

Inheritance of Drought Tolerance During Germination and Early Growth in a Multiparental Population of Common Bean (*Phaseolus vulgaris* L.)

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ABSTRACT

Objective: (1) Estimate the genetic variables related to drought tolerance during germination of F₃ from a MAGIC common bean population, and (2) Classify the F₃ as tolerant or susceptible to drought at an early stage.

Design/methodology/approach: Seeds from 200 F₃ of a MAGIC common bean population (designed as L-1, L-2, L-3... L-200) and their eight parents (R-bufa-80, R-bufa-60, T-negro, T-amarillo, PS-AZH-15-1, P-saltito, USPT-WM-1 and Salinas) were used. A bioassay was established in the Plant Biophysics and Physiology Laboratory of the Colegio de Postgraduados, Montecillo, Mexico in July 2023. Seeds were germinated in Petri dishes at 27 °C in a growth chamber. The experimental design was a simple lattice with two replications. The evaluated treatment consisted of germination in a PEG-6000 solution at -0.49 MPa for 72 h. The parents R-bufa-80, R-bufa-60, T-negro and T-amarillo were used as tolerant controls. Germination was quantified 24, 48 and 72 h after the establishment of the bioassay.

Results: At 24 h, the germination percentage exhibited high heritability; however, it did not a quantitative inheritance pattern. For germination at 48 and 72 h, heritability was moderate, and for total length it was low. Nevertheless, these traits displayed a phenotypic distribution consistent with quantitative inheritance. F₃ L-184 appeared to exhibit transgressive segregation for germination at 24 h and for total length at 72 h. The evaluation of the complete multiparental population allowed the selection of F₃ with the best and worst response to water deficit, based on their germination and early growth under PEG-6000 induced osmotic stress.

Limitations on study/implications: Due to seed availability, the F₃ were not evaluated under control (water) conditions; therefore, their response were compared with those of the parents previously characterized for drought tolerance.

Findings/conclusions: Germination percentage and total length exhibited quantitative inheritance, except for germination at 24 h. F₃ L-184, L-198, and L-106 can be classified as drought tolerant, whereas L-69 and

L-182 can be classified as susceptible. This MAGIC population and their parents can be incorporated into breeding programs due to the range of identifiable responses.

Keywords: abiotic stress, heritability, MAGIC, *Phaseolus vulgaris* L., *Phaseolus acutifolius* A. Gray, osmotic potential.

INTRODUCTION

The common bean (*Phaseolus vulgaris* L.) is the main species of the Fabaceae family used for human consumption worldwide, contributing up to 30% of the total daily protein intake in developing countries (Labastida *et al.*, 2023). It is also a source of slow-digesting carbohydrates, dietary fiber, vitamins, and minerals (FAO, 2018). The bean plant is susceptible to drought, which has adverse effects at all developmental stages, especially during the reproductive phase (Ashraf and Iram, 2005). More than 60% of the world's bean production is affected by water scarcity (Domínguez *et al.*, 2014), which is likely the reason why the average yield remains below 900 kg ha⁻¹ (Moliehi *et al.*, 2017).

In Mexico, most bean production occurs under rainfed conditions, in regions with limited water availability, high temperatures, and poor soils with low moisture retention capacity (Acosta-Gallegos *et al.*, 2021). The semi-arid Mexican Highlands stand out as the main bean production area due to the large cultivated surface and are characterized by low and irregular rainfall (Borja-Bravo *et al.*, 2018). For this reason, yield losses of 80 to 100% are estimated (Beebe *et al.*, 2013). The severity and frequency of these conditions are expected to increase due to climate change (Beebe, 2012), which will have adverse consequences for food security (Llano *et al.*, 2012).

Among the various types of abiotic stress, drought is probably the most severe for crops due to the losses it causes (Sagar *et al.*, 2020). Drought occurs when there is a shortage of water because of a prolonged period of precipitation below the average level in a particular place and over a specific period. Agricultural drought occurs when the water available in the soil is insufficient to allow the proper development of a crop at any of its growth stages (Marcos, 2001). Counteracting its impact and understanding the mechanisms of tolerance in plants remain key challenges for agricultural research and plant breeding (Mujtaba *et al.*, 2016).

In rainfed regions, crops face water deficit from the early growth stages (Arce-Romero *et al.*, 2020). The processes involved in adaptation during germination and vegetative development are key to achieving efficient crop establishment (Batool *et al.*, 2022). Therefore, in the search for drought tolerance, the potential of seeds to germinate under limited water conditions must be considered (Aguilar *et al.*, 2019). Due to current climate change, it is necessary to develop varieties with rapid germination, tolerance to drought and high temperatures, and a short growth cycle. In this context, plant breeding is the most economical and sustainable strategy to stabilize and increase production under unfavorable conditions (Rosales-Serna *et al.*, 2000). The development and use of drought-tolerant genotypes and those capable of minimizing yield reduction will contribute to improving productivity (Darkwa *et al.*, 2016).

The development of tolerant varieties first requires the identification of tolerance sources. In beans, some *Phaseolus vulgaris* and *P. acutifolius* genotypes have been reported as drought-tolerant and can therefore be used for the improvement of common bean (Jiménez-Galindo *et al.*, 2018; Cilia-García *et al.*, 2025). In addition, it is necessary to understand the inheritance of traits related to tolerance, as this will allow the design of the most appropriate selection program for their improvement (Ayala-Ruiz *et al.*, 2023; Cilia-García *et al.*, 2025). Based on the above, the study of inheritance and the mechanisms that confer drought tolerance in common bean becomes highly relevant.

In the search for alternatives, multiparental populations have been developed in recent years with the aim of improving the mapping of quantitative trait loci (QTL) (Diaz *et al.*, 2020). However, their use has expanded as a source of germplasm for the improvement of some crops (Scott *et al.*, 2020) and to better understand the genetic basis of phenotypic responses to abiotic stress (Diaz *et al.*, 2020).

One type of these are the Multiparent Advanced Generation Intercross (MAGIC) populations. For their development, multiple parental genotypes are selected based on their genotypic and phenotypic diversity (such as tolerance to drought, high temperature, and major diseases or pests) (Diouf and Pascual, 2021). Subsequently, to achieve recombination, four, eight, or sixteen parents are chosen and crossed following a single or multiple funnel scheme. All schemes are balanced so that the expected contribution of each parental genotype to the derived lines is equal (Ladejobi *et al.*, 2016). Generally, the eight-parent single funnel scheme is used. Finally, the offspring are self-pollinated for several generations (Scott *et al.*, 2020). These recombinations generate greater allelic and phenotypic diversity compared to traditional biparental populations (Kover *et al.*, 2009). The new allele combinations can reveal transgressive phenotypes that are useful for plant breeding (Diouf and Pascual, 2021).

Despite previous and ongoing efforts, obtaining tolerant germplasm has been challenging due to the lack of reliable selection criteria. Plant breeders have evaluated tolerance through yield stability in field trials under irrigated and drought conditions (Jiménez-Galindo and Acosta-Gallegos, 2013), since yield reflects the cumulative effect of the environment on the genotype. However, this approach does not explain the plant's capacity to tolerate water deficit at each developmental stage (Beebe *et al.*, 2013). In seeds, an alternative system to evaluate genotypes with potential drought tolerance is the use of polyethylene glycol (PEG) in the laboratory. PEG-6000 is a high-molecular-weight compound that simulates drought by lowering the water or osmotic potential of the medium (Batool *et al.*, 2022), thereby reducing water availability for seed germination and seedling growth (García *et al.*, 2015). The level of stress generated is proportional to the polymer concentration (Moliehi *et al.*, 2017). A high and positive correlation has been reported between germination in osmotic solutions and field emergence, suggesting a predictive value for these tests (Mohammadkhani and Heidari, 2008). Genotypes that were tolerant in the laboratory maintained this tolerance in the field, which was reflected in seed production (García *et al.*, 2015).

Based on the above, the genetic variables related to drought tolerance during germination of F_3 from a MAGIC common bean population were estimated, and the F_3

were classified as tolerant or susceptible to drought at an early stage. This information can be used in plant breeding programs and studies, as well as in rainfed production systems in Mexico.

MATERIALS AND METHODS

Plant material

The study included seeds from 200 F₃ of a MAGIC common bean population (designated as L-1, L-2, L-3... up to L-200), harvested in 2022 in Santiago Ixcuintla, Nayarit, as well as their eight parents (R-bufa-80, R-bufa-60, T-negro, T-amarillo, PS-AZH-15-1, P-salttillo, USPT-WM-1, and Salinas). The parental genotypes and F₃ belong to the *Phaseolus* spp. germplasm bank of the National Institute of Forestry, Agricultural and Livestock Research (INIFAP). The seeds of the 200 F₃ were derived from the development of a multiparental population with eight parents selected for desirable traits, including genetic diversity (two of them belong to *Phaseolus acutifolius* A. Gray); high yield and seed quality (slow seed coat darkening and shorter cooking time); pest resistance; disease resistance; and stable and consistent drought tolerance (under laboratory and field conditions) (Table 1).

Four of the parents are drought-tolerant, two are susceptible, and two have unknown tolerance in the Mexican Highlands (Table 2). Through pairwise crosses of the parents via intraspecific introgression, four simple two-way crosses were obtained among *P. vulgaris* cultivars (R-bufa-80×USPT-WM-1; PS-AZH-15-1×P-salttillo; R-bufa-60×Salinas) and *P. acutifolius* (T-negro×T-amarillo). Using seeds from the simple crosses, two double four-way crosses were made (R-bufa-80×USPT-WM-1×T-negro×T-amarillo and PS-AZH-15-1×P-salttillo×R-bufa-60×Salinas), which were then crossed to obtain F₁ seeds from an eight-way cross (R-bufa-80×USPT-WM-1×T-negro×T-amarillo×PS-AZH-15-1×P-salttillo×R-bufa-60×Salinas), as described by Butrón *et al.* (2003) (Figure 1). The F₁ and F₂ generations, which already contained a combination of genes from all eight parents, were self-pollinated using the single-seed descendant method, resulting in the final set of 200 F₃.

Table 1. Key traits of the parents of the MAGIC population (Jiménez-Galindo, 2022).

Genotypes	Drought tolerance	Resistance to <i>Brachystola magna</i>	Resistance to <i>Acanthoscelides obtectus</i>	Resistance to <i>Zabrotes subfasciatus</i>	Slow darkening of the seed coat	Shorter cooking time	High grain yield
R-bufa-80	X						X
USPT-WM-1					X		X
T-negro	X		X				
T-amarillo	X	X	X				
PS-AZH-15-1				X	X	X	
P-salttillo					X	X	X
R-bufa-60	X						X
Salinas					X		X

Table 2. Parents of the MAGIC population classified by their level of drought tolerance.

Genotype	Species	Growth habit*	Drought tolerance level
R-bufa-80	<i>P. vulgaris</i>	II	Tolerant (Jiménez-Galindo and Acosta-Gallegos, 2013)
USPT-WM-1	<i>P. vulgaris</i>	III	Unknown
T-negro	<i>P. acutifolius</i>	III	Tolerant (Jiménez-Galindo <i>et al.</i> , 2018)
T-amarillo	<i>P. acutifolius</i>	III	Middle tolerant (Jiménez-Galindo <i>et al.</i> , 2018)
PS-AZH-15-1	<i>P. vulgaris</i>	II	Susceptible (Jiménez-Galindo <i>et al.</i> , 2018)
P-saltillo	<i>P. vulgaris</i>	III	Susceptible (Jiménez-Galindo <i>et al.</i> , 2018)
R-bufa-60	<i>P. vulgaris</i>	II	Tolerant (Jiménez-Galindo, 2022)
Salinas	<i>P. vulgaris</i>	III	Unknown

*II: Indeterminate growth habit, with a vegetative terminal bud on the main stem and branches; the production of nodes and leaves occurs after flowering. Both the main stem and branches are strong and erect. III: Indeterminate growth habit. Branches are relatively weak and open, semi-prostrate, or intertwined. Pod load is largely concentrated in the basal part of the plant. Maximum yield is achieved under monoculture conditions (Singh, 1981).

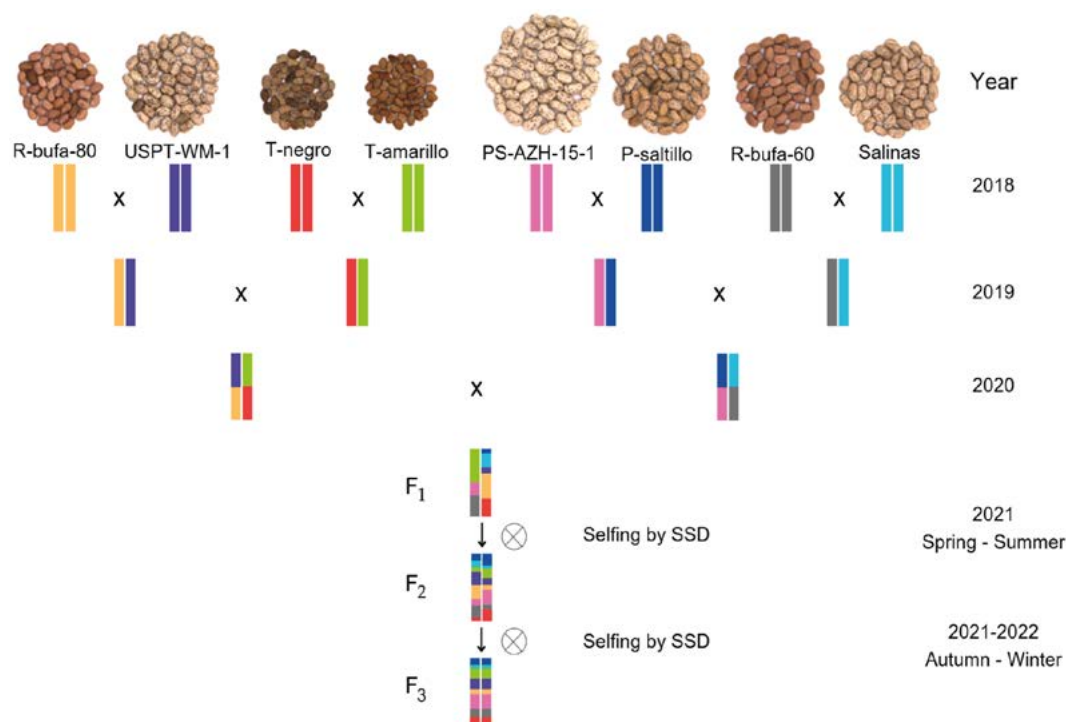


Figure 1. Schematic of the development of the MAGIC common bean population. SSD: Single Seed Descendant.

Experimental conditions, experimental design, and evaluated variables

A bioassay was established in the Environmental Plant Biophysics and Physiology Laboratory of the Colegio de Postgraduados, Montecillo, Mexico, during July 2023. Germination and early hypocotyl+radicle growth of the 200 F₃ and the eight parents were evaluated in 10 cm-diameter Petri dishes with a layer of sterilized filter paper and a 17% (w/v) PEG-6000 solution with an osmotic potential of -0.49 MPa (Michel and Kaufmann,

1973) in order to simulate water deficit conditions. This PEG-6000 concentration was chosen based on data obtained in previous germination trials of common bean and Tepary bean (Jiménez-Galindo *et al.*, 2018). The experimental design was a simple lattice with two replications. The experimental unit was a Petri dish with four seeds of each F₃ or parent per replication. The treatment consisted of adding 8 mL of PEG-6000 solution to each experimental unit. The parents R-bufa-80, R-bufa-60, T-negro, and T-amarillo were used as tolerant controls (Jiménez-Galindo *et al.*, 2018). The experimental units were kept in a controlled environment chamber, in darkness, at 27 °C for 72 h. Germination was visually evaluated and quantified 24, 48, and 72 h after the establishment of the test. A seed was considered germinated when the radicle was at least 2 mm long. The length of the hypocotyl plus the radicle (total length) was measured using photographs taken with a semi-automatic imaging platform system (Scanalyzer PL LemnaTec GmbH, Aachen, Germany) after 72 h of establishment; the ImageTool for Windows software, Version 3.0, was used for this purpose.

Statistical analysis

The data from the experimental plots of the F₃ were evaluated for normality using the PROC UNIVARIATE procedure of SAS (SAS Institute, 2016). The mixed model procedure (PROC MIXED) of SAS was used to obtain the best linear unbiased predictor (BLUP) of each mean phenotypic value per line. All factors —replications, blocks within replications, and F₃— were considered random effects. The genotypic (*rg*) and phenotypic (*rp*) correlations among germination at 24, 48, and 72 h, and total length were calculated according to Holland (2006). All the above analyses were performed using SAS software, version 9.4.

Heritability

Heritabilities (h^2) for each trait were estimated on a family mean basis, as described by Holland *et al.* (2002).

RESULTS AND DISCUSSION

Means, ranges, and heritabilities of the MAGIC population

The MAGIC bean population showed wide variability: the germination percentage of the F₃ ranged from 0 to 87.5% at 24 h and from 0 to 100% at 48 and 72 h. The total length (hypocotyl+radicle) ranged from 0.0 to 35.5 mm. Rapid germination during the first 24 h exhibited high heritability ($h^2=0.54$), while at 48 and 72 h heritability was moderate ($h^2=0.37$ and $h^2=0.27$, respectively). In contrast, total length showed low heritability ($h^2=0.23$) (Table 3). In tomato (*Lycopersicon* sp.) under water deficit, a heritability of 0.47 for rapid germination has been reported (Foolad *et al.*, 2003). These values indicate the proportion of total phenotypic variance attributable to genetic differences among individuals (the remainder being due to the environment); that is, “the extent to which a phenotype is genetically determined” (Schmidt *et al.*, 2019). Heritability is a property of each trait and population, and its value allows the selection of the most appropriate breeding program for its improvement (Ayala-Ruiz *et al.*, 2023; Cilia-García *et al.*, 2025).

In general, high heritability of a trait indicates that variations are mainly genetic and less influenced by the environment; this ensures the transmission of favorable genes for such traits in simple phenotypic selection programs (Melendres-Martínez *et al.*, 2018). Phenotypic selection for traits with low heritability would be less effective due to the greater influence of environmental factors (Cilia-García *et al.*, 2025).

The differences in all variables among the parents were significant, which justifies the crosses to continue this study. T-amarillo and T-negro stood out as the best parents, showing 25% germination at 24 h. However, at 48 and 72 h, T-amarillo, T-negro, R-bufa-80, R-bufa-60, and USPT-WM-1 showed the highest germination percentages and total length, and the differences among these parents were not significant. In contrast, the least outstanding parents were PS-AZH-15-1, Salinas, and P-saltillo, which showed the lowest germination percentages and total lengths (Table 3). The response of the parents to water deficit corresponded with the reported level of drought tolerance (Jiménez-Galindo and Acosta Gallegos, 2013; Jiménez-Galindo *et al.*, 2018; Jiménez-Galindo, 2022), indicating that germination and early growth in the F_3 reflect their tolerance to water deficit.

Genotypic and phenotypic correlations

Total length showed a positive and significant rg with germination at 24 h (0.62) and 72 h (0.81), and germination at 72 h was significantly correlated with germination at 48 h (0.90). The rp between total length and germination at 24 h (0.41) and 72 h (0.66),

Table 3. Means and ranges of germination (-0.49 MPa) and h^2 of the MAGIC common bean population and the eight parents for drought tolerance.

	Germination (%)			Total length [#] (mm)
	24 h	48 h	72 h	
MAGIC population (F_3)				
Mean	3.9	54.5	75.1	9.5
Range	0.0-87.5	0.0-100.0	0.0-100.0	0.0-35.5
LSD	25.3	58.8	49.8	10.1
h^2	0.54	0.37	0.27	0.23
Parents				
T-amarillo	25.0 a [†]	75.0 a	75.0 ab	19.1 a
T-negro	25.0 a	75.0 a	87.5 ab	14.6 a
R-bufa-60	0.0 b	87.5 a	100.0 a	14.3 a
R-bufa-80	0.0 b	87.5 a	100.0 a	16.4 a
USPT-WM-1	12.5 ab	75.0 a	87.5 ab	16.0 a
PS-AZH-15-1	0.0 b	12.5 b	25.0 c	1.7 b
Salinas	0.0 b	12.5 b	25.0 c	1.7 b
P-saltillo	0.0 b	0.0 b	50.0 bc	3.1 b
LSD	14.7	44.6	44.6	8.1
R^2	0.87	0.88	0.85	0.90

LSD: Least significant difference. h^2 : heritability. [†]Means followed by the same letter within each column are not statistically different ($p \leq 0.05$). [#]Hypocotyl+radicle.

and between germination at 72 h and germination at 48 h (0.72) were also positive and significant (Table 4). A positive and significant correlation between two traits of interest in the same individual indicates that both can be improved simultaneously. High rg means that selection to improve one trait will allow a correlated response in the other; this is used to guide breeding programs because it is the only correlation of heritable nature (Lagos *et al.*, 2013). Therefore, the strong rg between germination at 72 h and total length (0.81) indicates that seeds with higher germination at 72 h under water-limited conditions will also develop greater total length; that is, in this case, due to drought tolerance, early seed germination coincides with greater root growth over a given period.

The rp measures the association between the two traits evaluated in this study and includes both genetic and environmental effects. Generally, rg values are higher than rp , with some exceptions among trait combinations, which indicates that the association between them is mainly due to genetic rather than environmental effects. This effect could facilitate the process of indirect selection for a trait X through another trait Y that is easier to measure, identify, or has higher heritability, thereby achieving genetic progress (Lagos *et al.*, 2013). Using indirect screening of the F₃ from the MAGIC population based on germination percentage and hypocotyl+radicle length aims to select F₃ that are drought tolerant.

Phenotypic distribution

The frequency distribution of germination percentage at 24 h differed from that at 48 h and 72 h (Figure 2A, Figure 2B, and Figure 2C). The distribution of germination at 48 h and total length (Figure 2D) showed a normal distribution with continuous variation. Therefore, these traits are considered to be quantitatively inherited, and their expression depends on polygenes. The frequency distribution of germination percentage at 72 h was skewed to the right; however, based on the number of frequency intervals (bars), the trait is also likely quantitatively inherited (Figure 2C), but further study is needed. Quantitative traits are influenced by the environment and are usually classified as having low or medium heritability (Table 3). Germination percentage at 24 h did not show a normal distribution (Figure 2A); therefore, this trait also requires further study, as it exhibited the highest heritability (0.54). The distribution of this trait was skewed to the left because few F₃ germinated prematurely, even before the parents with the fastest germination, T-negro and T-amarillo.

Table 4. Genotypic (rg , upper diagonal) and phenotypic (rp , lower diagonal) correlation coefficients among drought-tolerance traits of the MAGIC population.

Variable	Germination at 24 h (%)	Germination at 48 h (%)	Germination at 72 h (%)	Total length [#] (mm)
Germination at 24 h (%)		--	0.10	0.62*
Germination at 48h (%)	--		0.90*	--
Germination at 72 h (%)	0.10	0.72*		0.81*
Total length (mm)	0.41*	--	0.66*	

*Correlation coefficients exceeding twice their standard error. #Hypocotyl+radicle.

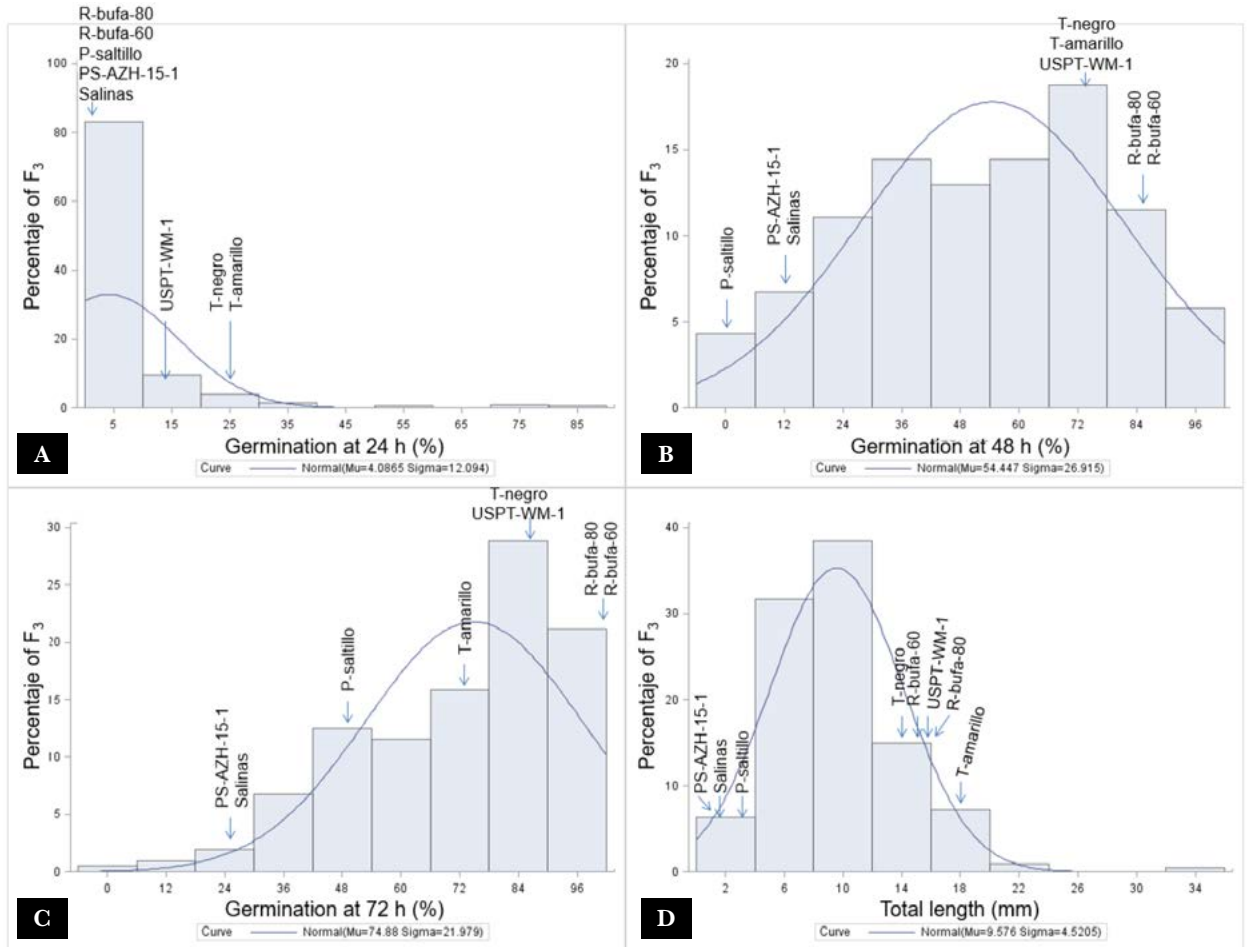


Figure 2. Frequency distribution of (A) germination percentage at 24 h, (B) 48 h, and (C) 72 h, and (D) total length (hypocotyl + radicle) at 72 h of 200 F_3 MAGIC common bean and their eight parents. Arrows indicate the position of the parents in each evaluation.

The distribution showed that at least one F_3 (L-184) had a high germination percentage (around 85%); moreover, practically all seeds germinated within 24 h. This behavior is relevant because, due to the variability in the MAGIC population resulting from the combination of eight parents, complementary genes or mechanisms likely exist that favor the expression of transgressive inheritance or segregation related to rapid germination and drought tolerance in L-184. In 2023 and 2024, severe bean germination problems were observed in the Mexican Highlands, attributed to increased evapotranspiration caused by rising temperatures and the effects of climate change. The rapid germination and drought tolerance of L-184 could be utilized in current plant breeding programs, given the approximate 4 °C increase in temperatures and nearly double the evapotranspiration over the last decade in the Mexican Highlands. For this reason, new bean lines with rapid germination, adapted to low-water-availability conditions and drought tolerance throughout the crop cycle, are needed.

In a MAGIC common bean population evaluated under drought conditions up to yield, transgressive segregation was observed in most of the traits evaluated (Diaz *et al.*,

2020). Similarly, in a MAGIC soybean population, transgressive segregation was observed in the selected traits, along with a higher frequency of recombination across the genome (Hashemi *et al.*, 2022). The results obtained in this study show variability in the traits evaluated, which allowed the selection of F₃ with high drought tolerance.

Comparison of means of the eight parents and the F₃ with the best and worst performance for drought tolerance

The evaluation of the complete multiparental population allowed the selection of a subgroup composed of contrasting F₃; for example, the three F₃ (L-184, L-198, and L-106) with the best response to water deficit and the two F₃ (L-68 and L-182) with the worst response. The three outstanding F₃ generally showed rapid germination, and at 72 h, their germination percentages were not significantly different from the parents T-amarillo, R-bufa-80, T-negro and R-bufa-60, which had previously been identified as drought-tolerant (Jiménez-Galindo and Acosta-Gallegos, 2013; Jiménez-Galindo *et al.*, 2018; Jiménez-Galindo, 2022). F₃ L-184 stood out for its highest germination percentage across the three evaluation periods (87.5%, 100%, and 100% at 24, 48, and 72 h, respectively), but specifically at 24 h, it was superior and significantly different from the best parents, suggesting transgressive inheritance of this F₃ for germination at 24 h. The worst response to water deficit was manifested as a low or null germination percentage, which was not significantly different from the parents P-saltillo and PS-AZH-15-1, identified as drought-susceptible (Jiménez-Galindo *et al.*, 2018). Based on the values obtained for germination percentage, the F₃ with the best response were classified as drought-tolerant, while those with the worst response were classified as susceptible (Figure 3).

F₃ L-184 also stood out for total length (35.5 mm) at 72 h, significantly surpassing the tolerant parents, which also appears to represent transgressive inheritance for this trait. L-198 and L-106 matched the tolerant parents for this trait, while L-68 and L-182 matched the susceptible parents (Figures 4 and 5); therefore, the absolute values of total length also support the classification of F₃ as tolerant or susceptible. Water restriction by polyethylene glycol reduces germination percentage, radicle length, hypocotyl, epicotyl,

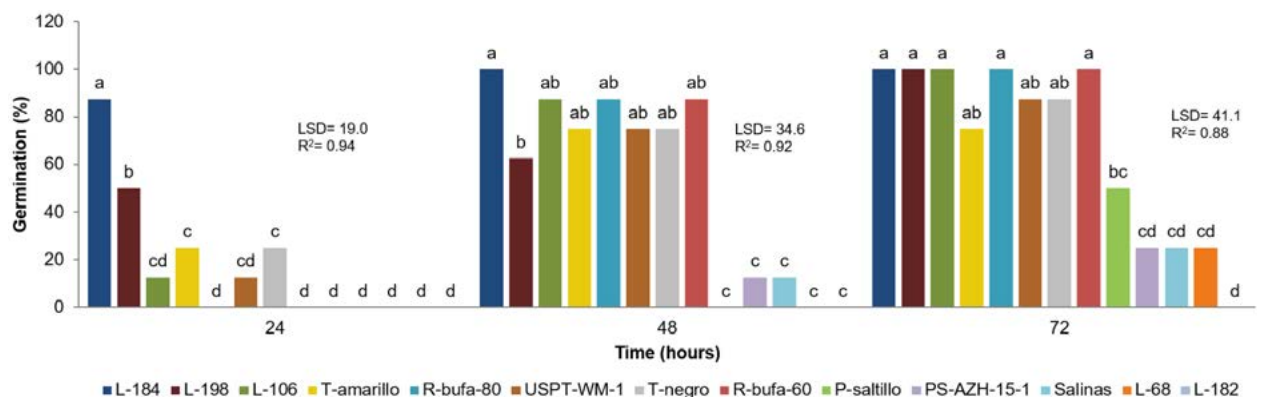


Figure 3. Germination percentage of the most contrasting F₃ MAGIC common bean and their eight parents at 24, 48, and 72 h under an osmotic potential of -0.49 MPa. Values represent the mean of eight determinations. Bars with the same letters are not statistically different ($p < 0.05$). LSD: Least significant difference.

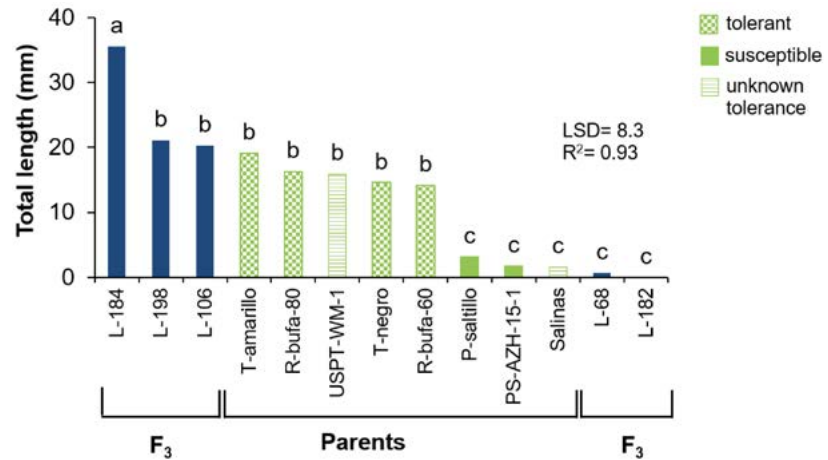


Figure 4. Total length (hypocotyl+radicle) of the most contrasting F₃ MAGIC common bean and the eight parents. Values represent the mean of eight determinations. Bars with the same letters are not statistically different ($p < 0.05$). LSD: Least significant difference.

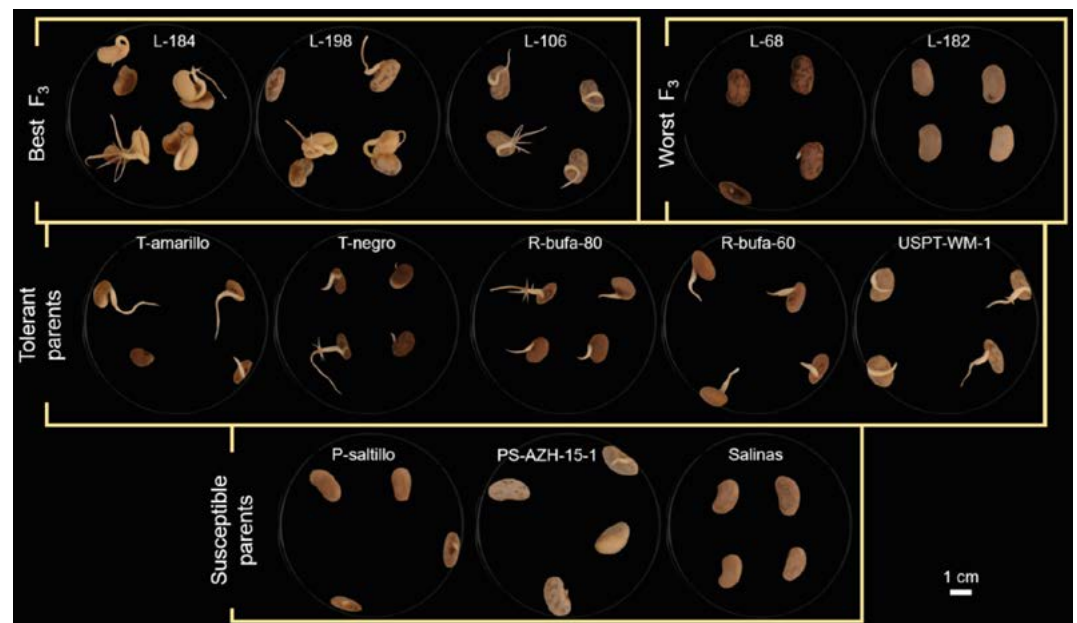


Figure 5. Effect of an osmotic potential of -0.49 MPa, induced by PEG-6000, on total length in the F₃ MAGIC common bean with the best and worst performance for drought tolerance and their eight parents, 72 h after treatment.

and the formation of foliar structures (Torres-Hernández *et al.*, 2022). This effect is directly proportional to the PEG-6000 concentration, as it decreases the osmotic potential of the external medium, and significant differences between F₃ or varieties have highlighted their tolerance potential (Sagar *et al.*, 2020). A high and positive correlation has been documented between germination rate in osmotic solutions and seedling emergence rate in the field, emphasizing the predictive value of PEG-6000 assays under laboratory conditions (Mohammadkhani and Heidari, 2008). Therefore, it is expected that F₃ tolerant in the

laboratory will maintain this response in the field, reflected in seed production (García *et al.*, 2015).

CONCLUSIONS

Germination percentage at 24 h showed high heritability; however, due to the left-skewed distribution, the inheritance of rapid germination is not quantitative. For germination percentage at 48 and 72 h, heritability was moderate, and for total length, it was low; nevertheless, these results are consistent with a phenotypic distribution characteristic of quantitative inheritance. L-184 stood out for germination at 24 h and total length at 72 h, even surpassing the tolerant parents, suggesting some type of transgressive segregation. The evaluation of the complete multiparental population allowed the selection of F₃ with the best and worst response to water deficit, based on germination and early hypocotyl+radicle growth in the presence of PEG-6000. This justifies indirect screening based on these traits, as early seed germination correlates with greater root growth over a given period. L-184, L-198, and L-106 can be classified as drought-tolerant, whereas L-69 and L-182 can be classified as susceptible. The F₃ MAGIC bean and their parents can be incorporated into breeding programs due to the range of identifiable responses.

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