Efecto del estrés hídrico sobre la germinación y el vigor de las plántulas de maíz, mostrando respuestas contrastantes entre materiales: mejorado, nativo y silvestre

Water stress effects on germination and seedling vigor in maize, showing contrasting responses among improved, native, and wild materials

Efeito do estresse hídrico na germinação e no vigor das mudas de milho, mostrando respostas contrastantes entre materiais melhorados, nativos e silvestres

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RESUMEN
Este estudio evaluó el efecto del estrés hídrico inducido sobre la germinación de semillas y el vigor de plántulas en tres materiales de maíz: un híbrido mejorado, una raza nativa (Tabloncillo) y *Zea perennis*. Las semillas se sometieron a tres niveles de potencial hídrico: 0 (control), −0.5 y −1.0 MPa. En general, los porcentajes finales de germinación se mantuvieron elevados en todos los materiales; sin embargo, el estrés hídrico provocó un retraso significativo en el proceso germinativo. El análisis de varianza indicó efectos significativos del potencial hídrico, del material vegetal y de su interacción sobre el tiempo medio de germinación (TMG), se observaron respuestas contrastantes al incremento del déficit hídrico. El aumento del TMG fue más pronunciado en el híbrido bajo −1.0 MPa, mientras que *Zea perennis* mostró valores de TMG más estables a lo largo del gradiente de estrés. El vigor de las plántulas disminuyó notablemente con la reducción del potencial hídrico: bajo condiciones de control, el 29.4% de las plántulas se clasificaron como de alto vigor, proporción que descendió a 10.3% y 7.2% bajo −0.5 y −1.0 MPa, respectivamente. La prueba exacta de Fisher confirmó diferencias significativas en la proporción de plántulas de alto vigor entre tratamientos. En síntesis, el estrés hídrico inhibe parcialmente la germinación principalmente por el aumento del TMG y la reducción del vigor, más que por una pérdida de viabilidad de las semillas.

Palabras clave: osmótico, velocidad de germinación, tolerancia a la sequía, variación genética

RESUMO
Este estudo avaliou o efeito do estresse hídrico induzido sobre a germinação de sementes e o vigor de plântulas de três materiais de milho: um híbrido melhorado, uma raça nativa (Tabloncillo) e *Zea perennis*. As sementes foram submetidas a três níveis de potencial hídrico: 0 (controle), −0,5 e −1,0 MPa. De modo geral, as porcentagens finais de germinação permaneceram elevadas em todos os materiais; entretanto, o estresse hídrico causou um atraso significativo no processo germinativo. A análise de variância indicou efeitos significativos do potencial hídrico, do material vegetal e de sua interação sobre o tempo médio de germinação (TMG), evidenciando respostas contrastantes ao aumento do déficit hídrico. O aumento do TMG foi mais acentuado no híbrido sob −1,0 MPa, enquanto *Zea perennis* apresentou valores mais estáveis ao longo do gradiente de estresse. O vigor das plântulas diminuiu de forma expressiva com a redução do potencial hídrico: sob condições de controle, 29,4% das plântulas foram classificadas como de alto vigor, proporção que se reduziu para 10,3% e 7,2% sob −0,5 e −1,0 MPa, respectivamente. O teste exato de Fisher confirmou diferenças significativas na proporção de plântulas vigorosas entre os tratamentos. Em síntese, o estresse hídrico inibe parcialmente a germinação, principalmente pelo aumento do TMG e pela redução do vigor, e não por perda de viabilidade.

Palavras-chave: estresse osmótico, velocidade de germinação, tolerância à seca, variação genética

ABSTRACT
This study evaluated the effect of induced water stress on seed germination and seedling vigor in three maize materials: an improved hybrid, a native landrace (Tabloncillo), and *Zea perennis*. Seeds were subjected to three water potential levels: 0 (control), −0.5 and −1.0 MPa. Overall, final germination percentages remained high across all materials; however, water stress caused a significant delay in the germination process. Analysis of variance indicated significant effects of water potential, plant material, and their interaction on mean germination time (MGT), revealing contrasting responses to increasing water deficit. The increase in MGT was more pronounced in the hybrid under −1.0 MPa, whereas *Zea perennis* showed more stable MGT values across the stress gradient. Seedling vigor decreased markedly with decreasing water potential: under control conditions, 29.4% of seedlings were classified as high vigor, a proportion that declined to 10.3% and 7.2% under −0.5 and −1.0 MPa, respectively. The Fisher exact test confirmed significant

differences in the proportion of high-vigor seedlings among treatments. In summary, water stress partially inhibits germination primarily through increased MGT and reduced vigor, rather than through loss of seed viability.

Keywords: osmotic stress, germination rate, drought tolerance, genetic variation

1 INTRODUCCIÓN

Water availability is one of the main environmental factors regulating seed germination and seedling establishment, particularly in rainfed agroecosystems where soil moisture is highly variable. Under current climate change scenarios, the frequency and intensity of drought events are increasing, amplifying uncertainty during crop development and threatening agricultural productivity (Farooq et al., 2009; IPCC, 2021). Consequently, seed germination and establishment have become critical bottlenecks that determine plant survival and performance under water limited conditions (Cairns et al., 2013).

Germination success is not determined solely by the final proportion of germinated seeds, but also by the dynamics of the process. Traits such as germination speed, mean germination time (MGT), and seedling vigor strongly influence establishment success, competitive ability, and tolerance to environmental stress (Ranal and Santana, 2006; Finch-Savage and Bassel, 2016). Under suboptimal moisture conditions, delayed germination and reduced vigor can have lasting consequences, even when final germination percentages remain relatively high.

Water stress typically restricts water uptake during imbibition and delays metabolic activation, thereby slowing germination and reducing seedling vigor. Reduced water potential limits membrane rehydration, enzymatic activity, reserve mobilization, and cell elongation, which are essential for radicle protrusion and growth (Bradford, 1990; Bewley et al., 2013). Importantly, several studies have shown that water stress may delay germination dynamics without necessarily causing irreversible loss of seed viability, resulting in a physiological decoupling between germination timing and final germination percentage (Michel and Kaufmann, 1973).

To experimentally evaluate the effects of reduced water availability, polyethylene glycol of high molecular weight (PEG 8000) has been widely used as an osmotic agent, as it lowers the water potential of the medium without penetrating plant cells or causing direct toxic effects (Michel, 1983). This approach allows the simulation of drought conditions in a controlled and reproducible manner and has proven effective for assessing germination and growth responses in maize. Induced water stress has been associated with reductions in germination rate, delays in germination timing, and decreased seedling growth, making it a useful tool for identifying materials with greater

tolerance to water limitation during developmental stages (Bewley et al., 2013; Laynez-Garsaball et al., 2014).

Maize (*Zea mays* L.) encompasses a wide range of genetic materials, including improved hybrids, native landraces, and wild relatives, each shaped by distinct selective pressures. Improved maize materials have been predominantly selected for rapid and uniform germination and high vigor under managed agricultural conditions, whereas native and wild materials have evolved or been maintained under heterogeneous and often stressful environments, where tolerance to environmental variability may be favored over maximum productivity (Sánchez-González et al., 2000; Mercer et al., 2008). As a result, contrasting germination and establishment responses to water stress are expected among maize materials with different degrees of domestication (Sánchez González et al., 2000; Mercer et al., 2008; Matesanz and Milla, 2018).

Wild and native maize relatives may exhibit conservative germination strategies characterized by slower but more stable germination under adverse conditions. Such strategies are considered adaptive in unpredictable environments, as they reduce the risk of recruitment failure and enhance population persistence (Baskin and Baskin, 2014; Donohue et al., 2010). Under increasing climatic variability, these conservative responses may represent an ecological advantage over rapid but stress-sensitive germination strategies (Simons, 2011; Gremer and Venable, 2014).

Despite extensive research on the effects of water stress on maize germination, most studies have focused on single response variables or exclusively on cultivated materials. Previous work has commonly evaluated final germination percentage or germination timing under osmotic stress (Bradford, 1990; Laynez-Garsaball et al., 2014), or has addressed genetic differentiation and local adaptation without explicitly considering germination processes (Sánchez-González et al., 2000; Mercer et al., 2008). Previous studies in maize have also examined seed germination responses under different water availability conditions and stress conditioning, demonstrating effects on germination potential and drought tolerance (Pérez-León et al., 2021). Consequently, few studies have simultaneously compared germination percentage, germination dynamics, mean germination time, and seedling vigor across improved, native, and wild maize materials under a common gradient of water availability. Recent studies have shown that water stress significantly affects maize germination and early seedling performance, with marked genotypic variation when multiple germination and vigor traits are evaluated (Du et al., 2025; Ruiz-Ramírez and Hernández-Martínez, 2024; Durán-Sequeda et al., 2026). Therefore, the objective of this study was to assess the effects of water stress on germination and seedling vigor in three maize materials representing different levels of domestication, with the aim of identifying ecophysiological traits associated with tolerance to limited water availability.

2 MATERIALS AND METHODS

2.1 MAIZE MATERIALS

Seeds from three maize materials were obtained from the Seed Analysis Laboratory, Centro Universitario de Ciencias Biológicas y Agropecuarias (CUCBA), Universidad de Guadalajara, Mexico, and were used to evaluate germination performance and seedling vigor. Seeds of an improved commercial hybrid maize were included as a commercial reference characterized by high germination capacity and uniform growth. Seeds of *Zea perennis*, a perennial teosinte, were used as a wild reference; in this species, kernels are naturally enclosed by hardened glumes, a structural trait that influences water uptake and germination dynamics. Native maize seeds corresponded to the Tabloncillo race (Harinoso de ocho), a floury endosperm landrace selected based on uniform size and physical integrity, named for the characteristic arrangement of its kernels in eight longitudinal rows and the predominance of soft, floury endosperm. This experimental design allowed direct comparisons of germination percentage, mean germination time, and seedling vigor among the three Zea materials under identical conditions.

2.2 GERMINATION TEST AND EXPERIMENTAL CONDITIONS

Three water potential treatments were evaluated: 0 (control), −0.5, and −1.0 MPa. Water stress during germination was simulated using polyethylene glycol (PEG 8000), following the method described by Michel (1983). The control treatment represented optimal water availability, whereas −0.5 and −1.0 MPa corresponded to moderate and severe water limitation thresholds, respectively. The selection of these water potentials is supported by the hydro time model, in which −0.5 MPa represents a moderate stress level capable of reducing imbibition rate and seed vigor while maintaining metabolic activity (Guan et al., 2009). In contrast, −1.0 MPa approaches the base water potential reported for *Zea mays* as a critical point at which germination of the most sensitive fraction of the seed population is strongly inhibited (Bradford, 1990).

For each seed variety, a total of 300 seeds were used. Each treatment consisted of five replicates of 20 seeds, with each replicate considered an experimental unit. Seeds were placed separately in sterile Petri dishes (6 × 15 mm). A cotton pad was used as a substrate and moistened with 10 mL of the corresponding solution for each treatment. Petri dishes were sealed to prevent evaporation and placed in a single germination chamber (LUZEREN, model SPX250) under a 12 hours photoperiod and a constant temperature of 25 ±1°C. The experiments were conducted under controlled laboratory conditions at the CUCBA, Center for Ecological Research Studies.

Germination was evaluated daily after sowing, and a seed was considered germinated when radicle emergence was >1 mm (Baskin and Baskin, 2014). The experiment was conducted for 14 days, allowing the observation of four consecutive days without germination in each treatment.

2.3 GERMINATION PARAMETERS AND STATISTICAL ANALYSIS

The response variables analyzed were final germination percentage and mean germination time (MGT), used as an indicator of germination speed (Soltani et al., 2015), which was calculated according to Ranal and Santana (2006) using the following equation:

$$MGT = \frac{\sum_{i=1}^{k}(n_i t_i)}{\sum_{i=1}^{k} n_i}$$

Where n_i is the number of germinated seeds in the i^{th} time, k is the last hour of evaluation, and t_i is the time from the beginning of the experiment until the i^{th} observation given in the corresponding experimental unit.

Final germination data were obtained using the GerminaR library. Germination percentages were subjected to an arcsine square root transformation prior to statistical analysis to meet assumptions of normality and homogeneity of variances. Transformed germination percentages and MGT were tested for normality using the Shapiro Wilk test and for homogeneity of variances using Bartlett test (Crawley, 2012). A two-way analysis of variance (ANOVA) was performed to evaluate the effects of maize materials (three levels), water potential (three levels), and their interaction on germination percentage and MGT. When significant effects were detected, differences among treatments were assessed using a Student Newman Keuls multiple comparison test ($\alpha = 0.05$). All statistical analyses and graphical outputs were performed using R software v. 4.1.1 (R Core Team, 2021).

2.4 SEEDLING VIGOR ASSESSMENT AND STATISTICAL ANALYSIS

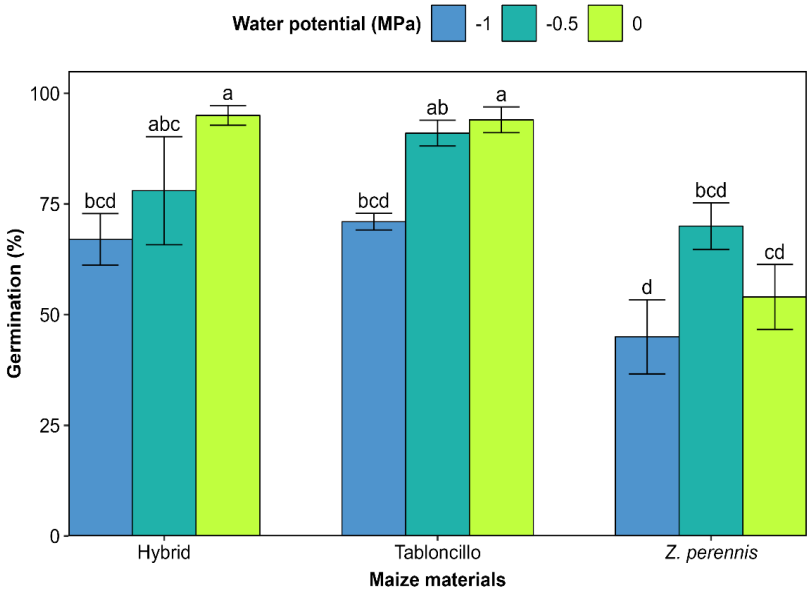
Seedling vigor was evaluated 14 days after the onset of germination for the three maize materials under the same water potential treatments (0, −0.5, and −1.0 MPa). Seedlings were classified according to the morphological criteria established by the International Seed Testing Association (ISTA, 2023). Seedlings exhibiting complete and proportional development of essential structures including a vigorous primary root, presence of seminal roots, intact coleoptile, and fully expanded primary leaves were classified as high vigor. Seedlings showing delayed growth, necrosis, or clear disproportions between the root system and shoot were classified as low vigor.

The number of high and low vigor seedlings was recorded for each treatment and maize materials, and differences in the proportion of seedlings among water potential levels were evaluated using Fisher exact test based on contingency tables ($\alpha = 0.05$). These 14 days evaluation period allowed quantification of the effects of osmotic stress on seedling establishment and vegetative robustness. All statistical analyses and graphical outputs were performed using R software v. 4.1.1 (R Core Team, 2021).

3 RESULTS

The analysis of variance of germination percentages revealed significant main effects of maize materials ($F = 16.41$, $p<0.001$) and water potential ($F = 18.98$, $p<0.001$). The variety × water potential interaction was not significant ($p>0.05$), indicating that although germination capacity differed among maize materials and decreased under induced water stress, the response pattern to water potential was consistent across varieties. (Figure 1).

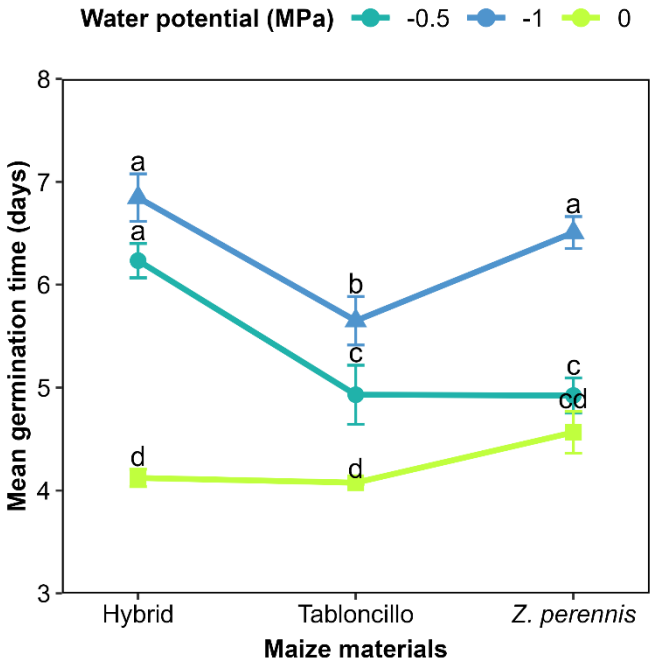
Figure 1. Germination percentage of maize materials under different water potential levels. Bars represent mean values ± standard error. Different letters indicate significant differences among treatments according to the Student Newman Keuls test ($p<0.05$). Source: Authors' own elaboration (2025).



Mean germination time (MGT) was significantly affected by species and water potential, as well as by their interaction (Figure 2). The significant species × water potential interaction ($F = 6.76$, $p = 0.00036$) indicates that the effect of water deficit on MGT was species dependent; therefore, the influence of water potential should be interpreted within each maize variety rather than as an overall main effect. Accordingly, variations in MGT along the water potential gradient

reflect contrasting germination responses among the evaluated maize, highlight species specific strategies under water stress conditions.

Figure 2. Changes in mean germination time (MGT) over time under different water potential treatments in the maize materials evaluated. Bars represent mean values ± standard error. Different letters indicate significant differences among treatments according to the Student Newman Keuls test ($p<0.05$). Source: Authors' own elaboration (2025).



Cumulative germination curves differed markedly among maize varieties and water potential treatments. Under control conditions (0 MPa), the hybrid (Figure 3A) showed the fastest and highest germination accumulation, whereas both water stress treatments (−0.5 and −1.0 MPa) delayed germination onset and reduced accumulation rate. A similar pattern was observed in the Tabloncillo landrace (Figure 3B), although this variety maintained relatively stable cumulative germination under −0.5 MPa compared with −1.0 MPa. In contrast, *Zea perennis* (Figure 3C) exhibited the slowest germination dynamics and the lowest cumulative germination under water stress, particularly at −1.0 MPa. These patterns were consistent with the significant effects of maize variety, water potential, and their interaction on mean germination time (MGT), indicating species specific responses of germination dynamics to increasing drought.

Seedling vigor responded to water potential in all three maize types evaluated, although the magnitude and pattern of the response differed among them (Table 1). In the commercial maize hybrid, non stress conditions showed a significantly higher proportion of high vigor seedlings compared with both moderate and severe water stress, whereas increasing stress intensity from moderate to severe did not result in additional changes in vigor. A similar response pattern was

observed in Tabloncillo, with optimal water availability favoring high vigor seedlings relative to water stress treatments. In contrast, *Zea perennis* exhibited a distinct response pattern, with significant variation in seedling vigor across water potential levels, indicating a differential sensitivity to increasing water deficit (Figure 4).

Figure 3. Cumulative germination (%) of three maize materials under PEG-induced water stress. (A) Hybrid, (B) Tabloncillo, and (C) *Zea perennis were* evaluated at three water potentials (0, −0.5, and −1.0 MPa). Values represent cumulative germination over time (days) ± SE. Source: Authors' own elaboration (2025).

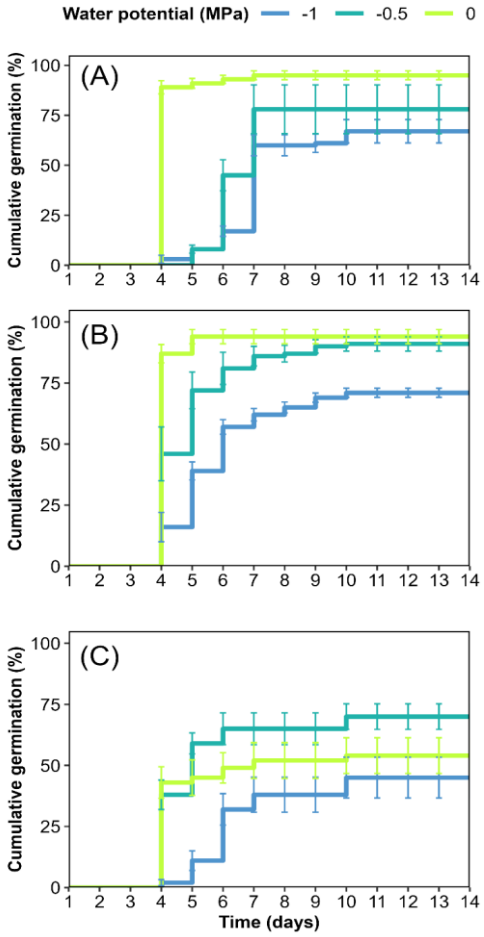


Figure 4. Representative seedlings classified as high (*a*) and low (*b*) vigor in the three maize materials: evaluated: (A) Hybrid, (B) Tabloncillo, and (C) *Zea perennis*. Images illustrate morphological differences associated with seedling vigor categories after 14 days of germination. Source: Authors' own elaboration (2025).

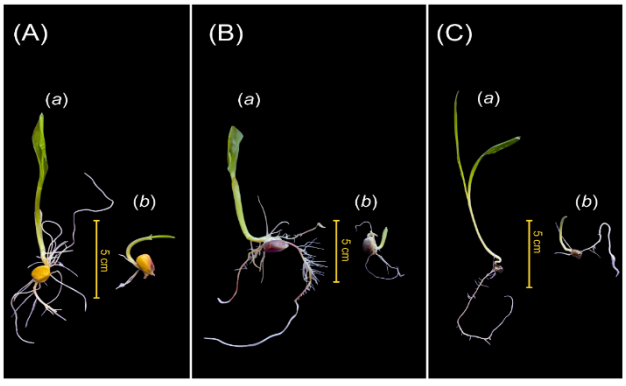


Table 1. Pairwise comparisons of high and low vigor seedling proportions in the three maize materials evaluated: Hybrid, Tabloncillo, and *Zea perennis* under different water potential treatments, as assessed by Fisher exact test.

Maize materials	Comparison (MPa)	Seedling vigor		Odds ratio	95% CI	p-value
		High (n)	Low (n)			
Hybrid	0 vs –0.5	30 vs 8	65 vs 70	4.01	1.64-10.87	**0.0008**
	0 vs –1.0	30 vs 4	65 vs 63	7.19	2.34-29.73	**0.0001**
	–0.5 vs –1.0	8 vs 4	70 vs 63	1.79	0.45-8.54	0.3847
Tabloncillo	0 vs –0.5	77 vs 32	17 vs 56	7.82	3.82-16.70	**0.0001**
	0 vs –1.0	77 vs 35	17 vs 36	4.61	2.19-10.04	**0.0001**
	–0.5 vs –1.0	32 vs 35	56 vs 36	0.59	0.30-1.17	0.1091
Zea perennis	0 vs –0.5	24 vs 9	30 vs 61	5.34	2.9-14.69	**0.0016**
	0 vs –1.0	24 vs 15	30 vs 30	1.59	0.65-3.96	0.3049
	–0.5 vs –1.0	9 vs 15	61 vs 30	0.30	0.10-0.82	**0.01047**

Bold letters indicate significant differences. Odds ratios >1 indicate that seedlings grown under the first water potential in each comparison have a higher probability of exhibiting high vigor. Source: Authors' own elaboration (2025).

4 DISCUSSION

Water availability is a key environmental factor regulating the germination, seedling establishment, and crop performance, particularly in rainfed agroecosystems (Farooq et al., 2009; IPCC, 2021). The present study demonstrates that germination percentage, mean germination time, and seedling vigor in maize are strongly influenced by water potential, with clear differentiation among genetic materials. The significant main effects of maize materials and water potential on final germination percentage confirm that both intrinsic seed traits and external hydric conditions jointly determine germination success, a pattern widely documented in cereals exposed to osmotic stress and seed physiological constraints (Bradford, 1990; Bewley et al., 2013).

The absence of a significant maize materials × water potential interaction for germination percentage indicates that, although crops differed in absolute germination capacity, the overall decline in germination under induced water stress followed a similar trend across varieties. This suggests the existence of shared physiological thresholds for germination completion related to water uptake, metabolic reactivation, and radicle protrusion during imbibition (Bradford, 1990; Michel and Kaufmann, 1973). Under climate change scenarios, where early season drought events are expected to increase in frequency and intensity, such reductions in germination percentage may compromise crop establishment, particularly in regions where maize production relies heavily on rainfall, as occurs in large areas of Mexico and other rainfed systems (Cairns et al., 2013; CONABIO, 2020).

In contrast to final germination percentage, mean germination time (MGT) showed a significant maize material × water potential interaction, indicating that germination timing is more sensitive to genetic differentiation than germination completion. This highlights the ecophysiological relevance of germination speed as an adaptive trait and a key descriptor of the

germination process (Ranal and Santana, 2006). Delayed germination under reduced water potential may function as a drought avoidance mechanism, reducing the risk of seedling mortality under transient soil moisture deficits, albeit at the cost of slower emergence and reduced competitive ability (Finch-Savage and Bassel, 2016).

The commercial maize hybrid exhibited rapid and synchronized germination under non-stress conditions, consistent with breeding selection for uniform emergence and vigor under optimal management. However, under water stress, this material showed marked delays in germination and a pronounced reduction in seedling vigor, reflecting a tradeoff between high productivity under favorable conditions and reduced resilience under drought. Such vulnerability of improved germplasm to water limitation has been widely reported in crop species and reflects reduced phenotypic plasticity relative to wild progenitors (Tuberosa, 2012; Matesanz and Milla, 2018).

The Tabloncillo landrace displayed an intermediate response, maintaining relatively stable cumulative germination and seedling vigor under moderate water stress (−0.5 MPa), with pronounced declines only under severe stress. This behavior is consistent with local adaptation to heterogeneous and unpredictable moisture regimes typical of traditional maize agroecosystems in Mexico. Long term farmer mediated selection under rainfed conditions has favored genotypes with greater tolerance to environmental variability rather than maximal productivity, conferring ecological resilience and buffering establishment failure under moderate drought (Sánchez González et al., 2000; Mercer et al., 2008).

Although *Zea perennis* exhibited lower absolute germination percentages compared with cultivated maize materials, it showed remarkable stability in germination percentage across the water potential gradient. Unlike the hybrid and the landrace, whose germination declined sharply as water potential decreased, *Z. perennis* maintained relatively constant germination proportions under control, moderate, and severe water stress. This response indicates a conservative and buffered germination strategy that may confer long term ecological advantages in environments characterized by chronic or recurrent water limitation, as described for wild and perennial species (Baskin and Baskin, 2014; Donohue et al., 2010).

From a mechanistic perspective, this stability suggests that water stress in *Zea perennis* primarily affected the rate of seed imbibition and metabolic activation rather than causing immediate loss of seed viability. Osmotic stress restricts water uptake and delays enzymatic activation, reserve mobilization, and cell elongation during the initial phases of germination without necessarily compromising embryo viability (Michel and Kaufmann, 1973; Laynez-Garsaball et al., 2014). In agreement with this interpretation, Martínez González et al. (2024) reported that water deficit delayed germination dynamics and increased mean germination time without affecting final

germination percentage, supporting the view that delayed germination reflects a reversible physiological response. This physiological decoupling between germination timing and final viability explains why *Z. perennis* exhibited slow and delayed germination dynamics while maintaining relatively constant germination percentages across water potential treatments.

Such responses are characteristic of wild and perennial species, in which selection favors persistence and risk spreading strategies over rapid establishment (Baskin and Baskin, 2014). The stable germination of *Zea perennis* across contrasting hydric conditions is consistent with bet hedging strategies that minimize temporal variability in recruitment success, thereby enhancing population persistence under environmentally unpredictable conditions (Simons, 2011; Gremer and Venable, 2014). Under climate change scenarios, increased climatic variability rather than mean drought intensity is expected to exert strong selective pressure, favoring such conservative germination strategies (IPCC, 2021).

Seedling vigor responses further reinforce these ecophysiological tradeoffs. In the hybrid and the Tabloncillo landrace, optimal water availability strongly favored the production of high vigor seedlings, whereas water stress sharply reduced vigor regardless of stress intensity, suggesting the existence of a critical water potential threshold below which normal seedling development is severely constrained, as defined in international seed testing standards (ISTA, 2023) and ecophysiological frameworks of seed vigor (Finch-Savage and Bassel, 2016). In contrast, *Z. perennis* showed significant variation in vigor across water potential levels, indicating a gradual and continuous response to increasing water deficit, consistent with stress tolerance rather than stress avoidance strategies (Donohue et al., 2010).

From an ecological and agronomic perspective, these contrasting responses highlight fundamental relationships between rapid establishment, stress tolerance, and productivity among maize. While high yielding hybrids maximize performance under favorable conditions, their reduced stability under water stress may increase vulnerability in rainfed systems. Conversely, native landraces and wild relatives, despite lower productivity, offer greater ecological resilience and adaptive potential. The conservative germination strategy of *Z. perennis*, although disadvantageous for short term agricultural production, represents a valuable reservoir of traits related to germination stability, persistence, and tolerance to hydric variability, which are increasingly relevant for breeding programs aimed at enhancing resilience under climate change (Cairns et al., 2013; Tuberosa, 2012).

Overall, these findings emphasize the importance of conserving and integrating wild relatives and landraces into breeding and agroecological strategies aimed at enhancing the resilience of maize based food systems under ongoing climate change.

5 CONCLUSIONS

Water potential significantly affected germination and seedling vigor in all maize materials. Although final germination declined similarly under water stress, germination dynamics and vigor differed among genotypes. The hybrid was highly sensitive to water deficit, the Tabloncillo landrace showed greater stability under moderate stress, and *Zea perennis* exhibited slow but stable germination across water potentials, indicating higher tolerance to hydric variability.

As a limitation, this study was conducted under controlled laboratory conditions using PEG induced water stress, which may not fully represent soil water dynamics under field conditions. Future studies should evaluate these responses under field or semi field environments and incorporate physiological, biochemical, and molecular traits associated with drought tolerance. Such approaches will improve the understanding of adaptive mechanisms and support the use of landraces and wild relatives in breeding programs aimed at enhancing maize resilience under climate change.

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