the number of rows per ear were positively correlated with the number of grains per ear, and it can be directly calculated by counting or multiplying the number of rows per ear and the number of kernels. High heritability was observed between 0.57 and 1.0 (HALLAUER AND MIRANDA 1981, GOLAM et al. 2011), and low to moderate between 0.16 and 0.53 (ARHA et al. 1990). Although mean grain weight is not directly associated with grain yield, yield components such as ears per plant, the number of grains per ear, and the grain weight are potentially heritable (GOLAM et al. 2011).

2.8 Grain Quality Characteristics

Grain quality is the most important characteristic that plays a significant role in the cereal industry and holds immense significance in maize breeding research and development (AL-NAGGAR et al. 2016). YASOTHAI (2020) categories grain quality into intrinsic and extrinsic factors. The intrinsic factor of grain quality encompasses various characteristics that are inherent to the grain itself. These include colour, composition, bulk density, odour, aroma, size, and shape. On the other hand, the extrinsic actors of grain quality are external factors that can affect the grains during their production, handling, and storage. These factors include age, broken grain, immature grain, foreign matter, infected grain, and moisture content. In addition to these factors, grain quality also includes other essential components such as minerals, fibre, phytic acid, and tannins. These components can impact the nutritional value and health benefits of the grains (ABADASSI 2015). Proportions vary substantially depending on grain type, genetics, variety, agronomic practices, and post-harvest management.

2.8.1 Starch or Carbohydrate

The most significant constituent in maize grains is starch, or carbohydrate, which has great economic and nutritional value. This is because it accounts for around 73–75% of the grain's weight (AL-NAGGAR et al. 2016, MOTTO et al. 2011), and the starch content is in the endosperm. Normal maize starches have an amylose content of 24–28%, while waxy maize starches have a lower amylose content of less than 10% (BAJAJ et al. 2018). However, high-amylose maize starches have an amylose content exceeding 50% (LI et al. 2019, SINGH et al. 2006). Several genes regulate its presence (MOTTO et al. 2011, YANG et al. 2013). A study by YANG et al. (2013) found that starch content in maize grains is highly heritable, with broad-sense heritability estimates ranging from 0.77 to 0.89. This has significant implications for maize breeding and improvement. Breeders can select lines with high starch content to develop energy-efficient varieties for various applications. Understanding the genetic basis of starch content can also help researchers develop new strategies for improving the yield and quality of maize grains.

2.8.2 Protein

Several important and fascinating market trends are associated with grain nutritional quality, particularly protein and oil content (MITTELMANN et al. 2003). Maize has a protein content level ranging from 6 to 15 percent, depending on the cultivar (ABADASSI 2015). Th Protein content is correlated with the content of lysine and tryptophan, which are two essential amino acids for human and animal nutrition (IITA 1982). Protein content is a quantitative trait (DUDLEY AND LAMBERT 1992) with additive and non-additive effects, and dominance appears principally for characteristic reduction (BERKE AND ROCHEFORD 1995). However, protein content is negatively correlated with starch content and genetically controlled (LI et al. 2009). The effect of interaction with the environment is also important in detecting protein content (AL-NAGGAR et al. 2016). Additionally, water presence is another major factor influencing protein content, along with environmental considerations (OIKEH et al. 1998).

2.8.3 Oil

Maize is a grain with a high oil content (approximately 3 to 4%), which is primarily found in the germ layer and endosperm. Because of its low level of saturated fatty acids like palmitic acid and stearic acid and comparatively high content of polyunsaturated fatty acids like linoleic acid, maize oil is one of the highest-quality oils for human nutrition (IITA 1982, MOTTO et al. 2011). According to SONG AND CHEN (2004), oil content has a positive correlation with protein and lysine content, while starch content has a negative correlation. DUDLEY (1977) stated that the oil content in maize grain is a quantitative characteristic, and additive genetic variance appears to be the key component controlling this character. Furthermore, the study conducted by DUDLEY AND JOHNSON (2009) revealed that non-additive gene effects, specifically dominance and epistasis, significantly influence the inheritance of oil content in maize grains. Heritability values for oil content in maize grain have been observed to range from moderate to high (SONG AND CHEN 2004).

2.8.4 Moisture Content

Moisture content in maize grains exists in both free and bound forms, as it does in other living organisms. Carbohydrates and proteins are examples of colloidal compounds that contain bound water, while free water is the physical moisture of the grain. It is crucial to consider the free water content when determining the water content, as it is essential for germination activity and storage purposes. Most plants require a moisture content of 14-15% for storage (GYŐRI 2017). Reducing grain moisture content during harvest is a significant goal, particularly in temperate maize breeding (LI et al. 2021). The moisture content at maturity and the rate of drying in the field are genetic variables that affect the grain moisture content at harvest (WANG et al. 2019), while environmental conditions control the drying process in the field (MARTINEZ-FERIA et al. 2019).

2.9 Effect of Nitrogen Fertilization on Yield and Quality

Nitrogen is an essential nutrient for plant growth and development, and it plays a crucial role in the production of maize. Nitrogen application has been shown to increase maize grain yields by promoting plant growth and development, can improve quality characteristics such as grain protein content and concentration more consistently (AMANULLAH et al. 2009), with a significant effect on protein as nitrogen fertiliser levels increase (CORRENDO et al. 2021). However, the amount of nitrogen required by maize plants varies depending on several factors, including soil type, climate, and plant genetics.

However, the quality of maize can be influenced by both low and high nitrogen dose rates. Excessive nitrogen doses can lead to several negative impacts on maize quality, including reduced grain quality, increased susceptibility to diseases, and decreased nutrient uptake efficiency. Conversely, insufficient nitrogen doses can result in stunted growth, reduced yields, and poor grain quality. Therefore, it is essential to ensure the optimum supply of nitrogen doses to improve maize quality, and maize grain yields respond positively to nitrogen application (HAMMAD et al. 2011). The use of nitrogen fertiliser in grain production has played a significantly role in global food security (ZHAI et al. 2019).

Therefore, it is important to maintain an optimal nitrogen supply to improve the quality of maize. Decreasing fertilizer application can reduce maize grain yield as shown by LOCH (2015). Similarly, MOSER et al. (2006) discovered that increasing nitrogen dosages can increase maize yields, but it primarily affects the 1,000-grain weight rather than the number of grains. Meanwhile, fertilization and plant protection can also increase yields, potentially reducing nitrogen consumption (ARENDÁS et al. 2012). Nutrient application, as highlighted by NAGY (2012) and ÁRENDÁS et al. (2014), has a significant impact on productivity and quality. Furthermore, proper nutrient application plays an important role in modern crop production to ensure crop safety (PEPÓ 2017). Additionally, selecting stress-resistant maize hybrids can help plants withstand high temperatures (MARTON et al. 2012).

In Hungary, nitrogen fertiliser application is generally between 60 and 70 kg per hectare, yielding around 7 metric tonnes per hectare. Several studies conducted in Hungary have focused on determining the optimal nitrogen use in grain crops (ZSOLT et al. 2005, RÁCZ et al. 2021, OMAR et al. 2022b). Efficient and sufficient nitrogen management practices are crucial for increasing maize biomass production as well as improving yield and protein content. In addition, the application of Nitrapyrin technology has been found to enhance maize physiology and productivity by increasing nitrogen uptake (RÁCZ et al. 2021). Additionally, nitrogen content positively affects chlorophyll concentration, yield, and protein content. Monitoring chlorophyll content during the R1 growth phase can serve as an indicator for predicting yield and protein content, although this relationship may vary depending on the hybrid and crop year (ADRIENN et al. 2012). Moreover, OMAR et al. (2022b) stated that increasing the dose of nitrogen does not always lead to an increase in yield, as excessive or lack of water can cause stress and reduce yields (SZÉLES et al. 2012).

New technology involving intelligent agriculture monitoring systems, or the Internet of Things (IoT), has gained popularity in Hungary. It ensures the optimal fertiliser use, waste reduction, nutrient uptake optimisation. These technologies offer cost-effectiveness, increased profits, and environmental safety, while also promoting rational farm management plans (AMBRUS et al. 2022). Additionally, maintaining an optimal nitrogen supply is crucial for enhancing maize grain quality, which can be achieved through appropriate nitrogen fertilizer rates and nitrogen-efficient maize varieties.

2.10 Genetic Diversity in Maize

Even though maize was first domesticated in Mexico, many landraces of maize can be found throughout the continent due to their wide adaptation to the environment (PRASANNA 2012). The Northern Flint race, which was cultivated in pre-Colombian times in north-eastern America, is one of the most prominent maize types in this adaptation history. Also, Lancaster Surecrop and Reid Yellow Dent varieties, both of which belong to the same race, have been the primary sources of heterosis in the American Corn Belt over the past 80 years. While Reid Yellow Dent has divided into two genealogical lines in the last 20 years, i.e., Stiff Stalk Synthetic and Iodent (ZUBER et al. 1980), In addition to these sources, European Flint and Central European Dent are employed as heterosis sources throughout Europe (HADI et al. 2004).

Many studies conducted in Mexico and other countries revealed genetic diversity in maize germplasm, which follows the widespread use of molecular markers to see the genetic pattern of maize globally over the last two decades. The diversity of maize germplasm with beneficial alleles is useful for future challenges that will contribute to increased yield, abiotic stress tolerance, disease resistance, and nutritional quality improvement (SOLIMAN et al. 2021). However, these alleles are often scattered over a wide array of landraces or populations (PRASANNA 2012).

In Latin America, molecular marker techniques are used to trace the route of maize migration from the centre of origin and understanding the fate of genetic diversity during maize breeding. The genome sequencing of B73 (Corn Belt inbred, US) and Palomero (popcorn landrace, Mexico) has provided valuable insights into the organization and evolution of the maize genome (PRASANNA 2012). Thus, a study of 93 maize landrace accessions from the International Maize and Wheat Improvement Institute (CIMMYT) in Morelos, Mexico, revealed that maize landrace cultivation has decreased in the examined area over the last 50 years (MCLEAN-RODRGUEZ et al. 2019). This is because climate change causes growing areas to become warmer and drier, which increases disease and insect infestations and reducing maize yield in warmer countries due to changing rainfall patterns (EDMEADES 2013). To address these challenges, it is necessary to gather information on diversity and implement systematic initiatives to expand the genetic base of maize and develop climate-resilient and high-yielding cultivars for different agroecologies.

According to HALLAUER AND MIRANDA (1981), maize has a wide range of shapes and forms, with over 280 races. Meanwhile, only 59 maize races have been identified through conventional farmer management and accepted based on extensive morphological and isozyme data analysis (SÁNCHEZ et al. 2000). It has been observed that there are limited gene pools in maize that can be utilised to increase average yield, resulting in a scarcity of sources for heterosis. Dent, a type of maize, has become widespread in central Europe and consists of two unrelated gene pools derived from Rumai 122 and Mindszenpusztai Yellow Dent (HADI et al. 2004). Rumai 122 was bred in the 1890s from Southern Dent varieties brought from the Corn Belt and Korai Bánáti Flint grown on the Ruma estate. It was used to successfully breed parental lines used in commercial hybrids and is considered a European source of heterosis (HADI 2005).

Many studies have been conducted on the Rumai gene pool, but there is limited information available on the Mindszentpusztai Yellow Dent (MYD) variety. The MYD has been cultivated by the Pap family in southern Hungary for almost two decades and has become a widely used source of heterosis in other parts of Europe. The first maize hybrid was registered in 1953 by Endre Pap in Martonvásár, Hungary (MARTON AND HADI 2007). Endre Pap initiated his breeding programme in 1917 using the pedigree method and later developed inbred lines, viz., 156, 014, 0118b, 0118a, and 01, which served as parents for cultivated hybrids. Additionally, at least 14 second-cycle lines became known after the development of these lines by Endre Pap. The first maize hybrid was registered in 1953 by Endre Pap in Martonvásár, Hungary (HADI 2009).

2.11 Maize Breeding

Plant breeding, a prehistoric activity that started with inactive agriculture by ancient farmers 9,000–11,000 years ago, involves the observation and selection of the best plants and saving their seeds for future use. This, coupled with a small initial population, creates a population problem that significantly limits genetic diversity (TANKSLEY AND MCCOUCH 1997). According to POEHLMAN AND SLEPER (2013), plant breeding is both an art and a science, aiming to change traits and create desirable characteristics in new varieties by manipulating plant heredity. Also, breeding is the process of changing and improving the genetic or genotype content of an individual or population to a superior or desired level (YAP et al. 1990). It has been used to improve the quality of nutrition in products for humans and animals. It can also be defined as the production of new or improved crop varieties that are tolerant to biotic and abiotic factors. People and society can also benefit from the great diversity of crops and crop products (ACQUAAH 2012, LUCKETT AND HALLORAN 1995). Therefore, the main purpose of plant breeding is to develop superior varieties based on yield, resistance to disease, high quality, acceptance by consumers, or nutritional value.

In prehistoric times, maize breeding was radically altered through selective breeding. Ancient farmers would carefully assess kernel size, toughness, and ease of grinding to preserve their plants. Within a few thousand years, maize had already reached a length of one inch (BRADLEY et al. 2016). Prior to 1909, farmers and seedmen utilised the mass selection breeding technique, as described by HALLAUER et al. (1988), where they would choose the best ear from the finest plant in a maize population. However, modern breeding began with individuals selecting particularly good yields from their fields and then selling the seed to other farmers. In the early 1900s, intensive breeding activities focused on increasing maize productivity through phenotype selection. The ancient breeders have taken advantage of existing genetic variations to adapt new varieties of maize to new environments (PRUITT 2016). Later, hybridization becomes an important breeding technique for producing new varieties or hybrids with certain desired traits.

Nowadays, maize cultivation has become widespread, and scientists are continuously adopting advanced breeding techniques. The development of molecular marker systems in the 1980s has led to an increase in the number of polymorphic markers available to plant breeders and molecular biologists (CROSSA et al. 2017). This has resulted in seed companies turning to genetic engineering to produce better crops quickly. Scientists have successfully inserted genes from Bt soil bacteria into maize to repel pests and have also conducted studies to produce drought-resistant maize varieties. Recently, scientists also conducted a study to produce maize varieties that can withstand drought and other abiotic stresses (BRADLEY et al. 2016). However, achieving successful outcomes requires a deep understanding of the complex biology of quantitative traits and a thorough assessment of the broad genetic base of maize (SMITH et al. 2005).

2.11.1 Maize Inbred Line Development

Inbred lines are genotypes that are homozygous and have been produced through repeated selfing with selection or by using individuals with the same genotype. These inbred lines are developed from a variable source population, which is generally an open-pollinated variety, or by synthetic single or double crosses (ACQUAAH 2012). The concept of pure inbred lines was first proposed by SHULL (1909). He utilised selfing and homozygous biotype selection in his maize breeding experiment. In 1910 and 1911, Shull advocated various state agricultural experiments to develop pure lines. He also aimed to develop hybrids by using inbred lines as parents, but the low seed yield made this approach impractical (DARRAH et al. 2019). Considering the issue, MANGELSDORF AND JONES (1926) suggested using a double cross to take advantage of the hybrid vigour effect observed in two single crosses. By combining inbred lines with different genetic backgrounds, they were able to achieve higher yields and improved performance in hybrids. However, the process of developing maize hybrids is not without its challenges. HALLAUER AND MIRANDA (1988) noted that the identification of suitable inbred lines is the most expensive and time-consuming aspect of hybrid development. The performance of inbred lines alone does not necessarily predict the performance of maize hybrids in terms of grain yield.

This is because hybrid performance is influenced by the degree of heterosis, or hybrid vigour, between the inbred parents and their related hybrids (BETRÁN et al. 2003).

2.12 Genetic Variability

A fundamental prerequisite for the success of breeding programs is an understanding of genetic variability, heritability, and genetic advancement of characteristics in every plant population. In maize breeding programs, the primary goal is generally to promote genetic variability in attributes that are commercially desirable while maintaining an appropriate degree of variability. Hence, progress in crop improvement depends on selecting the best breeding resources, analysing genetic variability, and understanding quantitative factors associated with production. According to HALLAUR (1972) and GRZESIAK (2001), maize genotypes exhibit significant genotypic variability for various characteristics. IHSAN et al. (2005) also found significant genetic variations for maize genotypes based on morphological criteria. This variability could be used for crop improvement purposes (WELSH 1981).

Maize crops exhibit diverse phenotypic and genetic characteristics, and the presence of genetic variation among individuals in a population enables successful selection. Previous researchers have examined genetic variation in maize, focusing on characteristics that contribute to yield, including grain weight, kernel weight, days to maturity, ear height, silking, tryptophan content, cob length, ear length, days to 50% anthesis, silk emergence, days to maturity, ear aspects, grain yield, plant height, ear height, and diseased cobs. These variables aid in the assessment of genetic variability (MUCHIE AND FENTIE 2016, SESAY 2016, BELAY 2018).

The components of genetic variability, including heritability and genetic advance, are crucial for identifying population differences. The increments of genotypic coefficient variation (GCV) and phenotypic coefficient of variation (PCV) values for yield and yield components demonstrated the significance of genetic variability in plant selection (ANURADHA et al. 2020), and the consistency with genetic characteristics having high GCV indicates high potential for effective selection (MANSIR 2010). According to GHOSH (2020), the traits viz., number of grains per cob, grain yield per plant, number of grains per row, plant height, and ear height showed higher GCV, heritability, and genetic advance. These characteristics were governed by additive gene action, making the selection for these characteristics effective.

In general, crop improvement programs require a comprehensive understanding of genetic variation, heritability estimates, and genetic advances in maize grain yield and yield components. Broad-sense heritability helps breeders determine the proportion of genetic variance transmitted to offspring through additive gene effects, which is crucial for achieving genetic advancement. However, non-additive gene actions should also be considered to ensure comprehensive improvement in maize crops.

2.13 Heterosis

Heterosis, also known as hybrid vigour, is a phenomenon in which hybrids exhibit superior performance compared to their parents. This concept has been extensively studied and utilised in maize breeding programmes to improve yield and other desirable traits. The concept of heterosis has been observed since the discovery of hybridization in plants by KOLREUTER (1766) and other early hybridizers. These early experiments showed that when two different varieties of plants were crossed, the resulting hybrid offspring often displayed traits that were superior to those of either parent. This led to the realisation that hybridization could be a powerful tool in plant breeding. In addition, MENDEL (1865) applied his discovery by observing its manifestation in his pea hybrids. Although, in Mandel's previous trial in 1845, he had obtained Pyrus and Sorbus tree hybrids (ROBERTS 1929), consequently, he realised that not only new varieties, but also new species would occur among self-pollinating progenies. In addition, DARWIN (1876) stated that inbreeding would reduce the vigour of the plant, while crossbreeding would restore the vigour of the hybrid.

Maize was an early beneficiary of heterosis through the breeding of filial-one (F_1) hybrids with greater vigour for plant growth and grain yield. Beal conducted the first study on artificial hybridization between 1877 and 1882. He began the early, extensive testing for seed purity and viability in 1877 (BEAL 1877), and the first evidence of hybrid vigour in maize was obtained by controlling the crossing process in 1878 (BEAL 1878). Therefore, the first turfgrass experiment conducted with polystand compatibility took place in 1880 (BEAL 1880). In addition, Beal's teaching philosophy, outlined in his book *The New Botany*, had a significant global influence on pedagogy (BEAL 1882). He emphasized the importance of hands-on experimentation and observation in scientific research, and his approach to teaching botany was widely adopted by universities and colleges around the world. In addition to his work on hybridization and plant breeding, Beal also claimed that hybrids from open-pollinated varieties could increase yields by up to 40% compared to their parents. This insight further contributed to the development of high-yielding maize hybrids, which have become a cornerstone of modern agriculture.

Since the discovery of Mandel's Law in 1900, the study of heterosis has become more systematic and has shown good prospects for its growth. As a result, independent studies were initiated between 1905 and 1912 by East at the Connecticut Agricultural Experiment Station and Shull at the Carnegie Institution Station at Cold Spring Harbor to discover inbreeding and crossbreeding in maize (EAST 1908, SHULL 1908). This was an important advancement in scientifically conducted maize breeding and led to a better understanding of the underlying issue of heterosis. Therefore, Shull was the first to provide scientific evidence of depression caused by inbreeding and vigour restoration in maize. Meanwhile, it took until 1933 to release the first hybrid maize produced by crossing inbred lines.

SHULL (1912) was the pioneer who proposed the term "heterosis," which in classical genetics is defined as an increase in hybrid vigour over the better parent while, in statistical quantitative genetics, it must exceed the average of both parents (SHULL 1952). In addition, he highlighted that heterosis can be expressed as greater vigour, size, fruitfulness, fast growth, resistance to diseases and insect pests, or climate rigours, among other things. Meanwhile, ALLARD (1960) stated that heterosis is a hybrid strength that shows up in hybrids and exhibits superiority in hybrid performance when compared to their parents. Heterosis has also been defined as the difference between the hybrid value for a trait and the mean value of two parents for the same trait, with the degree of dominance of the trait controlling the expression of heterosis (FALCONER AND MACKEY 1996).

In maize breeding programmes, heterosis has been extensively utilised to identify genetically distinct populations as a foundation for the development of inbred lines used in hybrid crosses (HALLAUER 1990). A prior experimental investigation involving 1394 hybrid combinations found that the proportion of mid-parent heterosis ranged from 4.2 to 72, with an average of 19.5%. High heterosis estimations can be seen in the results of different races in maize (HALLAUER AND MIRANDA FILHO 1995). Heterosis ranged from -11.0% to 101.0% for 12 Brazilian maize races (PATERNIANI AND LONNQUIST 1963), while the heterosis effect on hybrids between Mexican maize races was 64.0% (WELLHAUSEN 1965), and interracial crossings ranged from 8.8% to 136.3% (PATERNIANI 1968). Then, CASTRO et al. (1968), CROSSA et al. (1990), and PATERNIANI (1980) discovered comparatively high heterosis and a high level of heterosis expression, with average heterosis of 24.8%, 39.0%, and 18.6%, respectively.

The consequences of heterosis have been addressed in detail by hypotheses that explain the genetic basis and physiology impact of the dominance hypothesis (BRUCE 1910, JONES 1917, COLLINS 1921), the overdominance hypothesis (SHULL 1908, EAST 1936), and the epistasis hypothesis (POWERS 1944). Furthermore, this hypothesis stably answers all intractable difficulties and proposes that heterosis does not depend on a single genetic effect. In maize, grain yield is predicted to contain heterosis of partial to complete dominance genes that influence the trait (HALLAUER

AND MIRANDA FILHO 1995). Otherwise, the expression of heterosis is also influenced by the degree of genetic divergence between parents; that is, variation in allele frequency is required for the expression of heterosis. As a result, the expression of heterosis should be lower in crosses across broad-based open-pollinated populations (MIRANDA FILHO 1999). Also, the heterosis study in maize crops is actively ongoing and has resulted in numerous findings that heterosis increased maize production (ALI 2003, HADI 2009, AL-NAGGAR et al. 2016), as single-cross maize varieties have contributed to the increases in maize production yield in the last few decades (HOCHHOLDINGER AND BALDAUF 2018).

3. METHODOLOGY

3.1 Overview of Methodology

This study comprises four main experiments, which were conducted either in the laboratory, the field, or both. The first two experiments designed to assess the germination potential of various hybridization pathways, including the parents, single cross hybrids, three-way cross hybrids, and double cross hybrids. Moreover, the second experiment built upon the findings of the first experiment by also examining the yield and its components in the field. In addition to evaluating germination potential, this information is crucial for assessing germination potential as well as understanding how different hybridization pathways impact the overall productivity of the maize crop. Emphasising, particularly seed viability, vigour, and their influence on maize crop yield and productivity. By analysing these yield components, the experiment's aim was to determine which hybrid types resulted in the highest crop yields.

The third experiment investigated the impact of different nitrogen levels on maize yield performance and grain quality. Nitrogen is an essential nutrient for plant growth and development, and its availability in the soil can greatly influence crop productivity. By varying the nitrogen levels, the study aimed to determine the optimal amount of nitrogen required for maximising maize yield and ensuring high-quality grain.

Lastly, the fourth experiment concentrated on the genetic variability, heterosis, and genetic advance of different maize genotypes. Maize genotypes refer to different varieties or hybrids of maize that possess distinct genetic traits. These traits can influence the plant's agronomic characteristics, such as yield performance, disease resistance, and tolerance to environmental stresses.

The flowchart in Figure 5 illustrates the experimental activities conducted throughout the research.

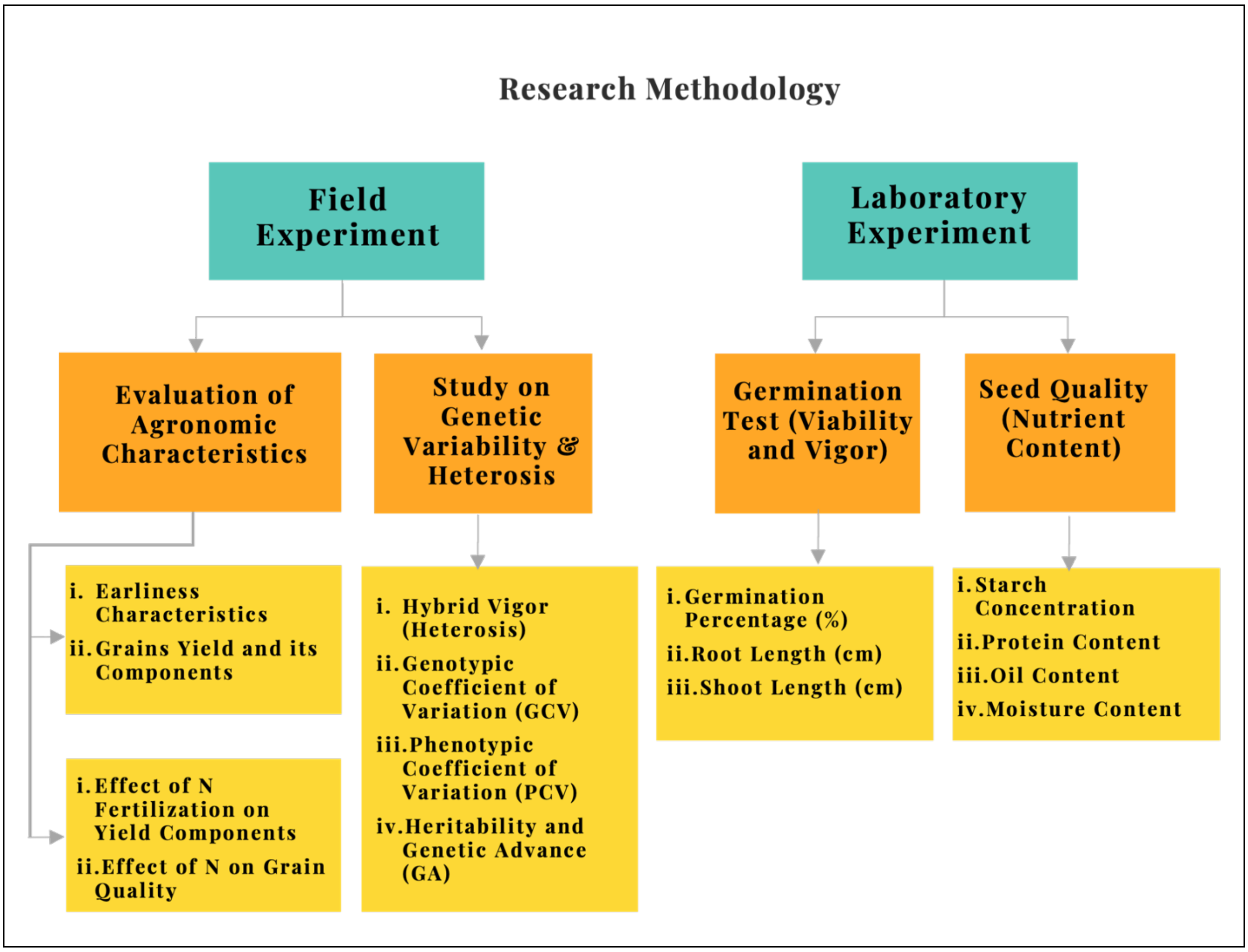


Figure 5. Flowchart illustrating the chronology of the research activities in this study.

3.2 Germination Characteristics of Different Maize Hybrids and Their Parental Lines

3.2.1 Experimental Materials

The maize seed varieties in this study were obtained from the Agricultural Research Centre, Martonvásár, Hungary. Single cross (SC), double cross (DC) and three-way cross (TC) hybrids and their parental inbred lines were studied. Four parents, viz. B1026/17 (SC (F)), TKAPA/15/ DV (SC (M)), TK1083/19 (DC (F)) and MCS901/19 (TC (F)) together with three hybrids; B1026/17 X TKAPA/15/ DV (SC (F_1)), TK1083/19 X MCS901/19 (DC (F_1)), and MCS901/19 X B1026/17 (TC (F_1)) were tested in this trial. All maize seeds used have been treated with fungicide to prevent any fungus infections.

3.2.2 Growing Conditions

The trials were conducted in January 2021 at the Laboratory of Crop Production of the Institute of Agronomy, Hungarian University of Agricultural and Life Sciences (MATE), Gödöllő, Hungary. The standard germination test was applied where all seeds were allowed to germinate in 13.5 cm

Petri dishes, lined with single layer Whatman filter paper (AOSA 1992). The filter paper was moistened with 8 ml distilled water at the beginning and added 10 ml on day seven of the trial. Each treatment contained five seeds and was laid out in a completely randomized block design with four replicates. Then, the seeds were incubated in a growth chamber at 23 °C for 12 days. The observation and data collection were recorded for germination rate (%), root length (cm), and shoot length (cm) at 5, 7, 9, 12 days.

3.2.3 Statistical Analysis

Analysis of variance (ANOVA) was performed using the IBM SPSS version 23. Data were subjected to a one-way analysis of variance to explain differences between maize varieties and treatment (days). The mean value of the treatment was compared with the least significant difference (LSD) at $p < 0.05$. Post hoc test for multiple comparisons using the least significant difference (LSD) was also used at $p < 0.05$.

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

3.3.1 Planting Materials

In this study, the experimental research involves two parts, which are laboratory experiments and open-field experiments. The seed of maize hybrids and lines were obtained from Szeged University, Hungary, and the Centre for Agricultural Research, Martonvásár, Hungary, and commercial hybrid as a control. The type of seeds used in the study is shown in Table 7.

Table 7. Maize genotypes were 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

3.3.2 Laboratory Experiment

A laboratory experiment was conducted at the Laboratory of Agronomy, Hungarian University of Agriculture and Life Sciences (MATE), Gödöllő, Hungary. The selected hybrids and lines and check variety were allowed to germinate in 13.5 cm Petri dishes and lined with a single sheet of Whatman filter paper as part of a standard germination test (ISTA 2014). Ten millimetres 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 laid out in a Completely Randomized Design (CRD). The seeds are then incubated for nine days at a temperature of 20 °C with 70% relative humidity (RH) in a growth chamber. The observations and data collection were made for seed viability and vigour, germination rate (%), radicle length (cm), and plumule length (cm) on days 3, 5, 7, and 9. All seeds used in this study were treated with fungicide, i.e., Sodium hypochlorite by 10%.

3.3.3 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, KA 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 6 and 7.

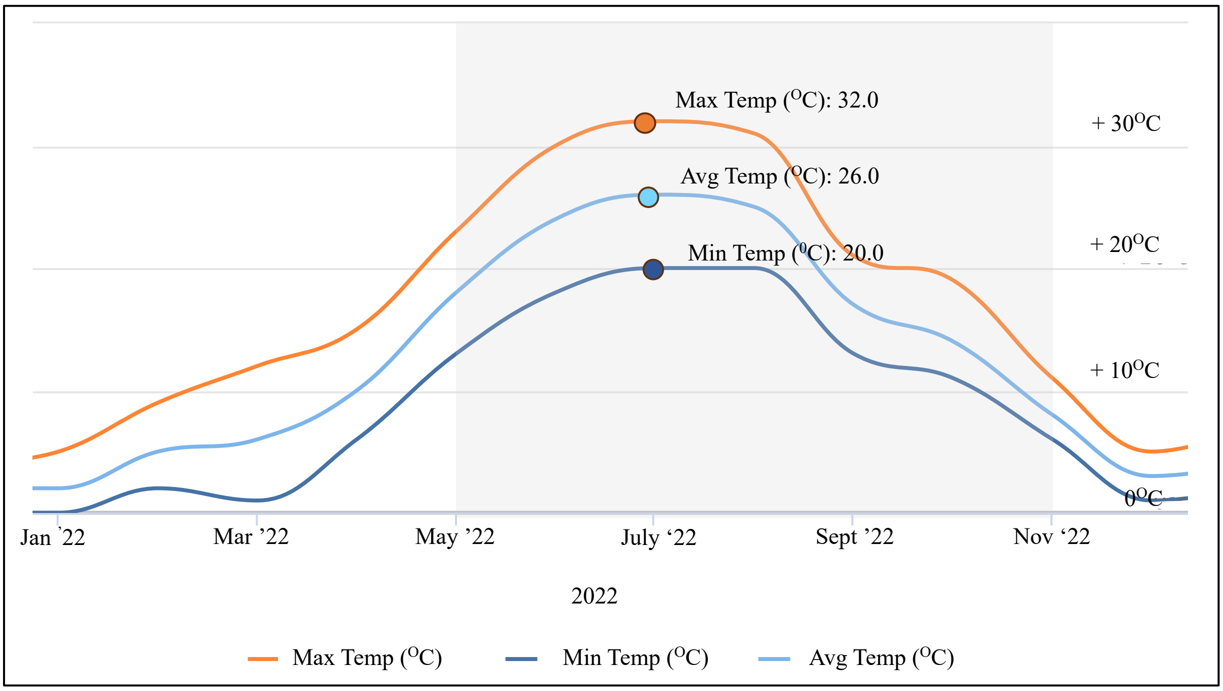


Figure 6. Max, min, and average weather temperature 2022 (Gödöllö, Hungary). Source: WORLD WEATHER ONLINE (2023).

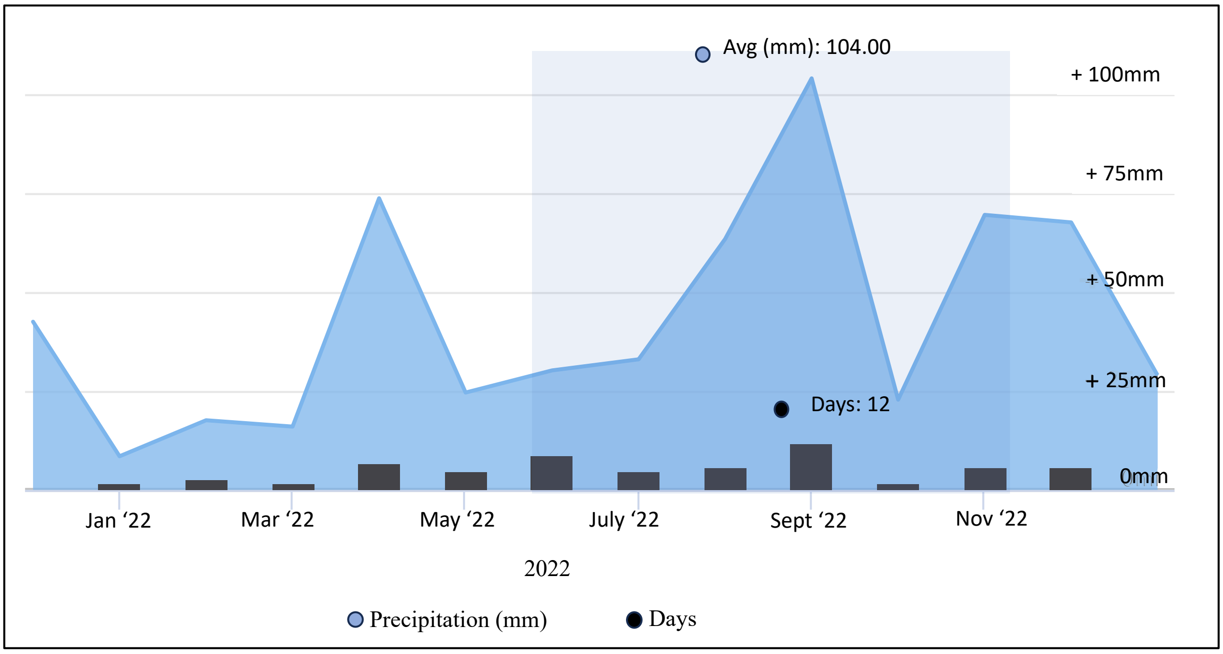


Figure 7. Average precipitation amounts and rainy days in 2022 (Gödöllö, Hungary). Source: WORLD WEATHER ONLINE (2023).

3.3.4 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**.**

3.3.5 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.

3.3.6 Statistical Analysis

The data from the current study were analysed 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 (RCBD). In addition, Duncan's multiple range test (DMRT) was used to compare the means with a probability of 0.05 using IBM SPSS version 23 statistical analysis software and Microsoft Excel version 16.77 for descriptive statistics, including correlation analysis.

3.4 The Effect of Nitrogen Fertilization on the Yield and Quality of Maize

3.4.1 Experimental Site

A field experiment was conducted to investigate the effect of N levels on yield and quality of maize at an experimental plot of the Department of Agronomy, The Hungarian University of Agriculture and Life Sciences, Hungary, in 2021. This experimental site is located in a hilly section of the country, near-average climatic zone, 242 m above sea level (47046′N, 19021′E) on sandy loam, brown forest soil (Chromic Luvisol). The humus content was 3.12%, while sand, silt, and clay contents were 10%, 54%, and 36% respectively, at the top of the 20 cm layer (TÓTH et al. 2018). The soil had a slightly acidic pH of 6.2 (H_2O) and a pH of 5.1 (KCl) (DEKEMATI et al. 2020). In 2021, the average annual precipitation in Gödöllő was 531.0 mm (20.91 inches). In Hungary, the precipitation estimation is between 400 and 500 mm (15.8–19.7 inches) per year, the western parts are slightly wetter than the eastern.

3.4.2 Treatment

The maize hybrid seed variety MV 277 was sown on 26 May 2021 using a Wintersteiger Plotman maize planter machine with a plant density of 75 thousand plant ha^{-1}. The experimental site consisted of four observation plots with N levels of T1 (0 kg N ha^{-1}), T2 (50 kg N ha^{-1}), T3 (100 kg N ha^{-1}), and T4 (150 kg N ha^{-1}) of net sizes 2 × 5 m. Each treatment contained four replications with ten plants per replication. The various treatments were applied as spraying on the indicated plants during the vegetative growth stage (V12). Standard agronomic practices were applied uniformly to all treatments.

3.4.3 Measurement

At harvest, the total number of cobs was recorded from each plot. The seed obtained from four tagged plants per replications after threshing, cleaning, and sun-drying were measured for cob weight, the number of rows per cob, grain number per cob, also the grain yields per plot were calculated and expressed in kilograms. The 1000 grains were counted using a Contador 2 seed counter, and the total weight was measured using a Scaltec electric weight balance. Furthermore, grain quality parameters such as starch concentration, protein, oil, and moisture content were determined using the Mininfra grain analyzer. The lab equipment used in this study is shown in Figure 8.

Figure 8. Laboratory equipment used in this study.

A: Contador 2 seed counter, B: Scaltec electric weight balance, and C: Mininfra grain analyzer.

3.4.4 Statistical Analysis

One-way ANOVA was used to examine the effect of N fertilisation on grain yield and its components, as well as grain quality parameters (moisture, oil, protein, and starch concentrations) of maize at $p \leq 0.05$ probability level. Differences among treatment means were compared by Post

Hoc Multiple Comparison tests using Least Significant Difference (LSD) at $p \leq 0.05$. Analyses were conducted with the IBM SPSS version 23.

3.5 Assessment of Genetic Variability and Heterosis for Yield and Yield Components in Maize

3.5.1 Planting Materials

The maize seed genotypes used in this study were obtained from the Martonvásár Agricultural Research Centre and the University of Szeged. These included single-cross (SC), three-way cross (TC), and two-cross (DC) genotypes, as well as their parents and commercial check hybrids. The specific genotypes used in this study are listed in Table 8 and illustrated in Figure 9.

Table 8. List of parents, hybrids (SC, TC, and DC), commercial check hybrid and their descriptions.

No	Source	Entry	Genotypes	Description
1	Martonvásár	V1	(B1026/17) (SC, F)	Parent
2	Martonvásár	V2	(TK222/17)	TC Hybrid
3	Martonvásár	V3	(TKAPA15/DV) (SC, M)	Parent
4	Martonvásár	V4	(TK1083/19) (DC, F)	Parent
5	Martonvásár	V5	(TK623/18)	SC Hybrid
6	Martonvásár	V6	(MCS901/19) (TC, F)	Parent
7	Martonvásár	V7	(TK256/17)	DC Hybrid
8	Szeged University	V8	(GK155)	Parent
9	Szeged University	V9	(GK131)	Parent
10	Szeged University	V10	(GK154 X155)	SC Hybrid
11	Szeged University	V11	(Szegedi 521; GK131XGK150)	SC Hybrid
12	Szeged University	V12	(GK154)	Parent
13	Szeged University	V13	(GK150)	Parent
14	Szeged University	V14	(GK144)	Parent
15	Szeged University	V15	(GK144X GK150)	SC Hybrid
16	Commercial	V16	(Mv277)	Commercial Check Hybrid

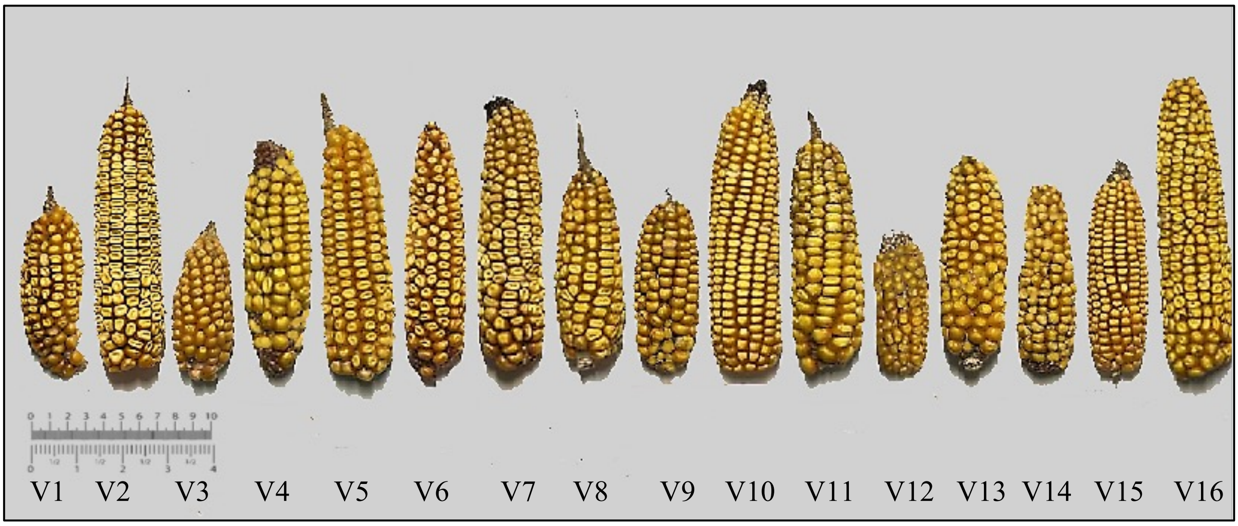


Figure 9. The ears of maize genotypes that were used in this study.

3.5.2 Experimental Site

A field experiment was initiated in the spring growing seasons of 2022 to study genetic variability and heterosis, as well as agronomic characteristics and yield components in maize (*Zea mays* L.). The experiment was conducted on an experimental plot at the Department of Agronomy, Hungarian University of Agriculture and Life Sciences. The experimental plot is in Gödöllö, between latitudes 47°59'46.46"N and 47°59'50.07"N, and longitudes 19°36'98.08"E and 19°37'02.81"E, in the northeast part of Budapest, Hungary (Figure 10). The average maximum temperature during the maize growing cycle was 32.0 °C (89.6 °F), while the average low temperature was 20.0 °C (68.0 °F). July was identified as the warmest month of the year. Additionally, the total rainfall amount was 917.20 mm (36.11 inches), with a monthly average of 175.2 mm (6.90 inches).

The type of soil in the experimental field was sand-based brown forest soil (Chromic Luvisol). It was prone to compaction and had a neutral sand texture with varying clay contents. With a humus content of 3.18%, sand, silt, and clay levels of 10%, 54%, and 36%, respectively, at the top of the 20 cm layer, drought had an impact on the soil. The soil had a pH of 5.1 (KCl) and 6.2 (H_2O), which were both slightly acidic.

Figure 10. The experimental field view by satellite in 2022.

3.5.3 Experimental Design

The experimental design involved a randomized complete block design (RCBD) with three sets of ten plants each, which included parents and hybrids, and commercial check hybrid. Maize seeds were planted using a Wintersteiger Plotman planter and the seeds were sown at a density of 75,000 plants per hectare, which was determined to be the optimal planting density for maize in this particular study. Throughout the duration of the experiment, weeding and irrigation were carried out as needed. Weeding and irrigation were carried out as needed to remove unwanted plants and ensure adequate water availability for optimal growth. All treatments were subjected to standard agronomic practices, including the application of fertilizers, pesticides, and other necessary inputs based on maize cultivation requirements.

3.5.4 Data Collection

In general, all data on grain yield and other important agronomic characteristics collected were:

i. Plant height (cm): The plant height is measured using a measuring tape from the ground level to the shoot or the base of the tassel every week.

ii. Days to 50% flowering: The number of days from plant emergence to when 50% of the plants in a plot are flowering.

iii. Ear weight (g): Ear weight is determined by weighing a fresh single ear after harvest/ or mature stage.

iv. Ear length (cm): Average length of selected sample from Ear length from the base to the tip of the ear at time of harvest.

v. Ear diameter (cm): The ear diameter is measured in the middle portion of the ears, where the maximum dimeter was found.

vi. Rows number per ear: The row number of per ear is calculated by counting the number of rows within each ear.

vii. Kernel number of per ear: The Kernel number of per ear is determined by the total number of kernels present in the ear.

viii. 1000-kernel weight (g): The randomly selected 1000-kernels from bulk grain for each experimental unit were counted and weighed.

3.5.5 Data Analysis

Data analysis for variance components (ANOVA) was used as recommended by STEEL AND TORRIE (1980). Mean comparison has been done using the Duncan Multiple Range Test (DMRT). Genotypic variances ($\sigma^2 g$), phenotypic variances ($\sigma^2 p$), phenotypic coefficient of variability (PCV), genotypic coefficient of variability (GCV), broad sense heritability ($h^2 b$) and genetic advance (GA) were calculated with the method suggested by ALLARD (1960), and SINGH AND CHAUDHURY (1985).

$$\sigma^2 g = \frac{[MSG - MSE]}{r}$$

$$\sigma^2 p = \sigma^2 g + VE$$

$$\sigma^2 e = MSE$$

$$GCV = \frac{\sqrt{\sigma 2g}}{\bar{X}} \text{ X } 100$$

$$PCV = \frac{\sqrt{\sigma 2p}}{\bar{X}} \text{ x } 100$$

$$h^2 b = \frac{\sigma 2g}{\sigma 2p}$$

$$GA = I \times h^2b \times \sqrt{\sigma 2p}$$

Where,

MSG = Mean squares of genotypes, MSE = Mean squares of error, r = Number of replications, VE = Environmental variances, (σ^2g) = Genotypic variances, (σ^2p) =Phenotypic variances, $\overline{X}$ = Grand mean and I = assumes a 5% (2.06) level of selection intensity. GCV and PCV were categorised as low (less than 10), moderate (less than 20), and high (greater than 20), as suggested by BURTON (1952). Broad sense heritability (h^2b) was expressed as the ratio of the amount of the genotypic variance (σ^2g) to the phenotypic variance (σ^2p). Heritability values were classified as low (less than 30), moderate (30-60) or high (greater than 60), as proposed by JOHNSON et al. (1955).

Mid parent and high parent heterosis for each character was calculated using the following formula:

$$\text{Mid parent heterosis (\%)} = \frac{F1-MP}{MP} \text{ X } 100$$

$$\text{High parent heterosis (\%)} = \frac{F1-HP}{HP} \text{ X } 100$$

Where,

F_1 = Mean of the hybrid for a specific trait, MP = Average mean of the parents for a specific trait which = (P_1 + P_2)/2, HP = Mean of the high parent in the cross for a specific trait, and P_1 and P_2 are the values of specific trait of the respective parents. By using a t-test (WYNNE et al. 1970), assessed the significance of F_1 hybrids in comparison to mid parent and high parent means as follows:

$$\text{t-test} = \frac{F1 - MP}{\sqrt{\frac{3}{8} \text{X } EMS}}$$

$$\text{t-test} = \frac{F1 - HP}{\sqrt{\frac{1}{2} \text{X } EMS}}$$

4. RESULTS AND DISCUSSION

4.1 Germination Characteristics of Different Maize Hybrids and Their Parental Lines

4.1.1 Germination Rate (%)

The ANOVA Table 9 revealed that there were no significant differences in germination rate between the groups of maize varieties F (6,133) = 1.759, p = 0.112. Germination started on the third day and was completed by the seventh day after placing seeds in the Petri dishes. All maize varieties had attained a 100% germination rate until the twelfth day except SC (M), 20% were extinct on the ninth day, and TC (F) was the latest variety to complete germination on the seventh day (Figure 11).

Table 9. Analysis of variance for germination rate (%) of different maize inbred hybrids and their parental lines.

Source of variation	Sum of square	*df*	Mean square	*F*	Sig.
Between groups	0.286	6	0.48	1.759	0.112
Within groups	3.600	133	0.27		
Total	3.886	139			

df: degree of freedom, Sig. significance, Significance level = $p < 0.05$.

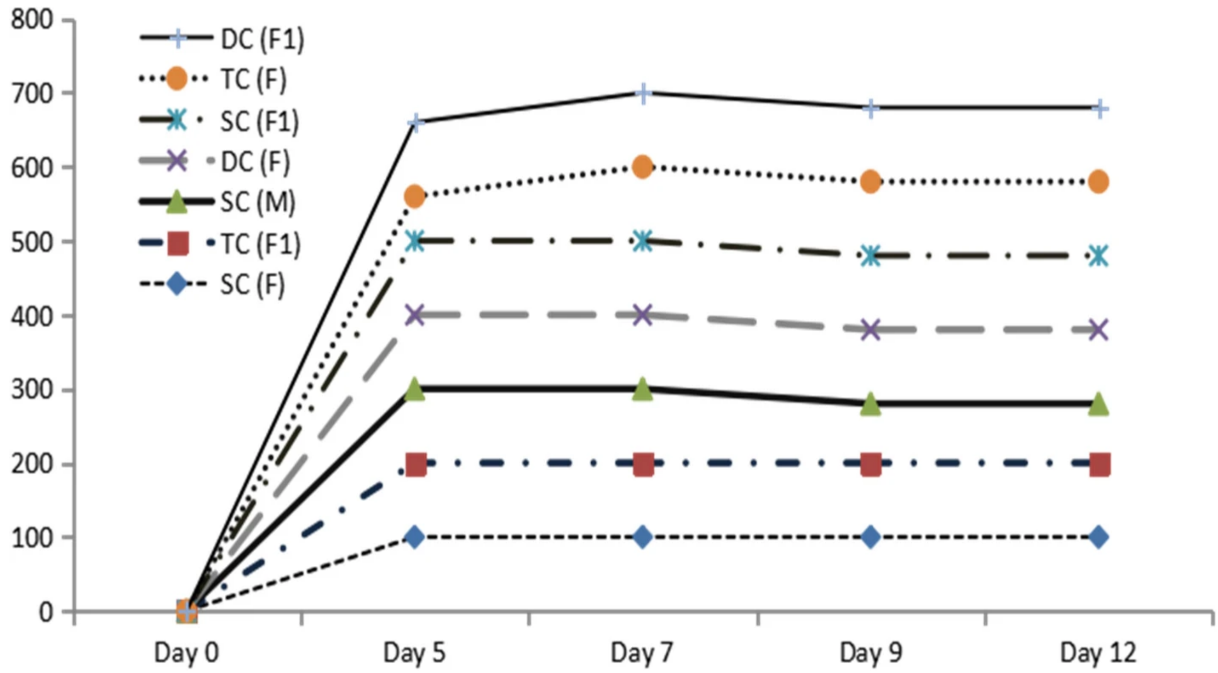


Figure 11. Germination rate (%) at day 5, 7.9 and 12 of inbred hybrids and their parental lines.

4.1.2 Shoot Length

The ANOVA Table 10 showed that the significance level is 0.045 ($p = 0.045$), which is below 0.05. There were statistically significant differences in the mean shoot length between groups of maize varieties. The result (Figure 12) showed the hybrid SC (F_1) produced the highest shoot length (7.9 cm), followed by DC (F_1) with 7.6 cm and TC (F) with 7.4 cm. The SC (F) recorded the lowest shoot length at 4.4 cm (12 days after sowing).

Table 11 revealed that there was a significant difference between the shoot length of the selected maize varieties in SC (F) and SC (F_1) $p = 0.023$, SC (F) and DC (F_1) $p = 0.032$, SC (F_1) and TC (F) $p = 0.006$, TC (F) and DC (F_1) p = 0.008. Moreover, there were no significant differences for the rest of the varieties.

Table 10. Analysis of variance for shoot length of different maize inbred hybrids and their parental lines.

Source of variation	Sum of square	*df*	Mean square	*F*	Sig.
Between groups	102.779	6	17.130	2.216	0.045
Within groups	1027.887	133	7.728		
Total	1130.66	139			

df: degree of freedom, Sig. significance, Significance level = $p < 0.05$.

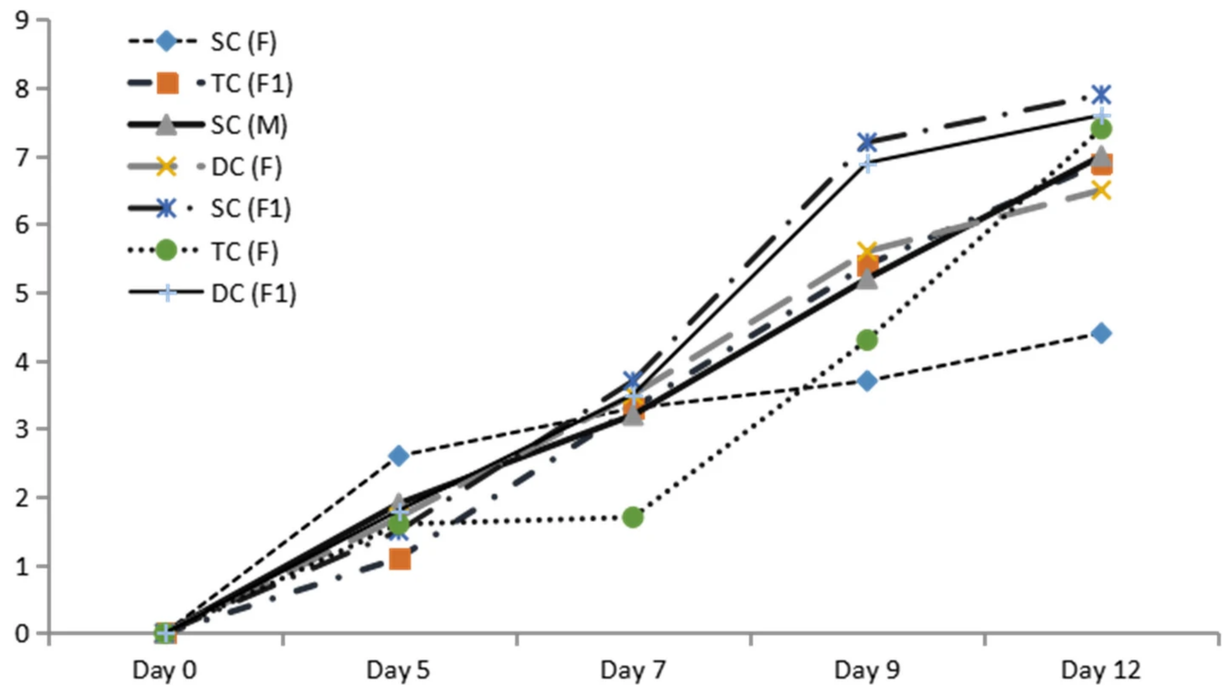


Figure 12. Shoot length (cm) at day 5, 7, 9 and 12 of inbred hybrids and their parental lines.

Table 11. Difference in shoot length of inbred hybrids and their parental lines - Post Hoc Test, LSD.

Variable			Mean Difference	Std. Error	Sig.	Inference
Shoot Length	SC (F)	TC (F1)	-1.13500	.87912	.199	Not Significant
		SC (M)	-.66000	.87912	.454	Not Significant
		DC (F)'	-1.26000	.87912	.154	Not Significant
		SC (F1)	-2.01500*	.87912	.023	Significant
		TC (F)	.46000	.87912	.602	Not Significant
		DC (F1)	-1.90000*	.87912	.032	Significant
	TC (F_1)	SC (F)	1.13500	.87912	.199	Not Significant
		SC (M)	.47500	.87912	.590	Not Significant
		DC (F)	-.12500	.87912	.887	Not Significant
		SC (F1)	-.88000	.87912	.319	Not Significant
		TC (F)	1.59500	.87912	.072	Not Significant
		DC (F1)	-.76500	.87912	.386	Not Significant
	SC (M)	SC (F)	.66000	.87912	.454	Not Significant
		TC (F1)	-.47500	.87912	.590	Not Significant
		DC (F)	-.60000	.87912	.496	Not Significant
		SC (F1)	-1.35500	.87912	.126	Not Significant
		TC (F)	1.12000	.87912	.205	Not Significant
		DC (F1)	-1.24000	.87912	.161	Not Significant
	DC (F)	SC (F)	1.26000	.87912	.154	Not Significant
		TC (F1)	.12500	.87912	.887	Not Significant
		SC (M)	.60000	.87912	.496	Not Significant
		SC (F1)	-.75500	.87912	.392	Not Significant
		TC (F)	1.72000	.87912	.053	Not Significant
		DC (F1)	-.64000	.87912	.468	Not Significant
	SC (F_1)	SC (F)	2.01500*	.87912	.023	Significant
		TC (F1)	.88000	.87912	.319	Not Significant
		SC (M)	1.35500	.87912	.126	Not Significant
		DC (F)	.75500	.87912	.392	Not Significant
		TC (F)	2.47500*	.87912	.006	Significant
		DC (F1)	.11500	.87912	.896	Not Significant

TC (F)	SC (F)	-.46000	.87912	.602	Not Significant
	TC (F1)	-1.59500	.87912	.072	Not Significant
	SC (M)	-1.12000	.87912	.205	Not Significant
	DC (F)	-1.72000	.87912	.053	Not Significant
	SC (F1)	-2.47500*	.87912	.006	Significant
	DC (F1)	-2.36000*	.87912	.008	Significant
DC (F_1)	SC (F)	1.90000*	.87912	.032	Significant
	TC (F1)	.76500	.87912	.386	Not Significant
	SC (M)	1.24000	.87912	.161	Not Significant
	DC (F)	.64000	.87912	.468	Not Significant
	SC (F1)	-.11500	.87912	.896	Not Significant
	TC (F)	2.36000*	.87912	.008	Significant

The mean difference is significant at the $p < 0.05$ level, LSD = Least Significant Difference.

4.1.3 Root Length

The ANOVA Table 12 shows that the highly statistically significant difference occurs 0.001 (p = 0.001) in the mean of root length between groups of maize varieties. From the result (Figure 13) shows, variety TC (F_1) produce the highest root length (14.9 cm), followed by DC (F_1) with 13.9 cm and SC (F_1) 12.9 cm, and the lowest value was obtained at SC (M) with 7.3 cm of root length (12 days after sowing).

The LSD post hoc test Table 13 revealed that most of the varieties showed highly significant differences for root length; between variety SC (F) and TC (F_1) $p = 0.02$, SC (F) and DC (F) $p = 0.022$, SC (F) and SC (F_1) $p = 0.042$, SC (F) and DC (F_1) $p = 0.009$, TC (F_1) and SC (M) $p = 0.002$, TC (F_1) and TC (F) $p = 0.018$, SC (M) and DC (F) p=0.002, SC (M) and SC (F_1) $p = 0.005$, SC (M) and DC (F_1) $p = 0.001$, DC (F) and TC (F) $p = 0.020$, SC (F_1) and TC (F) $p = 0.038$, TC (F) and DC (F_1) $p = 0.008$. However, there were no significant differences for the rest of the varieties. Figure 14 illustrates the different maize varieties seeds at 5, 7, 9, and 12 days of incubation.

Table 12. Analysis of variance for root length of different maize inbred hybrids and their parental lines.

Source of variation	Sum of square	*df*	Mean square	*F*	Sig.
Between groups	604.599	6	100.766	4.184	0.001
Within groups	3203.506	133	24.087		
Total	3808.104	139			

df: degree of freedom, Sig. significance, Significance level = $p < 0.05$.

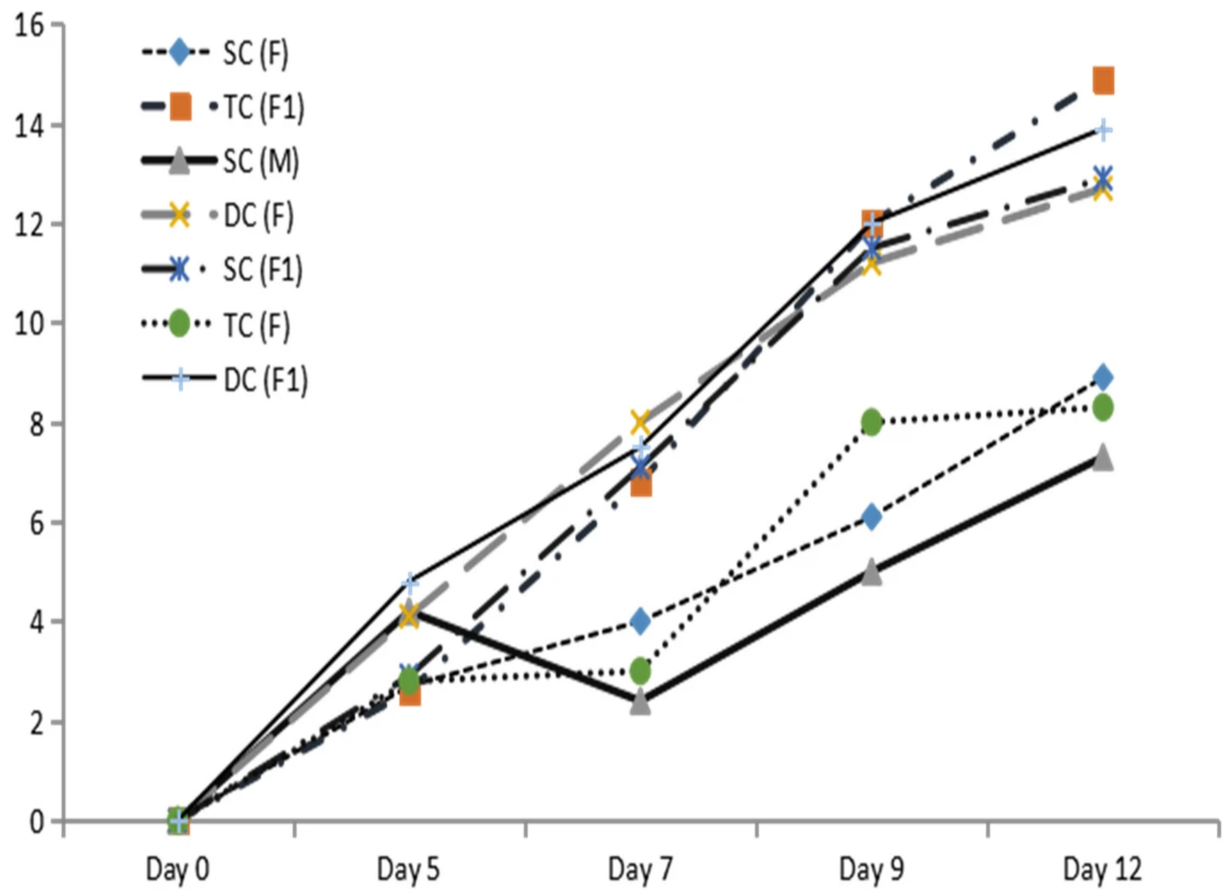


Figure 13. Root length (cm) at day 5, 7, 9 and 12 of inbred hybrids and their parental lines.

Table 13. Difference in root length of inbred hybrids and their parental lines - Post Hoc Test, LSD.

Variable			Mean Difference	Std. Error	Sig.	Inference
Root Length	SC (F)	TC (F1)	-3.64000*	1.55198	.020	Significant
		SC (M)	1.30500	1.55198	.402	Not Significant
		DC (F)	-3.59000*	1.55198	.022	Significant
		SC (F1)	-3.18000*	1.55198	.042	Significant
		TC (F)	.07500	1.55198	.962	Not Significant
		DC (F1)	-4.12000*	1.55198	.009	Significant
	TC (F_1)	SC (F)	3.64000*	1.55198	.020	Significant
		SC (M)	4.94500*	1.55198	.002	Significant
		DC (F)	.05000	1.55198	.974	Not Significant
		SC (F1)	.46000	1.55198	.767	Not Significant
		TC (F)	3.71500*	1.55198	.018	Significant
		DC (F1)	-.48000	1.55198	.758	Not Significant
	SC (M)	SC (F)	-1.30500	1.55198	.402	Not Significant
		TC (F1)	-4.94500*	1.55198	.002	Significant
		DC (F)	-4.89500*	1.55198	.002	Significant
		SC (F1)	-4.48500*	1.55198	.005	Significant
		TC (F)	-1.23000	1.55198	.429	Not Significant
		DC (F1)	-5.42500*	1.55198	.001	Significant
	DC (F)	SC (F)	3.59000*	1.55198	.022	Significant
		TC (F1)	-.05000	1.55198	.974	Not Significant
		SC (M)	4.89500*	1.55198	.002	Significant
		SC (F1)	.41000	1.55198	.792	Not Significant
		TC (F)	3.66500*	1.55198	.020	Significant
		DC (F1)	-.53000	1.55198	.733	Not Significant
	SC (F_1)	SC (F)	3.18000*	1.55198	.042	Significant
		TC (F1)	-.46000	1.55198	.767	Not Significant
		SC (M)	4.48500*	1.55198	.005	Significant
		DC (F)	-.41000	1.55198	.792	Not Significant
		TC (F)	3.25500*	1.55198	.038	Significant
		DC (F1)	-.94000	1.55198	.546	Not Significant
	TC (F)	SC (F)	-.07500	1.55198	.962	Not Significant

	TC (F1)	-3.71500*	1.55198	.018	Significant
	SC (M)	1.23000	1.55198	.429	Not Significant
	DC (F)	-3.66500*	1.55198	.020	Significant
	SC (F1)	-3.25500*	1.55198	.038	Significant
	DC (F1)	-4.19500*	1.55198	.008	Significant
DC (F_1)	SC (F)	4.12000*	1.55198	.009	Significant
	TC (F1)	.48000	1.55198	.758	Not Significant
	SC (M)	5.42500*	1.55198	.001	Significant
	DC (F)	.53000	1.55198	.733	Not Significant
	SC (F1)	.94000	1.55198	.546	Not Significant
	TC (F)	4.19500*	1.55198	.008	Significant

The mean difference is significant at the $p < 0.05$ level, LSD = Least Significant Difference.

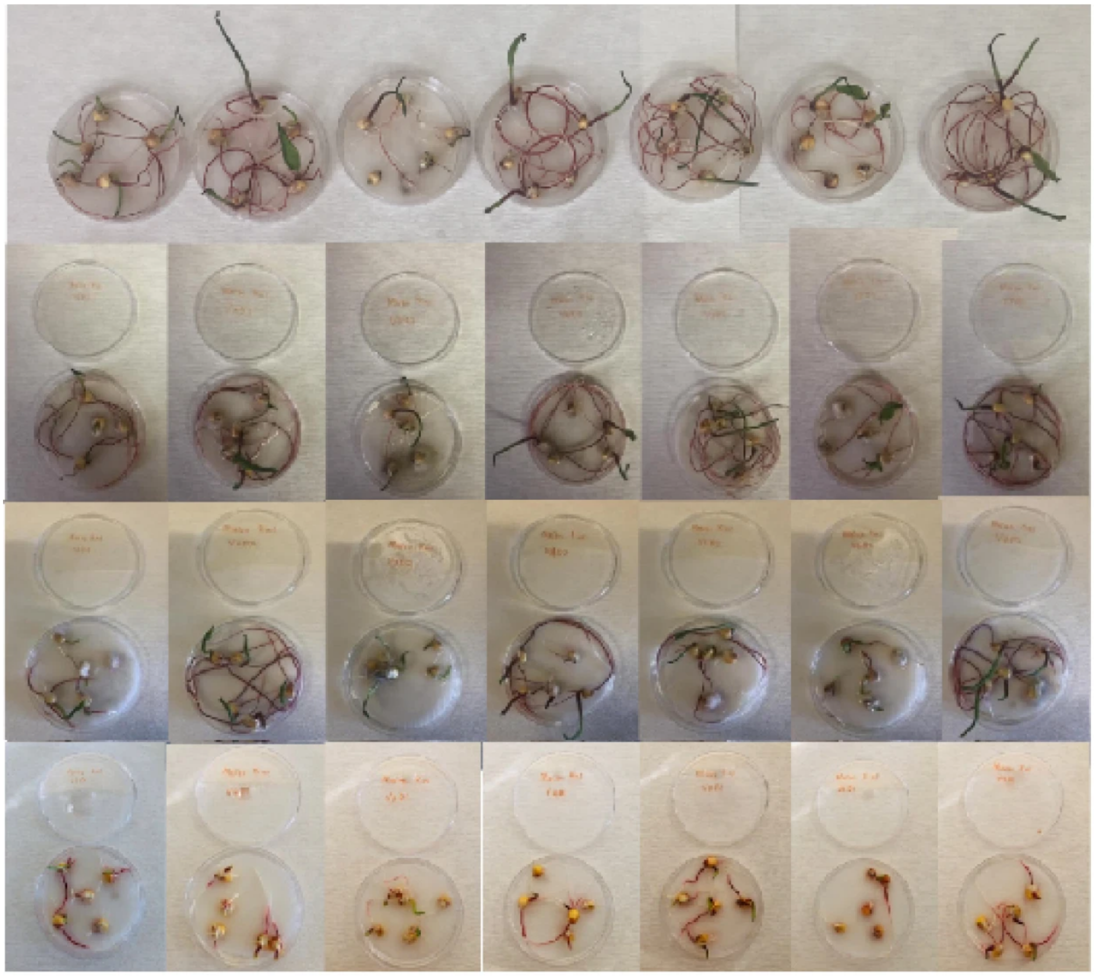


Figure 14. Different maize varieties seeds at 5, 7, 9, and 12 day of incubation time.

4.1.4 Discussion

The present investigation was carried out to determine the differences in performance of some hybridization pathways on seed germination characteristics. Our findings discovered the germination test and seedling evaluation which normally done between the fourth and seventh day after sowing by BRASIL (2009). They suggest that this is the best recommended time to get optimal evaluation results as each hybrid has a different growth performance. The fact that we found that the germination of maize seeds started after the third day and completely germinated on the seventh day after sowing, and all F_1 hybrid seeds performed better and reached 100% germination on the fifth day.

The results of seed germination indicated that F_1 hybrid seeds germinate faster than the parental lines. This is because in maize, F_1 hybrid seeds have a superior germination capacity as compared to their parental inbred lines, where hybrid seedlings elongate faster, both roots and shoots (SARKISSIAN et al. 1964). According to MEENA et al. (2018), mature seeds of the male and female parents of the F_1 hybrid exhibited significantly higher seed weight but showed slower seed germination rates. This result indicates that the heterosis was manifested in the early seed germinating stage in the F_1 hybrid used. GUO et al. (2013) reported that hybrid seeds were fully germinated within 48 h and showed early onset of heterosis in radicle emergence. ROMAGNOLI et al. (1990) noted that maize F_1 hybrid seeds have a superior germination capacity compared to the parental lines, while the molecular basis for heterosis for the emergence of radicals is still unknown.

However, because the percentage of germination rate is dependent on other factors, determining the factors that influence germination test becomes more challenging. At low temperatures, delayed germination occurs due to the difficulties in reorganized cell membranes (CARVALHO et al. 2009), and it is also influenced by the physiological quality and the plant genotype (GRZYBOWSKI et al. 2015). Meanwhile, according to BEWLEY AND BLACK (1982), seed germination, emergence and vigour are also controlled by genetic factors, and it has been demonstrated on a genotypic variation on seedling growth.

The results obtained showed a higher speed and more uniformly of the shoot elongation for hybrid seeds as compared to their parents. These findings suggest that hybrids seeds have better shoot elongation ability than the parent and it was due to the heterotic effect of the combination of two parental genes. As expected, three-way cross hybrids (TC (F_1)) were most uniform shoot elongation followed by double-crossing hybrids (DC (F_1)), and the highest was revealed in single cross hybrids (SC (F_1)). However, the findings revealed contrasting in rooting performances, which the highest root elongation was from the three-way cross (TC (F_1) followed by double-crossing hybrids (DC (F_1)) and single cross hybrids (SC (F_1)). According to ASHAKINA et al. (2016), the findings from three separate studies show that a subset of double cross hybrid lines exhibit extreme rooting behaviours than parental genotypes in tomatoes. YILDIRIM AND CAKMAK (2018) explained that the three-way cross performed better than the other hybrids and parents because the ratio of chromosomal structures will increase with the number of parents involved in the crossing procedures. Thus, detailed genetics studies are required to explain this occurrence. In addition, according to HOCHHOLDINGER et al. (2018), the superior root strength of a hybrid seed compared to its parent lineage is studied at the proteome level, and this finding provides new insights on complex proteomic interactions of complex maize root systems during development.

In summary, the findings revealed that maize seeds germinated after the third day and fully germinated on the seventh day after sowing. Varieties SC (F_1), DC (F_1), and TC (F_1) showed excellent germination performance with a 100% germination rate on the fifth day and produced the highest shoot and root lengths with 7.9 cm, 7.6 cm, and 6.9 cm (shoot length) and 12.9 cm, 13.9 cm and 14.9 cm (root length), respectively. Thus, the results obtained reveal that the hybrid seeds have a higher germination rate (100%), and the seedlings were more vigorous than the parents.

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

4.2.1 Seed Viability and Vigour

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 vigour viz. germination rate (%), radicle length (cm), and plumule length (cm) for the confidence interval of 0.95 (Table 14).

Table 14. 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 Squares**	***df***	**Means 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 x	Germination Rate (%)	62.422	45	1.387	1.522*
Genotypes	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)	25731.023	256		
	Plumule Length (cm)	5249.053	256		

* = $p < .005$; ** = $p < 0.001$.

The results displayed in Table 15 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 15. Mean values of germination rate (%), radicle length (cm) and plumule length (cm) of various maize genotypes.

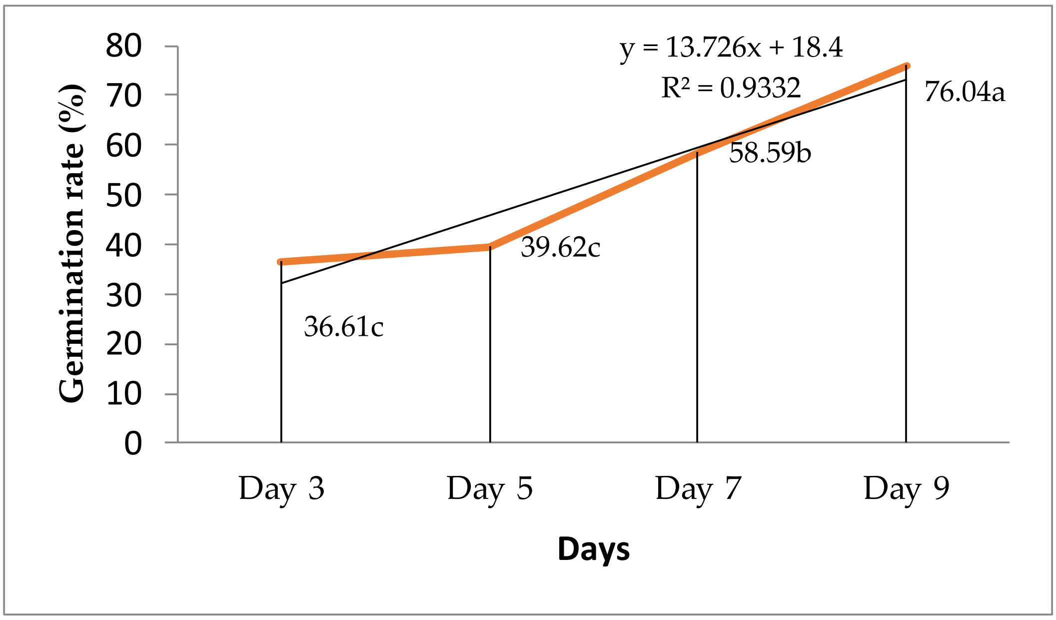
[1]Genotypes	[2]Germination rate (%)	[3]Radicle Length(cm)	[4]Plumule Length (cm)
V1 (parent)	83.33a-d	13.42fg	8.23b
V2 (parent)	95.83ab	18.95a	7.41b
V3 (parent)	100a	18.45ab	7.54b
V4 (parent)	87.50abc	14.60ef	7.45b
V5 (SC hybrid)	79.17bcd	16.92a-e	7.76b
V6 (DC hybrid)	100a	16.37b-e	7.22b
V7 (TC hybrid)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

Different lowercase letters (column) present significant differences between the means ($p < 0.05$), according to Duncan's Multiple Range Test (DMRT), 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).

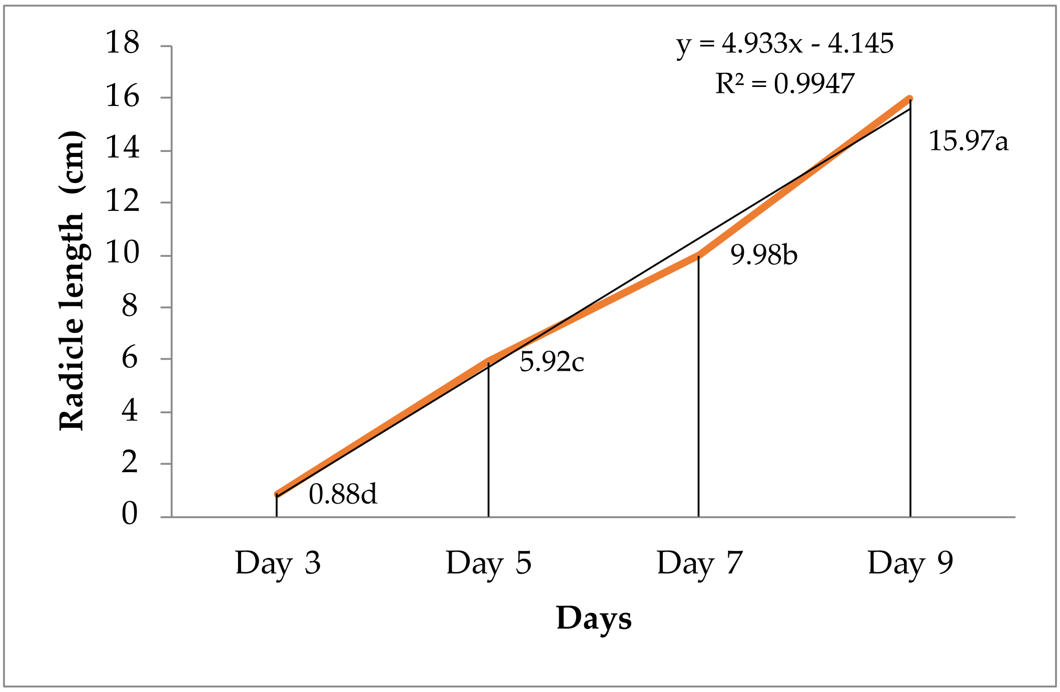
The greatest radicle length was found in genotypes V2 (parent), V3 (parent), and V12 (parent), with 18.95 cm, 18.45 cm, and 18.09 cm, respectively. However, V9 (parent) produced the shortest radical length throughout the investigation period (11.41 cm). The study, which also focused on plumule length, 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 15a 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%).

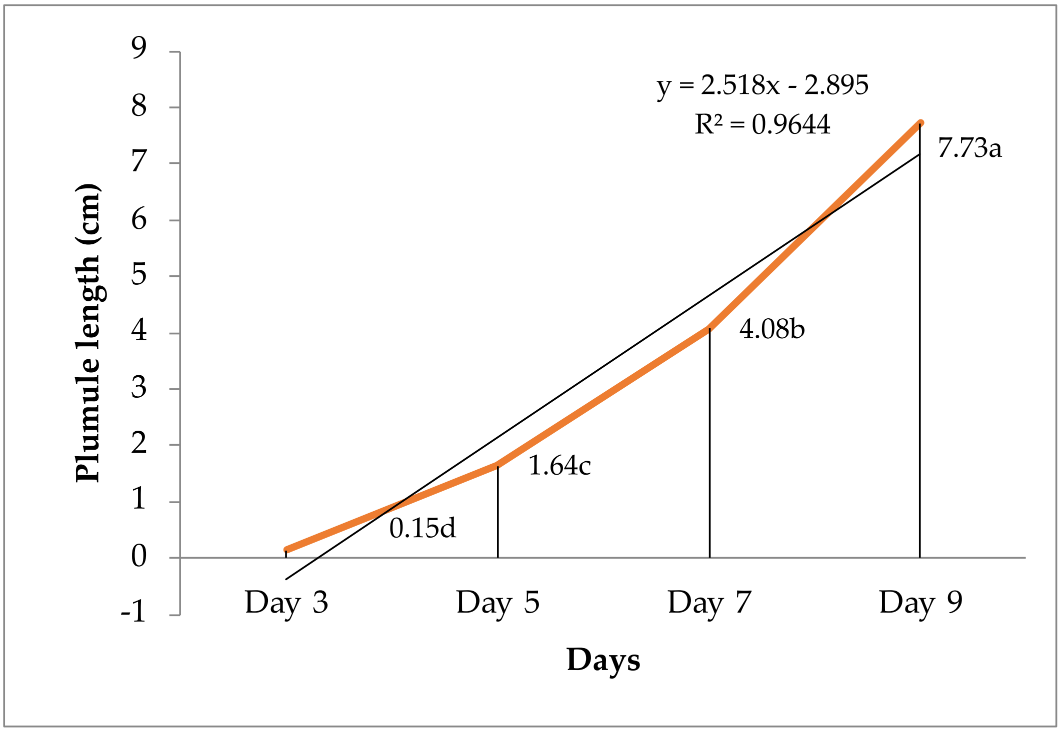
The radicle length increased sharply, revealing highly significant differences, with values of 0.88 cm on day 3, 5.92 cm on day 5, 9.92 cm on day 7, and 15.97 cm on day 9 (Figure 15b). Additionally, Figure 15c shows that the length of the plumule expanded significantly as the number of incubation days 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.



(a)



(b)



(c)

Figure 15. Seed viability and vigour respond to the incubation days. (a) Germination rate (%); (b) Radicle length (cm); (c) Plumule length (cm). Different lowercase letters present significant differences between the means ($p < 0.05$), according to Duncan's Multiple Range Test (DMRT), starting sequentially with the letter (a) being the most significant.

4.2.2 Yield Performance

4.2.2.1 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 16). (Table 17) 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 16 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 16. 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 17. Mean, minimum, maximum and Std. Deviation for number of rows per ear of various maize genotypes.

Source	**N**	**Mean**	**Minimum**	**Maximum**	**Std. Deviation**
Rows Ear^{-1}	240	12.3500	7.00	18.00	2.26174
Valid N (listwise)	240				

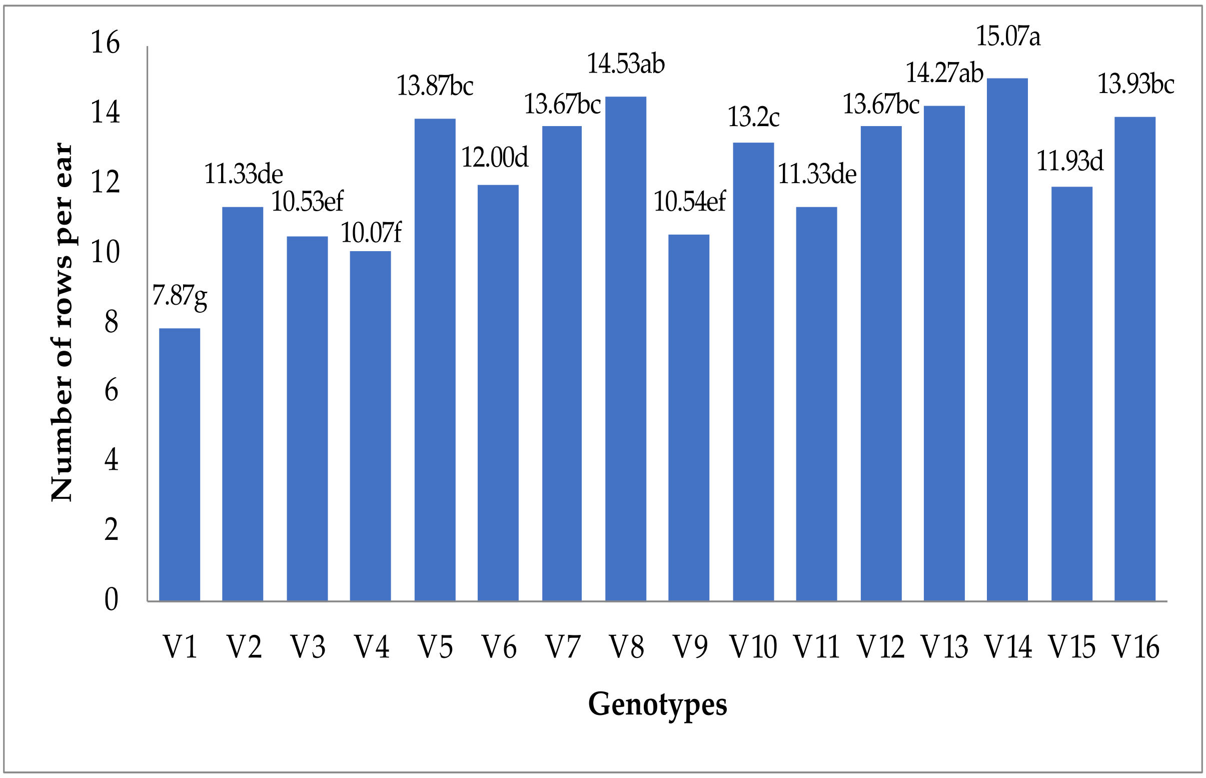


Figure 16. Histograms represent mean values of the number of rows per ear for various maize genotypes. Different lowercase letters present significant differences between the means ($p < 0.05$), according to Duncan's Multiple Range Test (DMRT), starting sequentially with the letter (a) being the most significant.

4.2.2.2 Number of Kernels per Ear

The results of the ANOVA in Table 18 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 19). Nonetheless, Figure 17 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 18. Analysis of variance (ANOVA) for kernels per ear of various maize genotypes.

Source		**Sum of Square**	***df***	**Mean Square**	***F***	**Sig.**
No. of kernels ear^{-1}	Between Groups	2064762.863	15	137650.858	118.243	.000
	Within Groups	260766.993	224	1164.138		
	Total	2325529.796	239			

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

Table 19. Mean, minimum, maximum and Std. Deviation for kernels per ear of various maize genotypes.

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

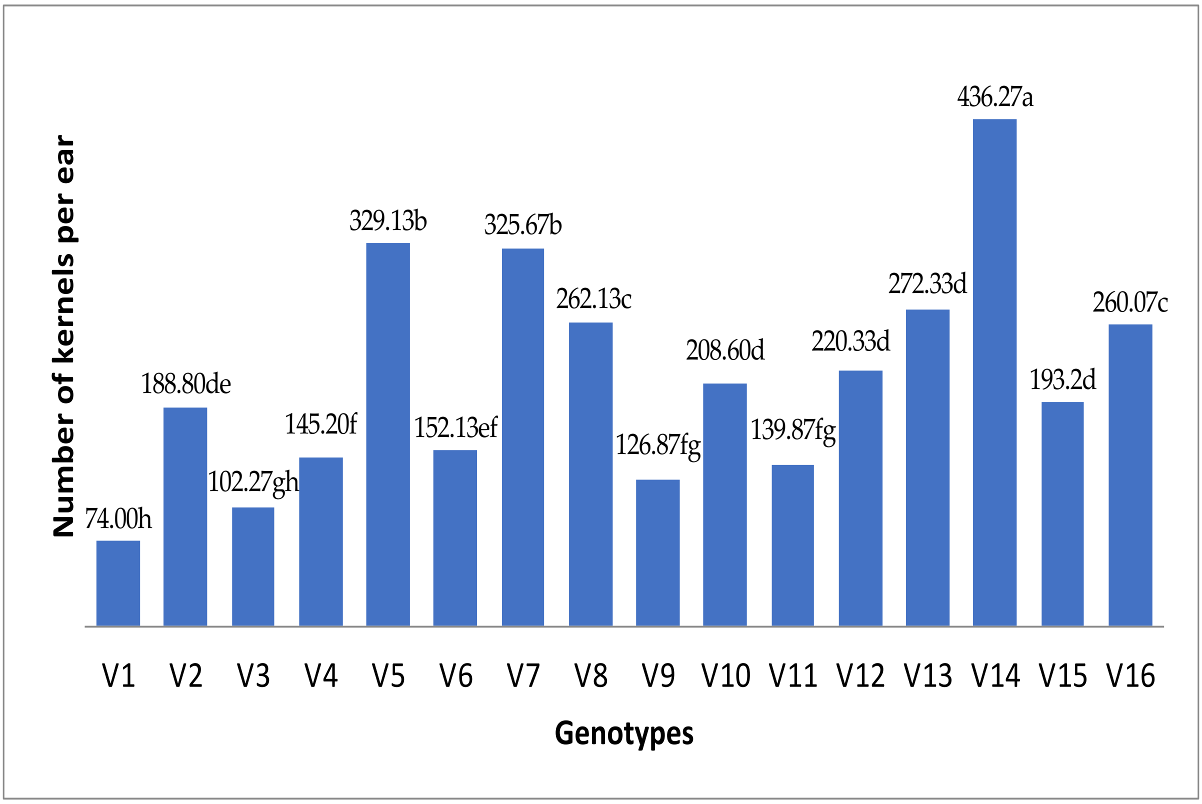


Figure 17. Histograms represent mean values of the number of kernels per ear for various maize genotypes. Different lowercase letters present significant differences between the means ($p < 0.05$), according to Duncan's Multiple Range Test (DMRT), starting sequentially with the letter (a) being the most significant.

4.2.2.3 1000 – Kernel Weight (g)

According to the results of the ANOVA in Table 20, 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 21). Meanwhile, Figure 18 reveals that V15 (SC hybrid) recorded the highest weight (438.87 g), whereas V3 (parent) recorded the lowest (220.33 g).

Table 20. Analysis of variance (ANOVA) for 1000 - kernel weight (g) of various maize genotypes.

Source		**Sum of Square**	***df***	**Mean Square**	***F***	**Sig.**
1000-kernel weight (g)	Between Groups	141061.910	15	9404.127	9.561	.000
	Within Groups	31476.453	32	983.639		
	Total	172538.363	47			

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

Table 21. Mean, minimum, maximum and Std. Deviation for 1000 - kernel weight (g) of various maize genotypes.

Source	**N**	**Mean**	**Minimum**	**Maximum**	**Std. Deviation**
1000 - kernel weight (g)	48	318.23	209.30	472.20	60.58902
Valid N (listwise)	48				

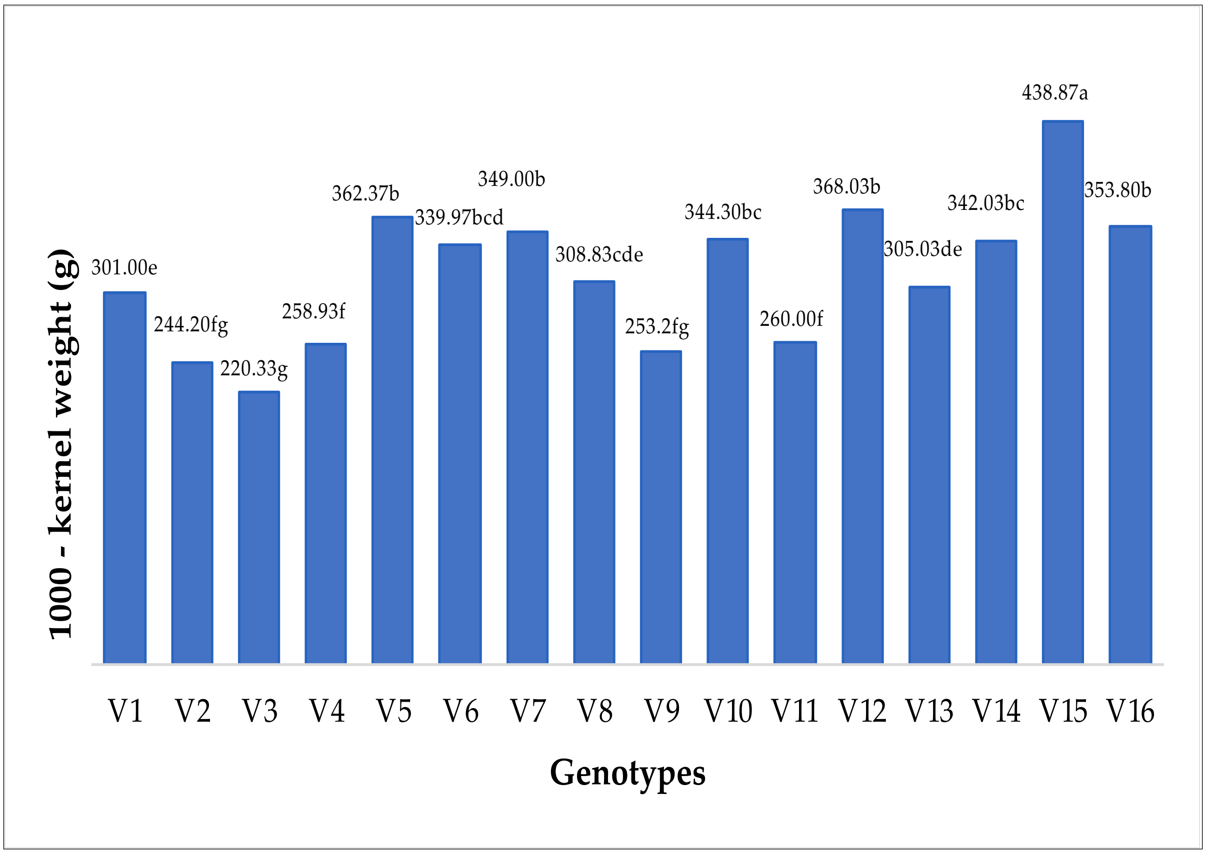


Figure 18. Histograms represent mean values of 1000 - kernels weight (g) for various maize genotypes. Different lowercase letters present significant differences between the means ($p < 0.05$), according to Duncan's Multiple Range Test (DMRT), starting sequentially with the letter (a) being the most significant.

4.2.2.4 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 22 (F (15, 224) = [41.815], p = [0.00]). On the other hand, Table 23 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 19).

Table 22. Analysis of variance (ANOVA) for ear weight (g) of various maize genotypes.

Source		Sum of Square	*df*	Mean Square	*F*	Sig.
Ear weight (g)	Between Groups	120460.654	15	8030.710	41.815	.000
	Within Groups	45822.069	224	192.054		
	Total	166282.723	239			

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

Table 23. Mean, minimum, maximum and Std. Deviation for ear weight (g) of various maize genotypes.

Source	N	Mean	Minimum	Maximum	Std. Deviation
Ear weight	240	318.23	22.20	140.40	26.15377
Valid N (listwise)	240				

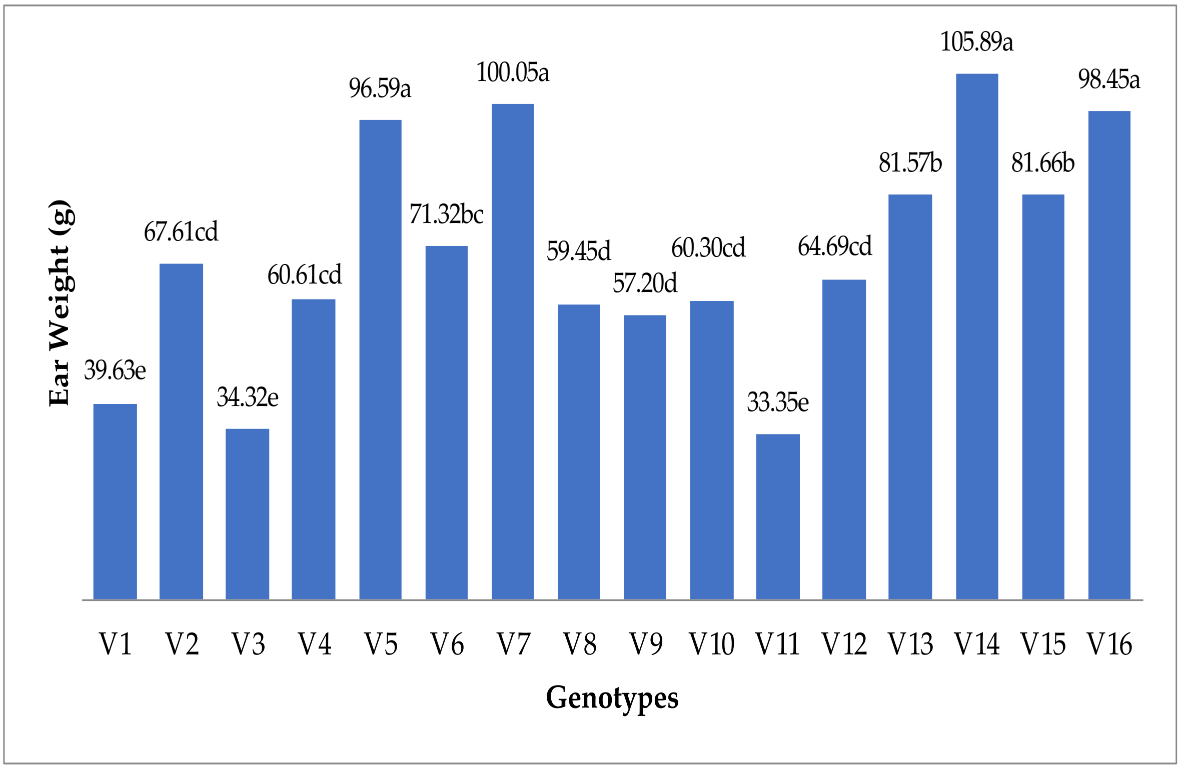


Figure 19. Histograms represent mean values of ear weight (g) for various maize genotypes. Different lowercase letters present significant differences between the means ($p < 0.05$), according to Duncan's Multiple Range Test (DMRT), starting sequentially with the letter (a) being the most significant.

4.2.3 Relationship Between Seed Viability, Vigour, and Yield Traits

The correlation analysis between seed viability, vigour, and yield traits is shown in Table 24. 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 24. Relationship between the seed viability, vigour 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 %	-0.04ns	0.12ns	-0.004ns	-0.06ns	1		
[6]RL	0.15ns	0.07ns	0.03ns	0.11ns	0.18*	1	
[7]PL	-0.19ns	-0.17*	-0.05ns	-0.08ns	-0.20**	0.09ns	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).

4.2.4 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, vigour, 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 vigour tests were carried out primarily according to ISTA's international rules for seed testing (SOYELU et al. 2001). Furthermore, field evaluation was carried out using hybrids and lines developed by local research institutes.

4.2.4.1 Seed Viability and Vigour

Seed viability and vigour 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 vigour 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 (SOYELU et al. 2001, BEWLEY AND BLACK 1982). 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 (OLUWARANTI et al. 2018), which found that single hybrids had the highest germination potential due to heterosis and genetic effects (VISHAL AND KUMAR 2018, BEWLEY AND BLACK 1982). However, numerous factors affect the germination rate, which often varies by orders of magnitude between and within plant species (LEISHMAN et al. 1995, SILVERTOWN AND BULLOCK 2003). Furthermore, previous studies also found significant paternal effects on seed germination characteristics (ANDERSSON et al. 2008). 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 (KADAFI et al. 2018). However, larger seeds retain their cotyledons for a longer amount of time, which is reflected in the strength and vigour 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 (LAFTA AND CHILAB 2019, JALLOW et al. 2009). On the other hand, larger seeds are associated with better performance in the field and more vigorous seedlings (AL-KARAKI 1998, AMBIKA et al. 2014, SHI et al. 2020). Although previous findings suggest that mature male or female plants would produce heavier seeds but are relatively slow to germinate (MEENA et al. 2018), a reduction in seed vigour is a direct consequence of seed aging, which can affect crop performance (GHASSEMI-GOLEZANI AND DALIL 2014).

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 vigour potential based on the observed characteristics and possessed a better ability to develop and survive even under stressful conditions (OLUWARANTI et al. 2018). The findings from three separate studies indicated that some DC hybrid tomatoes displayed extreme rooting behaviour compared to their parental lines (ASHAKINA et al. 2016), 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 (YILDIRIM AND CAKMAK 2018). 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 (OMAR et al. 2022a). The differences in seed-quality characteristics discovered in hybrid types demonstrates that there were variances because of the genetic composition of the hybrids (OLUWARANTI et al. 2018).

4.2.4.2 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 (OLUWARANTI et al. 2018), 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 (LI et al. 2021, JOSHI AND GAUTAM 2021). Additionally, it suggests that, in addition to environmental and nutritional factors, genetic factors also affect this trait (TAHIR et al. 2008, LADAN AND HASSAN 2020, ALI 1994) and that seed size directly affects the number of rows per ear (ENAYATGHOLIZADE et al. 2012).

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 (GELETATA AND LABUSCHAGNE 2004). On the other hand, increasing the number of rows and kernels per ear directly increases grain yield (TAHIR et al. 2008, STEPHEN 2016). 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 (HARDER et al. 1982). 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 (STEPHEN 2016). 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 (HERRERO AND JOHNSON 1980). Moreover, a statistically significant difference in the direct effect of temperature on the number of seeds per ear has been demonstrated (ENAYATGHOLIZADEH et al. 2012).

The 1000-kernel weight is entirely determined by kernel size, and most of it is influenced by genetic, environmental, and nutrient factors (ALI 1994, JING et al. 2003). It is also an important factor directly contributing to the final grain yield of the crop (TAHIR et al. 2008). 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 (ENAYATGHOLIZADEH et al. 2012). There was also a favourable 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 (MCCUTCHEON et al. 2001, TAHIR et al. 2008), 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 (ZENG et al. 2017, ZEMACH 2023).

4.2.4.3 Relationship Between Seed Viability, Vigour, and Yield Traits

The relationship between two variables can be measured quantitatively independent of other factors considered (OWEN AND JONES 1977). 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 (YAGDI AND SOZEN 2009). The relationship between seed viability, vigour, and yield traits also varies between hybrids and lines depending on production practices and crop market requirements (FINCH-SAVAGE AND BASSEL 2016). 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 vigour of the seed. Furthermore, the results suggest that seed viability and vigour were most affected by genetic variables (OMAR et al. 2022a, BEWLEY AND BLACK 1982), which do not affect yield performance in the field. Seven key characteristics affect seed germination and vigour, including genetic content, the environment and nutrition of the maternal plant, harvest maturity stage, seed size or weight, mechanical integrity, seed aging, and pathogens (FINCH-SAVAGE AND BASSEL 2016). Seed viability, vigour, and size can also directly and indirectly affect crop yield, in addition to seed emergence percentage and time from sowing to emergence (TEKRONY AND EGLI 1991). According to earlier studies, seed vigour 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 (TEKRONY AND EGLI 1991, FINCH-SAVAGE AND BASSEL 2016).

4.3 The Effect of Nitrogen Fertilization on the Yield and Quality of Maize

4.3.1 Effect of Nitrogen on Grain Yield and Its Components

The ANOVA Table 25 shows that there were no differences in grain yield, cob weight, row number/cob, grain number/row, grain number/cob, 1,000 grain weight, and grain oil content between the groups for various N treatments (0, 50, 100, and 150 kg N ha^{-1}). However, the different levels of N treatments showed significant differences on cob number ($F\,(3,12) = [4.798]$, $p = 0.02$).

Table 25. Analysis of variance of grain yield, cob number/plot, cob weight, row number/cob, Grain number/row, grain number/cob, and 1000 grain weight in various levels of N treatments (0, 50, 100, and 150 kg N ha^{-1}).

Characteristic	Source of variation	Sum of Squares	*df*	Mean Square	*F*	Sig.
Grain yield (kg)	Between Groups	.515	3	.172	1.597	.242
	Within Groups	1.289	12	.107		
	Total	1.804	15			
Cob number/plot	Between Groups	26.688	3	8.896	4.798	.020
	Within Groups	22.250	12	1.854		
	Total	48.938	15			
Cob weight (g)	Between Groups	6073.122	3	2024.374	2.621	.099
	Within Groups	9270.033	12	772.503		
	Total	15343.154	15			
Row number/cob	Between Groups	2.688	3	.896	.782	.527
	Within Groups	13.750	12	1.146		
	Total	16.438	15			
Grain number/row	Between Groups	38.688	3	12.896	.898	.470
	Within Groups	172.250	12	14.354		
	Total	210.938	15			
Grain number/cob	Between Groups	19556.188	3	6518.729	1.496	.265
	Within Groups	52275.750	12	4356.312		
	Total	71831.938	15			
1000 grain weight	Between Groups	761.612	3	253.871	.410	.748
	Within Groups	7422.223	12	618.519		
	Total	8183.834	15			

df: Degree of freedom; Sig. Significance; Significance level = $p \leq 0.05$.

The results Table 26 demonstrate that the maximum grain yield per plot (11.50 kg ±1.17) was provided by treatment T2 (50 kg N ha^{-1}), while the minimum (9.47 kg ± 1.71) was recorded in the plot with the highest N application T4 (150 kg N ha^{-1}). The cob number/plot produced statistically similar values for N rates of 0, 100, and 150 kg N ha^{-1}, which were significantly lower than for the 50 kg N ha-^{1}. Nitrogen application at T2 (50 kg N ha-^{1}) resulted in maximum cob number/plot (17.25 ± 1.71) followed by T1 (0 kg N ha^{-1}), T4(150 kg N ha^{-1}), and T3 (100 kg N ha^{-1}) with 14.75 ± 1.26, 14.25 ± 0.96, and 14.00 ± 1.4, respectively.

Table 26. Mean values (± standard deviation) and Post Hoc LSD test results of grain yield and its components at different nitrogen fertilisation levels.

Treatment	**Grain yield/ plot (kg)**	**Cob number/ plot**	**Cob weight (g)**	**Row number/ cob**	**Grain number/ row**	**Grain number /cob**	**1000 grain weight**
T1 (0)	10.41 ±0.78^{a}	14.75 ±1.26^{ab}	207.75 ±3.54^{a}	15.50 ±1.00^{a}	40.25 ±2.75^{a}	625.50 ±76.65^{a}	241.67 ±36.17^{a}
T2 (50)	11.5 ±1.17^{a}	17.25 ±1.71^{a}	210.73 ±2.71^{a}	15.50 ±1.00^{a}	43.75 ±6.13^{a}	675.00 ±73.86^{a}	250.38 ±23.56^{a}
T3 (100)	10.47 ±1.39^{a}	14.00 ±1.41^{b}	254.18 ±2.36^{a}	16.50 ±1.00^{a}	43.75 ±2.87^{a}	722.00 ±65.44^{a}	238.73 ±21.70^{a}
T4 (150)	9.47 ±1.71^{a}	14.25 ±0.96^{b}	241.28 ±2.34^{a}	15.75 ±1.26^{a}	44.00 ±2.00^{a}	691.75 ±42.57^{a}	231.10 ±11.84^{a}
LSD ($p \leq 0.05$)	NS	1.33	NS	NS	NS	NS	NS

Means within columns followed by the same letters are not significantly different at $p \leq 0.05$ level using post hoc LSD test, LDS (0.05) = Least significant difference at $p \leq 0.05$, NS = Not significant.

The maximum cob weight (254.18 ± 2.36 g) was recorded for treatment T3 (100 kg N ha^{-1}) and the lowest (207.75 ± 3.54 g) for the control treatment T1 (0 kg N ha^{-1}). Row number/cob values were statistically similar for all N treatments. N treatment at a rate of 100 kg N ha^{-1} provided the highest row number/cob (16.50 ± 1.00), whereas the lowest value (15.50 ± 1.00) was obtained for treatments T1 and T2 with 0 and 50 kg N ha^{-1}, respectively. The number of grains/rows was not significantly affected by the different N rates, with the highest value (44.00 ±2.00) obtained for T4 (150 kg N ha^{-1}) and the lowest (40.25 ± 2.75) for T1 (0 kg N ha^{-1}).

Grain number/cob of maize was not significantly affected by the different N rates (Table 26), however, treatment T3 (100 kg N ha^{-1}) provided the highest (722.00 ± 65.44) grain number/cob, followed by T4 (150 kg N ha^{-1}), T2 (50 kg N ha^{-1}), and T1 (0 kg N ha^{-1}) with values of 691.75 ± 42.57, 675.00 ± 73.86, and 625.50 ± 76.65, respectively. The application of N did not affect the

1,000-grain weight. Treatment T2 (50 kg N ha^{-1}) resulted in the maximum weight (250.38 ± 23.56) and it was statistically comparable to T1, T3, and T4 with 241.67 ± 36.17, 238.73 ± 21.70, and 231.10 ± 11.84, respectively.

According to our results, nitrogen application had no impact on maize grain yield and its components. This could be due to other factors contributing to maize grain yield, as researchers have shown that yield is influenced by several environmental or technological factors (BĂŞA et al. 2016). According to NGOUNE AND SHELTON (2020), maize grain yield is affected by several factors, including technology (agricultural practices, management decisions, etc.), biology (diseases, insects, pests, weeds), and the environment (climatic conditions, soil fertility, topography, water quality, etc.). Also, an adjusted crop arrangement would increase maize production by an average of 18 percent, making it the most promising component studied according to EASH et al. (2019).

However, many studies have proven that increasing N levels in maize crops can increase grain yields (REDDY et al. 1985, TSAI et al. 1992), as N has a positive effect on plant growth, promoting and increasing the yield (ELTELIB et al. 2006). Nitrogen deficiency will reduce vegetative and reproductive growth, which has the potential of reducing yield (FAGERIA AND BALIGAR 2005). It was fond in a previous research that grain yield rose as the amount of sprayed nitrogen increased up to a certain point, but levelled off after that, also, maize hybrids required the same amount of nitrogen for optimal grain yield (TSAI et al. 1992). Furthermore, if grain yield does not respond to an increase in N fertiliser rate, it shows that raising the N fertiliser rate is not a smart approach for achieving maximum grain yield (HAMMAD et al. 2011). In addition, ZHAI et al. (2019) claimed that nitrogen application combined with proper tillage procedures has a considerable impact on grain yield, nitrogen uptake, and nitrogen use efficiency. They also indicated that for the best economic results, deep vertical rotary tillage with a N rate of 225 kg ha^{-1} was the best option.

According to the results, grain yield had no positive relationship with the number of cobs, cob weight, row number of one cob, number of grains/rows, number of grains/cobs, and 1,000 grains. However, according to BĂŞA et al. (2016), the application of 80 kg N ha^{-1} in maize crops increases the values of yield components (except 1,000 grain weight) and in turn increases grain yield. Similar findings have been revealed by LI et al. (2019), according to their study, there was a relationship between yield and agronomic characteristics such as the number of seeds/tassels, the weight of 1,000 seeds, plant height and tassel length, and all these factors contributed to high grain yields in rice.

4.3.2 Effect of Nitrogen on Grain Quality

According to Table 27, there were significant differences in grain moisture content (F (3,12) = [74.935], p = 0.00), grain protein content (F (3,12) = [6.404], p = 0.08), and starch concentration (F (3,12) = [3.621], p = 0.45) between the groups with different N treatments (0, 50,100 and 150 kg N ha^{-1}). However, oil content was similar for all treatments (F (3,12) = [2.507], p = 0.11).

Table 27. Analysis of variance of grain quality parameters like moisture, oil, protein, and starch contents at four levels of N fertilisation (0, 50, 100, and 150 kg N ha^{-1}).

Characteristic	Source of variation	Sum of Squares	*df*	Mean Square	*F*	Sig.
Moisture (%)	Between Groups	7.213	3	2.404	74.935	.000
	Within Groups	.385	12	.032		
	Total	7.598	15			
Oil (%)	Between Groups	.061	3	.020	2.507	.108
	Within Groups	.097	12	.008		
	Total	.157	15			
Protein (%)	Between Groups	.867	3	.289	6.404	.008
	Within Groups	.542	12	.045		
	Total	1.409	15			
Starch (%)	Between Groups	.962	3	.321	3.621	.045
	Within Groups	1.063	12	.089		
	Total	2.024	15			

df: Degree of freedom; Sig.: Significance; Significance level = $p \leq 0.05$.

The results reveal that levels of nitrogen have a considerable impact on grain moisture content (Table 28). Treatment T3 (100 kg N ha^{-1}) provided the highest (14.43 ± 0.15%) grain moisture content, while the highest N rate (treatment T4) provided the lowest (12.65 ± 0.10%) grain moisture content. N treatment at 150 kg N ha^{-1} resulted in the highest oil content (3.53 ± 0.06%), but the differences were not statistically significant. The protein content was significantly affected by levels of N. Maximum protein content (5.23 ± 0.12%) was obtained for treatment T2 (50 kg N ha^{-1}) and T1 (0 kg N ha^{-1}) with no statistical differences, and the lowest (4.64 ± 0.10%) value was presented by T4 (150 kg N ha^{-1}). Starch content was significantly affected by N rates (Table 28), the highest (72.43 ± 0.33% and 72.43 ± 0.22%) values were recorded for treatments T3 and T4, followed by T2 and T1 with 71.98 ± 0.37% and 71.90 ± 0.24%, respectively.

Table 28. Mean values (± standard deviation) and Post Hoc LSD test results of grain quality parameters (moisture, oil, protein, and starch contents) at four levels of N fertilisation.

Treatment	Moisture (%)	Oil (%)	Protein (%)	Starch (%)
T1 (0 N)	13.58±0.30[b]	3.42±0.12[a]	4.99±0.32[ab]	71.90±0.24[b]
T2 (50 N)	13.00±0.08[c]	3.39±0.07[a]	5.17±0.23[a]	71.98±0.37[ab]
T3 (100 N)	14.43±0.15[a]	3.37±0.10[a]	5.23±0.12[a]	72.43±0.33[a]
T4 (150 N)	12.65±0.10[c]	3.53±0.06[a]	4.64±0.10[b]	72.43±0.22[a]
LSD (P<0.05)	0.17	NS	0.21	0.29

Means within columns followed by the same letters are not significantly different at $p \leq 0.05$ level using post hoc LSD test, LDS (0.05) = Least significant difference at $p \leq 0.05$, NS = Not significant.

In general, the grain yield of maize crops increases in response to N, and this condition is closely related to grain quality such as moisture, oil, protein, and starch content. However, the association between grain quality and N value was not significant in this study in contrast to the results discovered by ELTELIB et al. (2006), where nitrogen significantly increased the protein content of forage maize. Thus, recent research has demonstrated that increased N levels would increase seed protein content (SPC) in maize. On the other hand, low N conditions not only restrict grain yield but also grain quality including moisture and protein contents (TSAI et al. 1992, HAMMAD et al. 2011).

Since no difference was found in the effects of different N treatments in our study, we can only conclude that the optimal efficiency of N fertilising is between 50–100 kg N ha^{-1}. Further studies are needed to be able to determine the optimal application of N more accurately. Cultivation practices play an important role in improving grain yield and grain quality beside technology, biology, and the environment.

4.4 Assessment of Genetic Variability and Heterosis for Yield and Yield Components in Maize

4.4.1 Variance and Mean Performance

The mean square of eight characteristics from analysis of variance (ANOVA) is presented in Table 29. Highly significant variation ($p < 0.01$) among genotypes was observed for all characteristics contributing to yield and yield components. This indicates a wide range of viability for plant height, days to 50% flowering, ear weight, ear length, ear diameter, row number per ear, number of kernels per ear, and 1000-kernel weight that can be exploited through selection for future breeding programs. Similar studies by MAGAR et al. (2021), WAN ROZITA et al. (2022), and RASHEED et al. (2023) revealed significant variation between the genotypes for the characteristics studied, emphasising the importance of genotype-specific traits.

Table 30 shows a comparison of the mean yield and yield components. The V10 (GK154 X155), a hybrid (SC), produced vigorous plant growth with 121.50 cm of plant height and a highly significant difference with the lowest plant height of the parent V8 (GK155). Plant height is a crucial characteristic that allows the yield plant to compete directly with weeds and generally with other issues for light capture and photosynthetic activities (ABRO et al. 2021).

Among the 16 genotypes studied, the SC hybrid of V10 (GK154 X GK155) is the earliest genotype to flower, with a mean value of 58.20 days, followed by the parent of V9 (GK131) of 59.00 days and the commercial hybrid of V16 (Mv277) of 67.33 days, while the parent of V1 is the latest genotype to flower, which takes 91.53 days (Table 30). Days to flowering is an essential characteristic that controls maturity duration, which contributes to the yield in maize. Whereby earliness is a desirable characteristic in maize crops, as it assists the plants to avoid biotic and abiotic stresses (KHAN et al. 2014). Similar findings have been reported by MUCHIE AND FENTIE (2016) and KHAN et al. (2014), which found significant differences among the maize genotypes from day to flowering. While REDDY et al. (1986) have stated that there is a significant difference between hybrids and inbred lines. Therefore, for maize breeders, earliness characteristics are essential to take into account in selection since they will extend the grain fill before harvesting, which leads to a high yield.

The SC hybrid of V10 (GK154 X GK155) exhibited the heaviest ear weight of 105.89 g, followed by the TC hybrid of V2 (TK222/17) of 100.0 g and the commercial hybrid of V16 (Mv277) of 98.45 g, while the parent of V12 (GK154) had the lightest weight of 33.35 g. The SC hybrid of V10 (GK154 X GK155) subsequently produced the longest ear length (16.13 cm), the maximum row number per ear (15.07), and the number of kernels per ear (436.27), while the parent of V1 (B1026/17) produced the shortest ear length (7.67 cm), the minimum row number per ear (7.87), and the number of kernels per ear (74.00). However, the TC hybrid of V2 (TK222/17) produced the largest diameter of 4.07 cm and the smallest diameter of 2.12 cm of parent V1 (B1026/17) while the SC hybrid of V11 (GK131XGK150) produced the highest weight of 1000 kernels (438.87), and V3 (inbred line) produced the lowest weight of 217.00 g (Table 30). According to CIRILO AND ANDRADE (1994), ear weight is highly correlated with grain yield, which is greatly influenced by genotypes and the kernel set. However, it is very sensitive to environmental changes, particularly when tasseling and silking. Moreover, a higher number of kernel rows per ear enhances the grain weight and yield (MANIVANAN 1998), which have a positive correlation with ear weight and kernel number per ear. In addition, KHAN et al. (2014) also reported highly significant differences among maize genotypes for yield and its components. Also, MOJGAN AND HAMID (2008) found that grain yield had a positive correlation with yield components.

Table 29. Mean square for plant height, day to 50% flowering, ear weight, ear length, ear diameter, row number per ear, number of kernels per ear and 1000- kernel weight of different maize parents and hybrids.

Characteristics	Genotype	Rep	Error	CV (%)	Mean
PH (cm)	8011.02**	1753.48**	98.49	8.56	84.95
DFF (50%)	1706.80**	431.00ns	56.51	0.09	75.50
EW (g)	7835.46**	479.77ns	194.3	0.20	69.75
EL (cm)	84.31**	8.15ns	3.2	0.14	12.43
ED (cm)	4.89**	0.05ns	0.16	0.11	3.49
RNPE	59.54**	1.61ns	1.47	0.10	12.35
NKPE	135166.00**	15076.00**	1089	0.15	215.52
OTKW (g)	49556.30**	35.81ns	804.4	0.09	315.64
	df = 15	*df* = 2	*df* = 222		

PH, plant height (cm); DFF, days to 50% flowering; EW, ear weight (g); EL, ear length (cm); ED, ear diameter (cm); RNPE, row number per ear; NKPE, number of kernels per ear; OTKW, 1000-kernel weight (g).

df: Degree of freedom ** =Significant at $p < 0.01$; * = Significant at $p < 0.05$; ns = Not significant

Table 30. Mean performance for plant height, day to 50% flowering, ear weight, ear length, ear diameter, row number per ear, number of kernels per ear and 1000- kernel weight of different maize parents and hybrids.

Genotype	PH	DFF (50%)	EW	EL	ED	RNPE	NKPE	OTKW
Parent								
V1 (B1026/17)	65.07^{g}	91.53^{a}	39.63^{ef}	7.67^{g}	2.12^{g}	7.87^{f}	74.00^{h}	301.00^{e}
V3 (TKAPA15/DV)	59.43^{gh}	89.40^{ab}	37.20^{f}	8.10^{g}	2.49^{fg}	10.53^{de}	113.87^{gh}	220.33^{g}
V4 (TK1083/19)	98.95^{cde}	74.53^{de}	60.61^{d}	11.43^{ef}	3.24^{de}	10.07^{e}	145.20^{g}	258.93^{f}
V6 (MCS901/19)	91.73^{def}	67.73^{ef}	67.61^{cd}	12.83^{c-f}	3.39^{b-e}	11.33^{de}	188.80^{ef}	244.20^{fg}
V8 (GK155)	51.80^{h}	84.27^{abc}	64.69^{cd}	12.16^{def}	3.89^{ab}	13.67^{ab}	219.00^{de}	368.03^{b}
V9 (GK131)	88.01^{ef}	59.00^{fg}	59.45^{d}	13.37^{cde}	3.86^{ab}	14.53^{ab}	262.13^{c}	308.83^{cde}
V12 (GK154)	67.68^{g}	80.00^{bcd}	33.35^{f}	11.53^{def}	2.96^{ef}	11.13^{de}	139.87^{g}	260.00^{f}
V13 (GK150)	58.51^{gh}	88.00^{ab}	60.30^{d}	11.26^{def}	3.73^{a-d}	13.20^{bc}	208.60^{e}	344.30^{bc}
V14 (GK144)	50.54^{h}	89.80^{a}	57.20^{de}	10.57^{f}	3.22^{e}	10.53^{de}	126.87^{g}	253.20^{fg}
Hybrid								
V5 (TK623/18) (SC)	101.09^{cd}	71.13^{de}	96.59^{ab}	15.87^{ab}	4.03^{a}	13.87^{ab}	329.13^{b}	362.37^{b}
V10 (GK154 X155) (SC)	121.50^{a}	58.20^{g}	105.87^{a}	16.13^{a}	3.90^{a}	15.07^{a}	436.27^{a}	342.03^{bc}
V11 (Szegedi 521; GK131XGK150) (SC)	100.98^{cd}	75.80^{cde}	81.66^{bc}	13.11^{cde}	3.78^{abc}	11.93^{de}	193.20^{ef}	438.87^{a}
V15 (GK144X GK150) (SC)	84.51^{f}	70.40^{e}	81.57^{bc}	13.38^{cde}	3.93^{a}	14.27^{ab}	272.33^{c}	305.33^{de}
V2 (TK222/17) (TC)	115.91^{ab}	69.40^{e}	100.46^{a}	14.97^{abc}	4.07^{a}	13.67^{ab}	325.67^{b}	349.00^{b}
V7 (TK256/17) (DC)	107.03^{bc}	71.40^{de}	71.32^{cd}	12.83^{c-f}	3.35^{cde}	12.00^{cd}	153.47^{fg}	339.97^{bcd}
V16 (MV277) (CH)	96.46^{c-f}	67.33^{efg}	98.45^{ab}	13.73^{bcd}	3.85^{abc}	13.93^{ab}	260.07^{cd}	353.80^{b}

PH, plant height (cm); DFF, days to 50% flowering; EW, ear weight (g); EL, ear length (cm); ED, ear diameter (cm); RNPE, row number per ear; NKPE, number of kernels per ear; OTKW, 1000-kernel weight (g).

Values are presented as mean. Values with different superscript within the same column are significantly different $p \leq 0.05$ based on Duncan's Multiple Range Test (DMRT).

4.4.2 Genetic Variability

The estimates of genotypic coefficient of variation (GCV), phenotypic coefficient of variation (PCV), and components of variances for eight characteristics contributing to yield components are presented in Table 31. The greater difference observed between genotypic and phenotypic variances for plant height, days to 50% flowering, ear weight, number of kernels per ear, and 1000-kernel weight suggests that the phenotypic expression of these characteristics is highly influenced by environment (BELAY 2018). The characteristics evaluated in the present investigation had low (less than 10% phenotypic and genotypic coefficients of variation), moderate (10–20% phenotypic and genotypic coefficients of variation), and high (more than 20% phenotypic and genotypic coefficients of variation), similarly to the findings from the prior study by MAGAR et al. (2021). The GCV value ranged from 1.44% for 1000-kernel weight to 91.47% for ear diameter, while the PCV ranged from 9.10% for 1000-kernel weight to 92.18% for ear diameter. Low GCV values (6.12%, 4.20%, and 2.985) and moderate PCV values (13.19%, 10.81%, and 15.59%) were recorded for plant height, days to 50% flowering, and number of kernels per ear. High GCV values (23.83%, 91.47%, and 29.75%) and high PCV values (27.85%, 92.18%, and 31.33%) were recorded for ear length, ear diameter, and row number per ear, while low GCV values (5.25%) and high PCV values (20.66%) were recorded for ear weight. On the other hand, the remaining characteristic, 1000-kernel weight, resulted in low GCV and PCV of 1.44% and 9.15, respectively. The magnitude of PCV in the current study was a bit higher than GCV for each characteristic examined, demonstrating that the environment exhibited little influence on how these characteristics were manifested phenotypically. Additionally, it shows that selection can be beneficial for certain characteristics, even at the phenotypic level. The same findings were discovered before (SESAY et al. 2016, BELAY 2018).

4.4.3 Heritability (h_2b) In Broad Sense and Genetic Advance

The estimates of broad-sense heritability and genetic advance in percentage are presented in Table 31. The ear length, ear diameter, and row number per ear exhibited extremely high heritability (> 80%). SASEY et al. (2016) also found similar outcomes for the ear length characteristic. These characteristics showed high genetic variation and low environmental influence, suggesting that characteristic improvement can be made based on phenotypic performance (BELAY 2018). High heritability estimates suggest that variations were passed down to offspring, allowing for the development of high-yielding varieties by selecting desirable genotypes and plant material with desirable traits (MAGAR et al. 2021). Moderate heritability estimates (30-60%) were observed for plant height and days to 50% flowering. These results were in accordance with previous reports by SASEY et al. (2016) and BELAY (2018), while low heritability estimates (less than 30%) were observed for ear weight, number of kernels per ear, and 1000-kernel weight.

The highest value of genetic advance was recorded by number of kernels of 13.23, followed by plant height of 10.71, while ear length (6.10) had the lowest genetic advance. The genetic advance estimates can be used to understand the sort of gene activity involved in expression of various polygenic characteristics. According to SINGH AND NARAYAN (1993), high genetic advance values indicate additive gene action, while low values indicate non-additive gene action. Additive gene effects control characteristics, resulting in higher heritability and genetic advance, whereas non additive gene actions may cause high heritability but poor genetic advance (MOHANA KRISHNA et al. 2009). Accordingly, heritability and genetic advance are crucial selection parameters, with genetic advance estimation being more useful when combined with heritability estimates (JOHNSON et al. 1955).

Table 31. Estimation of genotypic and phenotypic coefficient variation, heritability and genetic advance for plant height, day to 50% flowering, ear weight, ear length, ear diameter, row number per ear, number of kernels per ear and 1000- kernel weight of different maize parents and hybrids.

Characteristics	**Mean**	**σ^2g**	**σ^2p**	**GCV (%)**	**PCV (%)**	***h^2B***	**GA**
PH (cm)	84.95	27.11	125.60	6.12	13.19	46.39	10.71
DFF (50%)	75.50	10.06	66.57	4.2	10.81	38.85	6.53
EW (g)	69.75	13.44	207.74	5.25	20.66	25.41	7.54
EL (cm)	12.43	8.78	11.98	23.83	27.85	85.57	6.10
ED (cm)	3.49	10.19	10.35	91.47	92.18	99.23	6.58
RNPE	12.35	13.50	14.97	29.75	31.33	94.96	7.57
NKPE	215.52	41.37	1130.37	2.98	15.59	19.11	13.23
OTKW (g)	315.64	20.53	824.93	1.44	9.1	14.82	8.77

PH, plant height (cm); DFF, days to 50% flowering; EW, ear weight (g); EL, ear length (cm); ED, ear diameter (cm); RNPE, row number per ear; NKPE, number of kernels per ear; OTKW, 1000-kernel weight (g).

4.4.4 Heterosis

Significant heterosis was observed for all characteristics studied illustrates in Table 33. Standard heterosis for plant height ranging from 12.26% to 103.38% and 14.74% to 134.56% over mid parent and better parent (Table 32). The maximum positive heterosis was recorded in the SC hybrid of V15 (GK144X GK150), with 103.38% for the mid parent and 134.56% for the high parent. The minimum heterosis effect was exhibited for SC hybrid V11 (GK131XGK150), which displayed a value of 12.26% for the mid parent and 16.68% for the high parent. Similar findings were discovered from previous studies on the heterosis effect of plant height in maize, including three-way cross hybrids (IQBAL et al. 2010, ZAID et al. 2014).

Table 32 displays the percentage of heterosis between mid-parent and high parent for days to 50% flowering. Mid parent heterosis values ranged from -29.14% to 3.13%, while high parent values ranged from -30.94% to 28.47%. The TC hybrid of V2 (TK222/17) had a significant positive mid parent heterosis value of 3.13%, while the SC hybrid of V15 (GK144XGK150) had a negative mid parent value of -29.14%. The maximum positive high parent heterosis value was 28.47% in the TC hybrid of V2 (TK222/17), while the minimum negative high parent heterosis value was -30.94% in the SC hybrid of V15 (GK144XGK150). These findings are consistent with GELETA AND LABUSHAGNE (2004) study, which found TC hybrid to be better for this particular characteristic.

The ranged percentages of heterosis values for ear weight, ear length, and ear diameter over the mid parent were 11.25% to 161.23%, 6.46% to 107.45%, and -13.68% to 79.06%, respectively (Table 32 and Table 33). Whereas the ranges of heterosis over the high parent for ear weight, ear length, and ear diameter were 5.49% to 143.73, -1.94% to 106.91, and -12.06 to 89.62%, respectively. The SC hybrid of V5 (TK623/18) contributed the maximum positive mid parent and high parent heterosis for ear weights of 161.23% and 143.73%, ear lengths of 107.45% and 106.91%, and ear diameters of 79.06% and 89.62%, respectively. Therefore, the minimum mid parent and high parent heterosis were represented by the SC hybrid of V11 (GK131XGK150) for ear weight of 11.25% and 5.49%, respectively, and the TC hybrid of V2 (TK222/17) for ear length (6.46% and -1.94) and ear diameter (-13.68% and 12.06%), respectively. The results obtained contradicted the findings from GELETA AND LABUSHAGNE (2004), where TC hybrids surpassed SC and DC hybrids in terms of heterosis performance for ear weight, ear length, and ear diameter characteristics. However, yield heterosis is a variable characteristic that is not only influenced by parent combinations but also by environmental factors (VIRMANI et al. 1982, YOUNG AND VIRMANI 1990).

Table 33 displays the heterosis values for kernel number per ear and number of kernels per ear over mid parent, which ranged from 13.94% to 50.73% and -17.92 to 273.45, respectively, while -9.60% to 76.27% and -18.71% to 344.77% heterosis values ranged over high parent. The maximum heterosis recorded for SC hybrid of V5 (TK623/18) over mid and high parent for row number per ear was 50.73% and 76.27%, respectively, compared to the minimum heterosis recorded for TC hybrid of V2 (TK222/17) over mid and high parent for row number per ear of -13.94% and -9.60%, respectively. Where the maximum heterosis values of the SC hybrid of V5 (TK623/18) over mid parent and high parent heterosis were 273.45% and 344.77%, respectively, while the TC hybrid of V2 (TK222/17) had a minimum mid parent heterosis of -17.92 and the SC hybrid of V11 (GK131XGK150) had a minimum mid parent and high parent heterosis.

The heterosis values for 1000-kernel weight ranged from 2.20% to 39.02% (mid parent) and -11.32 to 42.92% (high parent) (Table 34). Maximum heterosis over mid parent was recorded for the SC hybrid of V5 (TK623/18) at 39.02%, while maximum over the high parent was recorded for the SC hybrid of V10 (GK154 X155) at 42.92%. The minimum heterosis over mid parent and high parent was recorded from DC hybrids of V7 (TK256/17) of 2.20% and -11.32%, respectively. Our results aligned with the previous studies by ZAID et al. (2014), showing a positive increase in maize crosses for 1000-kernel weight.

Table 32. Mid and high parent heterosis for plant height, day to 50% flowering, ear weight, ear length of different maize hybrids.

	PH (cm)		**DFF (50%)**		**EW (g)**		**EL (cm)**	
Hybrids	**Mid parent (%)**	**High parent (%)**	**Mid parent (%)**	**High parent (%)**	**Mid parent (%)**	**High parent (%)**	**Mid parent (%)**	**High parent (%)**
V5 (TK623/18) (SC)	62.39**	55.36*	-21.37**	-22.29**	161.23**	143.73**	107.45**	106.91**
V10 (GK154 X155) (SC)	47.84*	26.36	-12.85	2.47	87.36**	48.59**	46.05**	23.01
V11 (Szegedi 521; GK131XGK150) (SC)	12.26	16.68	0.38	5.42	11.25	5.49	8.73	5.42
V15 (GK144X GK150) (SC)	103.38**	134.56**	-29.14**	-30.94**	116.01**	63.69**	36.18**	32.65**
V2 (TK222/17) (TC)	37.84*	14.74	3.13*	28.47	36.38*	35.42**	6.46	-1.94
V7 (TK256/17) (DC)	54.99*	44.44*	-18.14	-20.00*	38.84*	35.27*	22.583*	18.83

*PH, plant height (cm); DFF, days to 50% flowering; EW, ear weight (g); EL, ear length (cm).
** =Significant at $p < 0.01$; * = Significant at $p < 0.05$.

Table 33. Mid and high parent heterosis for ear diameter, row number per ear, number of kernels per ear and 1000- kernel weight of different maize hybrids.

	ED (cm)		RNPE		NKPE		OTKW (g)	
Hybrids	**Mid parent (%)**	**High parent (%)**	**Mid parent (%)**	**High parent (%)**	**Mid parent (%)**	**High parent (%)**	**Mid parent (%)**	**High parent (%)**
V5 (TK623/18) (SC)	79.06**	89.62**	50.73**	76.27**	273.45**	344.77**	39.02**	20.39**
V10 (GK154 X155) (SC)	48.00**	20.41*	42.36**	20.58**	147.84**	72.49**	28.03**	42.92**
V11 (Szegedi 521; GK131XGK150) (SC)	1.66	-0.30	12.15	5.88	-8.10	-18.71	35.14**	39.22**
V15 (GK144X GK150) (SC)	14.37*	0.78	21.51**	10.24*	143.14**	99.21**	8.92	-7.06
V2 (TK222/17) (TC)	-13.68*	-12.06	-13.94*	-9.6*	-17.92*	-7.38	34.39**	27.47**
V7 (TK256/17) (DC)	12.77	5.36	20.23**	8.08	62.36**	30.55*	2.20	-11.32

ED, ear diameter (cm); RNPE, row number per ear; NKPE, number of kernels per ear; OTKW, 1000-kernel weight (g).
** =Significant at $p < 0.01$; * = Significant at $p < 0.05$.

In the current study found, it was found that single cross hybrids (SC) outperformed three-way cross hybrids (TC) and double cross hybrids (DC) in terms of yield and yield components, indicating varying degrees of heterosis among the three hybrid forms. In addition, SC hybrids also showed higher uniformity, while double cross hybrids exhibited the highest heterogeneity, particularly when different genetic backgrounds were used to generate the hybrids (GELETA AND LABUSHAGNE 2004). However, each different cross-combination is found to be better for various characteristics.

5. CONCLUSION AND RECOMMENDATIONS

This chapter serves as an important component to conclude the findings of the study. Coupled with valuable recommendations for future research and practical application, ensuring that the results of the study have a lasting impact in the field.

5.1 Conclusion

Maize crop improvement requires information on genetic variability, heterosis, agronomic characteristics, grain quality, and fertilizer application. A comprehensive information package is crucial for research programs to meet increasing demand and address the impact of extreme global climate change on maize production. This is due to the lack of superior varieties and technology gaps, particularly in rural areas, which hinder yield production. Improving agronomic characteristics is crucial for ensuring plant growth, development, and yield. These characteristics include plant height, leaf area, root system architecture, blooming period, and seed size. Understanding agronomic characteristics helps breeders and farmers develop drought-resistant varieties, select appropriate fertilizers and pest management strategies, optimize crop growth, and minimize losses.

The entire set of results that contribute to the potential improvement of maize in our study begins with the germination test, which demonstrated that the maize seeds germinated after the third day and fully germinated on the seventh day after sowing. Additionally, the length of the plumule expanded significantly as the number of incubation days rose. Moreover, the findings found that the germination test also provided valuable insights into the vigour of the maize seeds. Varieties SC, DC, and TC not only had high germination rates but also displayed faster and more uniform germination compared to the parents. This suggests that these hybrids possess superior seed quality and vigour, which can contribute to better crop establishment and overall productivity.

The study conducted on maize yield performance revealed that hybrid lines performed better than the parental lines. Specifically, the SC hybrids were found to be the most dominant in terms of yield. The results indicate that several factors contributed to the final grain yield. These factors include the number of rows and kernels per ear, 1000-kernel weight, and ear weight. Crop yield is affected by 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 favourable association. These factors play a significant role in determining the overall productivity of the crop and can be optimised through proper agricultural practices.

Furthermore, the study emphasizes the impact of nitrogen fertilisation on maize yield and quality, focusing on yield and its components as well as grain quality. However, the results indicated that nitrogen fertilisation did not have a significant effect on these factors, suggesting that nitrogen alone may not be sufficient to improve these aspects of maize production. However, an optimal nitrogen application between 50 and 100 kg N ha^{-1} led to a noticeable increase in yield, protein, and starch content. This highlights the crucial role of the quantity of nitrogen applied in enhancing these important characteristics of maize.

The study on maize genotypes showed significant genetic variability among them, indicating the potential for enhancing yield through selective breeding and genetic modification. Additionally, the study found that environmental factors influence the expression of these genetic characteristics, meaning that the same genotype may perform differently in different environments. Therefore, when selecting and breeding maize varieties, it is important to consider environmental factors. The findings also revealed that the environmental influence on the manifestation of these characteristics phenotypically was greater than the genetic influence. This study has shown a contrast from the previous study, in which single-cross hybrids (SC) have a more prominent heterosis effect on yield and yield components compared to three-way crosses (TC) and double-crosses (DC) over mid-parent and high-parent. However, the heterogeneity in TC and DC hybrids also showed promising performance and can be utilised in future breeding programmes.

Overall, the findings of the study suggest that a comprehensive understanding of genetic variability, heterosis, agronomic characteristics, and fertiliser application is crucial for developing superior maize varieties and optimising crop growth. This knowledge can help meet the increasing demand for maize and address the challenges posed by extreme global climate change, such as droughts, heatwaves, and changing pest and disease patterns. By developing maize varieties that are resilient to these challenges and maximising crop productivity through effective management practices, farmers can contribute to food security and sustainable agriculture.

5.2 Recommendations

Additionally, future studies should also consider the impact of different farming practices and techniques on crop yield. This could involve comparing traditional farming methods with more sustainable and environmentally friendly approaches, such as organic farming or precision agriculture. Furthermore, it would be beneficial for researchers to explore the potential effects of climate change on crop yield in different regions. This could involve analyzing historical climate data and projecting future climate scenarios to understand how changing temperatures, precipitation patterns, and extreme weather events may impact crop production.

In order to obtain more accurate and reliable results, future studies should also aim to increase the sample size and diversity of the population being studied. This could involve including a wider range of crop varieties, as well as considering the influence of genetic factors on crop yield. Moreover, it would be valuable for researchers to investigate the socio-economic factors that may affect crop yield. This could involve analyzing the impact of factors such as access to resources, education, and market conditions on farmers' ability to achieve high crop yields.

In conclusion, further studies on this topic should focus on using different data sources, considering the population's size and various climate zones, and addressing the issue of repetition. Additionally, proper field preparation, including the implementation of irrigation systems, weed management systems, and appropriate fertilizer requirements, should be prioritized to minimize the detrimental effects of abiotic and biotic stress on crop yield. By expanding research efforts in these areas, we can gain a deeper understanding of the factors influencing crop yield and develop strategies to enhance agricultural productivity in a sustainable and resilient manner.

6. NEW SCIENTIFIC RESULTS

1. The research findings have shown that maize seeds germinate on the third day and fully germinate on the seventh day after sowing. However, the SC (F_1), DC (F_1), and TC (F_1) varieties demonstrated exceptional germination performance, achieving a 100% germination rate on the fifth day. These varieties displayed the longest shoot and root lengths, with shoot lengths of 7.9 cm, 7.6 cm, and 6.9 cm and root lengths of 12.9 cm, 13.9 cm, and 14.9 cm, respectively. Consequently, the hybrid seeds demonstrated a significantly higher germination rate (100%) and more vigorous seedlings compared to the parents.

2. The germination rate of the DC hybrid (100%) was higher than that of the parental lines (81.47%), SC hybrids (70.83%), and TC hybrids (66.67%). The parental lines had a better germination percentage and radicle elongation, while SC hybrids had better plumule length. In field evaluation, hybrid lines, particularly SC hybrids, outperform others in terms of the number of rows per ear, the number of kernels per ear, and the kernel weight and ear weight of 15.07, 436.27 g, 438.87 g, and 105.89 g, respectively.

3. The findings of the study show that increased nitrogen fertilisation does not significantly affect the yield or grain quality of maize. However, the use of an optimal amount of nitrogen, specifically between 50 and 100 kg N ha^{-1}, appeared to be the ideal amount that leads to higher yields and increased protein and starch content.

4. The research indicates that genetic variability exists among various types of maize, which can be utilised to improve crop productivity. The phenotypic coefficient of variation (PCV) surpasses the genotypic coefficient of variation (GCV), suggesting environmental factors significantly influence phenotypic expressions. Grain yield might be enhanced through an increase in the heritability and genetic advance of various traits, along with a high GCV and PCV. TC and DC hybrids show less heterosis than SC hybrids, but their performance is promising for future breeding programs. Moreover, further investigation is required to examine the influence of environmental factors and population size on hybrid combinations.

7. SUMMARY

Maize is a significant export crop in Hungary in addition to its extensive domestic use. It contributes more than half (55%) of the total production of major cereals such as wheat, barley, and others. Recent years have seen several constraints on maize productivity, including climate change, which has driven various abiotic and biotic stresses and poor soil fertility. Additionally, there are issues with a lack of access to essential inputs (superior varieties, seed quality, and fertiliser), low levels of mechanisation, and subpar post-harvest management. Due to this challenge, there have been very significant yield losses that may account for up to 100% of the crop's production.

This thesis comprehensively examines the entire process that has a significant impact on maize yield and quality. The research consists of four experiments, starting with the evaluation of germination characteristics and continuing with the second assessment of seed viability, vigour, and their correlation with yield performance. Furthermore, the third research investigated the optimal nitrogen application for maize growth, ensuring that it does not compromise yield production. Lastly, the study evaluates the genetic variability and heterosis of the parents and hybrids, which are essential factors in determining yield and its components. The genetic constitution of the plants plays a vital role in completing this process.

The first experiment was conducted at the Crop Production Laboratory, MATE, Gödöllő, with the aim of the study being to determine the differences in the performance of some hybridization pathways. The study focused on determining the performance differences among single-cross (SC), double-cross (DC), and three-way cross (TC) hybrids and their parental inbred lines. The results indicated that maize seeds started germinating on the third day and fully germinated by the seventh day after sowing. The SC (F_1), DC (F_1), and TC (F_1) hybrids exhibited excellent germination performance, achieving a 100% germination rate on the fifth day. Additionally, these hybrids displayed the highest shoot and root lengths, with values of 7.9 cm, 7.6 cm, and 6.9 cm (shoot length) and 12.9 cm, 13.9 cm, and 14.9 cm (root length), respectively. Overall, the findings clearly demonstrate that the hybrid seeds have a higher germination rate (100%) and produce more vigorous seedlings compared to the parental inbred lines.

The second experiment aims to investigate the impact of seed quality and hybrid types on maize germination, focusing on seed viability and vigour. The study was conducted in both a laboratory and a field experiment plot at the Hungarian University of Agriculture and Life Sciences. The experiment included nine parental lines, six hybrids, and a controlled hybrid, which were tested using a complete randomization design (CRD) in the laboratory and a randomised complete block design (RCBD) in the field. The results indicated significant differences in seed vigour between genotypes and days, with parental lines performing better in terms of germination percentage and radicle elongation, while single-cross hybrids (SC) produced better plumule length. Furthermore, radicle and plumule length expanded significantly as the number of incubation days rose. In field evaluation, hybrid lines demonstrated better performance compared to parental lines, with SC hybrids being more prevalent. Additionally, the number of rows per ear, number of kernels per ear, 1000-kernel weight, and ear weight all contribute directly to the final grain yield.

The third experiment examined the impact of different levels of nitrogen (N) on yield and quality of maize (*Zea mays* L.). The study was conducted at the Experimental Plot Department of Agronomy, The Hungarian University of Agriculture and Life Sciences, Hungary. The experimental site consisted of four observation plots with a net size of 2x5 m. Four N levels of T1, T2, T3, and T4 were sprayed at the indicated plants in four replications, with N rates of 0, 50, 100, and 150 kg N ha^{-1}. Overall, nitrogen application did not have a significant effect on maize yield, its components, or grain quality. However, out of the four N treatments, the optimal N application between 50 and 100 kg N ha^{-1} potentially increased the yield and the total expression of protein and starch contents in maize. This suggests that proper N fertilisation can enhance both grain yield and nutritional value.

The fourth and final experiment investigated how genetic variability and heterosis affect the productivity of maize crops. The study focused on different types of hybrids, including single-cross, double-cross, and three-way cross hybrids, as well as their parent plants and commercially available hybrids. Sixteen different genotypes and their hybrids were tested in the field during the spring growing season of 2022. The genetic variability and heritability were recorded for plant height, days to 50% flowering, ear length, and ear diameter, while low genotypic coefficient variation (GCV) and moderate phenotypic coefficient of variation (PCV) values were recorded. High GCV values (23.83%, 91.47%, and 29.75%) and high PCV values (27.85%, 92.18%, and 31.33%) were recorded in the range of mid parent and high parent for ear weights of 161.23%, 6.46% to 107.45%, and 13.68% to 79.06%, respectively. The SC hybrid of V5 (TK623/18) contributed the maximum positive mid-parent (ear weight) and high (ear diameter) heterosis over the mid parent, while the TC and DC hybrids contributed the minimum positive mid and high parent for ear length and row number per ear, respectively. However, the effect of heterogeneity in TC and DC hybrids shows promising performance and can be exploited for future breeding programs.

8. APPENDICES

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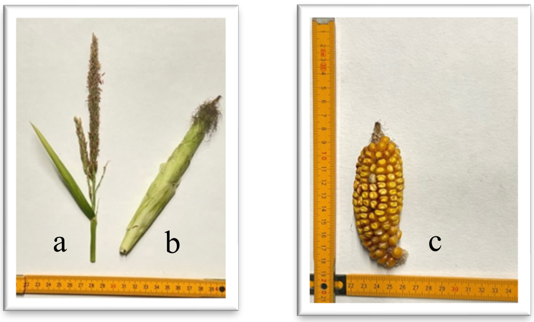
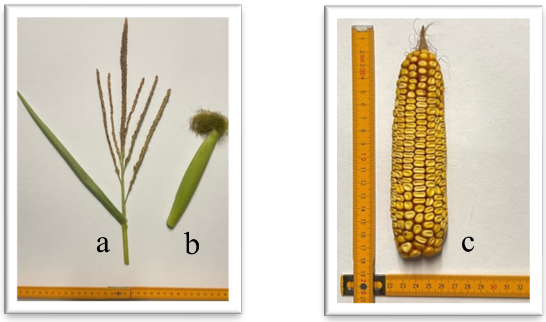
A2: Male inflorescence (tassel) (a), female inflorescence (ear) (b) and maize cob (c) of different genotypes that used in this study.



V1



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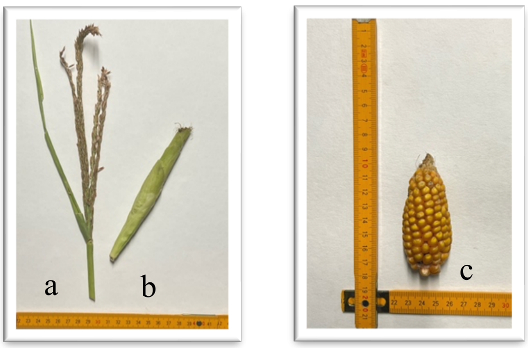

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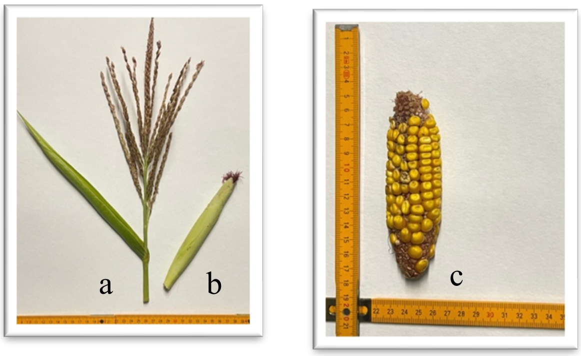
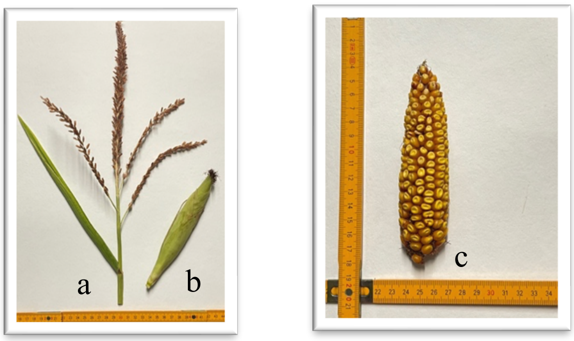


V4

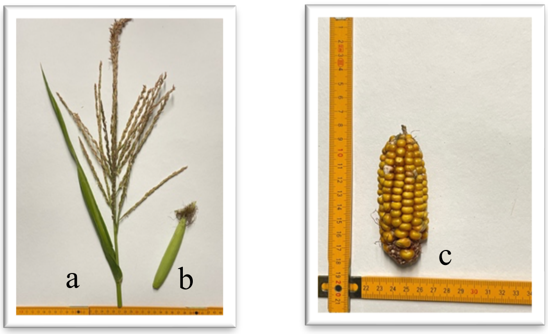
V5



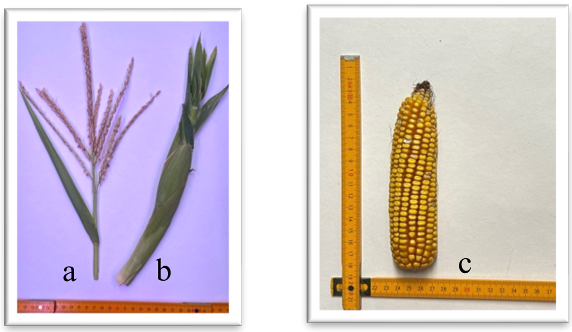
V6

V7

V8



V9



V10

V11

V12

V13

V14

V15

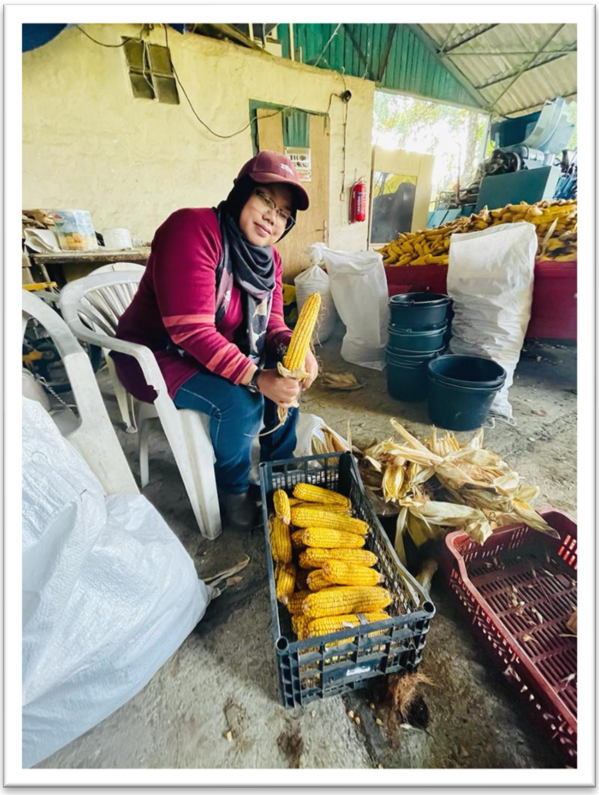
V16

A3: Research Activities

Laboratory Experiment

Field Experimental Plot

Data Measurement



Husking process

LIST OF PUBLICATIONS OF THE AUTHOR IN THE REASERCH FIELD

Publications

1. **Omar, S.**, Tarnawa, Á., Kende, Z. Abd Ghani, R., Kassai, M.K. and Jolánkai, M. (2022a). Germination characteristics of different maize inbred hybrids and their parental lines. *Cereal Research Communications*, 50(4), pp. 1229–1236. https://doi.org/10.1007/s42976-022-00250-9.

2. **Omar, S.,** Abd Ghani, R., Khaeim, H., Sghaier, A.H. and Jolánkai, M (2022b). The effect of nitrogen fertilisation on yield and quality of maize (*Zea mays* L.). *Acta Alimentaria*, 51(2), pp. 249–258. https://doi.org/10.1556/066.2022.00022.

3. **Binti Omar**, S., Binti Abd Ghani, R., Binti Khalid, N., Tarnawa, Ákos, Kende, Z., Kassai, M. K. and Jolankai, M. (2023). Impact of N Supply on Some Leaf Characteristics of Maize Crop. *COLUMELLA – Journal of Agricultural and Environmental Sciences*, 10(1), 15–25. https://doi.org/10.18380/SZIE.COLUM.2023.10.1.15.

4. **Omar, S**., Abd Ghani, R., Khalid, N., Jolánkai, M., Tarnawa, Á., Percze, A., Mikó, P.P. and Kende, Z., 2023. Effects of Seed Quality and Hybrid Type on Maize Germination and Yield in Hungary. *Agriculture*, *13*(9), p.1836. https://doi.org/10.3390/agriculture13091836.

5. Abd Ghani, R., Kende, Z, Tarnawa, Á, **Omar, S.,** Kassai, M.K., Jolánkai, M. (2021). The effect of nitrogen application and various means of weed control on grain yield, protein, and lipid content in soybean cultivation. *Acta Alimentaria*, 50(4), pp. 249–258. https://doi.10.1556/066.2021.00095.

6. Khalid, N., Tarnawa, Á., Balla, I., **Omar, S**., Abd Ghani, R., Jolánkai, M. and Kende, Z., 2023. Combination Effect of Temperature and Salinity Stress on Germination of Different Maize (Zea mays L.) Varieties. *Agriculture*, *13*(10), p.1932. https://doi.org/10.3390/ agriculture13091836.

Conference Presentations

1. **Suhana Omar** - Rosnani Abd Ghani - Noriza Khalid - Marton Jolankai: Evaluation of maize inbred lines and hybrids for agronomic characteristics, yield, and grain quality (HUALS-Gödöllő).

2. Jolankai, M., Abd Ghani, R., **Omar, S**., Kende, Z., Kassai, M.K. and Tarnawa, A. (2021). Water footprint of protein yield of field crop species based on evapotranspiration patterns. Oral presented in *First National Interdisciplinary Climate Change Conference* (HUPCC), Online conference. 12 - 15 April 2021.

OTHER SCIENTIFIC PUBLICATIONS OF THE AUTHOR

Publications

1. Abd Ghani, Rosnani and **Omar, Suhana** and El Chami, Elias and El Chami, Josepha and Jolánkai, Márton (2021). Agri-environmental impacts on yield formation of soybean crop. *COLUMELLA – Journal of Agricultural and Environmental Sciences*, 8 (2). pp. 5-10. ISSN 2064-7816. https://doi.10.1556/066.2021.00095.

2. Abd Ghani, R., **Omar, S**., Jolánkai, M., Tarnawa, Á., Kende, Z., Khalid, N., Gyuricza, C. and Kassai, M.K. (2023). Soilless Culture Applications for Early Development of Soybean Crop (Glycine max L. Merr). *Agriculture*, *13*(9), p.1713. https://doi.org/10.3390/agriculture13091713.

3. Abd Ghani, R., **Omar, S**., Jolánkai, M., Tarnawa, Á., Khalid, N., Kassai, M.K. and Kende, Z. (2023). Response of Shoot and Root Growth, Yield, and Chemical Composition to Nutrient Concentrations in Soybean Varieties Grown under Soilless and Controlled Environment Conditions. *Agriculture*, *13*(10), p.1925. https://doi.org/10.3390/agriculture 13101925.

4. Abd Ghani, R., Jolankai, M., **Omar, S**., Khalid, N and Tarnawa, Á. (2023). Influence of temperature and variety on seeds germination and seedlings emergence of soybean (*Glycine max* L. Merr) at different germination times. Manuscript submitted for publication in *Acta Agraria Debreceniensis*.

8.1 Conference Presentations

1. Asma Haj Sghaier - Noriza Binti Khaled - **Suhana Binti Omar** - Andras Varga - Zoltán Kende: Methodological approaches to the germination of sunflower and oilseed rape in vitro (HUALS-Gödöllő).

2. Rosnani Binti Abd Ghani - Zoltan Kende - Akos Tarnawa - **Suhana Binti Omar -** Maria Katalin Kassai - Marton Jolankai - Noriza Binti Khalid: Nitrogen nutrition and weed management effects on yield and chemical composition of soybean (*Glycine max L.* Merr) (HUALS-Gödöllő).

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