



Dormancy Breaking and Salt Tolerance in Wild Soybean: A Comparative Analysis of Genotypic Responses to Acid Scarification and Salinity

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ABSTRACT

Background: Physical seed dormancy complicates wild soybean (*Glycine soja* Sieb. and Zucc.) evaluation under salinity. Combined effects of scarification duration, NaCl concentration and genotype on germination and early seedling performance were assessed.

Methods: Three accessions were tested in a three-factor completely randomized design with sulfuric acid (H₂SO₄) scarification (0, 5, 10 min), five NaCl concentrations (0-100 mM) and four replicates per combination. Germination, growth and biomass traits were assessed using factorial ANOVA, correlation analysis and principal component analysis (PCA).

Result: Scarification increased germination from 17.1% (0 min) to 61.3% (5 min) and 59.3% (10 min), without a significant difference between durations. Mean germination time fell from 7.5 to 4.5 and 4.2 days. Salinity did not significantly affect final germination percentage but delayed germination and reduced vigor, seedling elongation and biomass. Genotype 2 showed higher germination index, germination coefficient and vigor index, whereas Genotypes 1 and 3 accumulated more root and shoot dry matter. Genotype 3 germination declined significantly between 5- and 10-min. Correlation and PCA revealed overlapping germination indices and additional biomass-related variation, supporting multi-trait assessment of early-stage salinity responses.

Key words: Germplasm evaluation, NaCl stress, Physical dormancy, Sulfuric acid pretreatment, Wild soybean.

INTRODUCTION

Wild soybean (*Glycine soja* Sieb. and Zucc.; Fabaceae), the wild progenitor of cultivated soybean (*Glycine max* (L.) Merr.), is a valuable genetic resource for soybean improvement (Gong *et al.*, 2025). Domestication bottlenecks have reduced genetic diversity in cultivated soybean relative to its wild progenitor (Hyten *et al.*, 2006). Wild soybean retains genetic variation relevant to stress-response research, including loci associated with salinity responses (Guo *et al.*, 2021; Shi *et al.*, 2022). Its cross-compatibility with cultivated soybean supports potential breeding applications; however, identifying useful accessions requires reliable assessment of germination and early seedling performance under stress conditions.

Soil salinity can impair crop establishment by restricting water uptake and disrupting ion homeostasis (Bouzroud *et al.*, 2023). In soybean, increasing NaCl concentrations may delay germination and reduce root and shoot development (Han *et al.*, 2025). Germination and early seedling establishment are particularly sensitive developmental stages, making their responses important for evaluating salinity stress (Çirka *et al.*, 2021; Çirka *et al.*, 2022). Assessing differences in germination timing, seedling elongation and biomass among wild soybean accessions can provide useful phenotypic information for subsequent stress-response research (Shi *et al.*, 2022). However, reliable comparisons require addressing physical seed dormancy, which can restrict germination independently of salinity.

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Physical seed dormancy complicates wild soybean germplasm evaluation because the compact seed coat, including its palisade layer and waxy cuticle, restricts water uptake (Gong *et al.*, 2025). Hard-seededness also has a genetic basis, with loci such as qHS1 and GmHs1-1 associated with seed-coat impermeability (Yan *et al.*, 2024). Scarification with concentrated sulfuric acid (H₂SO₄) can disrupt this barrier and improve germination (Uzun and Aydin, 2004; Avci *et al.*, 2013). However, exposure duration

requires careful consideration: insufficient treatment may leave dormancy unresolved, whereas prolonged exposure could damage the embryo. Evaluating scarification duration is therefore essential for reliable comparisons of wild soybean responses to salinity.

Previous studies have examined physical dormancy and scarification in wild soybean (Gong *et al.*, 2025) and germination responses to salinity (Shi *et al.*, 2022). However, the combined influence of scarification duration, NaCl concentration and genotype on germination and early seedling performance remains less clearly characterized. Accordingly, this study evaluated the individual and interactive effects of these factors on germination, germination timing, vigor, seedling elongation and biomass in three wild soybean accessions. The objective was to distinguish improvements associated with dormancy breaking from salinity-related growth constraints and characterize genotype-dependent early-stage responses.

MATERIALS AND METHODS

Plant material

The experiment was conducted at the Forage and Range Research Laboratory, Çukurova University, Türkiye, in 2026. Three wild soybean (*Glycine soja* Sieb. and Zucc.) accessions originating from South Korea were evaluated: Incheon Ongjin City (Genotype 1), Gangwon Hongcheon (Genotype 2) and Gyeongnam Uiryeong (Genotype 3). Seeds were stored at 4°C until the experiment and selected for uniformity in size and appearance before treatment.

Experimental design

The experiment was arranged in a three-factor completely randomized design (CRD) involving three sulfuric acid (H₂SO₄) scarification durations (0, 5 and 10 min), five NaCl concentrations (0, 25, 50, 75 and 100 mM) and three wild soybean genotypes. The factorial arrangement comprised 45 treatment combinations, each replicated in four independent Petri dishes containing 25 seeds, resulting in 180 experimental units.

Treatments

Seeds were surface-sterilized for 3 min in a 10% (v/v) dilution of sodium hypochlorite stock solution (Nazih *et al.*, 2024) and subsequently rinsed with distilled water to remove residual sodium hypochlorite. To break the physical dormancy, seeds were immersed in concentrated sulfuric acid (H₂SO₄, 95-98%) at 25°C for 5-10 min, whereas unscarified seeds served as the control (0 min). The seed-to-acid ratio was maintained consistently across treatments and seeds were gently stirred during immersion to ensure uniform exposure. Following acid treatment, seeds were rinsed under running tap water for 10 min, followed by three rinses with distilled water to remove residual acid. Control seeds underwent the same rinsing and drying procedure without acid exposure. All seeds were then blotted and air-dried at room temperature before sowing.

Seeds were placed in 10-cm Petri dishes containing two layers of filter paper and 10 mL of the appropriate NaCl solution (0 mM, distilled water; 25, 50, 75, or 100 mM) was added to each dish, with distilled water serving as the 0 mM control. The Petri dishes were sealed with parafilm to prevent water loss and incubated in a growth chamber at 25±1°C under a 16 h light/8 h dark photoperiod.

Measured parameters

Germination was recorded daily for 14 days, with radicle emergence of at least 2 mm considered the germination criterion (ISTA, 2018). Germination rate (GR), germination index (GI) and mean germination time (MGT) were calculated Javaid *et al.* (2022), Rice (1960) and Khan *et al.* (2025) and Kader (2005), respectively, using Equations 1-3.

$$GR(\%) = \frac{\text{Total number of seeds germinated}}{\text{Number of total seeds}} \times 100 \quad \dots(1)$$

$$GI = \sum \left(\frac{G_n}{D_n} \right) \quad \dots(2)$$

$$MGT(\text{days}) = \sum \left(\frac{G_n \times D_n}{\sum G_n} \right) \quad \dots(3)$$

Where,

G_n = Number of newly germinated seeds on day n.

D_n = Denotes the corresponding number of days from the beginning of the germination test (n = 1-14).

The germination coefficient (GC) and vigor index (VI) were calculated using Equation 4-5, respectively (Abdul-Baki and Anderson, 1973; Irik and Bikmaz, 2024; Han *et al.*, 2025).

$$GC = 1.00 \times gd_2 + 0.70 \times gd_4 + 0.30 \times gd_6 \quad \dots(4)$$

Where,

gd₂, gd₄ and gd₆ = Germination values recorded on days 2, 4 and 6, respectively.

$$VI = \text{Seedling length (cm)} \times \text{Germination percentage on day 14} \quad \dots(5)$$

Ten seedlings were randomly selected from each replicate and their root and shoot lengths were measured in centimetre. Mean root and shoot lengths were calculated for each replicate (Ertekin *et al.*, 2022). Fresh roots and shoots were excised and weighed using an analytical balance with 0.0001 g readability and mean total fresh weight was calculated per seedling. For dry-weight determination, roots and shoots were dried in a forced-air oven at 70°C for 48 h, weighed and expressed as root dry weight and shoot dry weight (mg seedling⁻¹) (Dönmez, 2025).

Statistical analysis

Statistical analyses were performed in R using RStudio (R Core Team, 2024). Each Petri dish was considered an experimental unit, with four replicates per treatment combination. Seedling measurements were summarized as replicate means before analysis. Data were subjected to three-way factorial analysis of variance (ANOVA),

considering acid scarification duration (A), salinity (S), genotype (G) and their two-way ($A \times S$, $A \times G$ and $S \times G$) and three-way ($A \times S \times G$) interactions as fixed effects. Homogeneity of variance was assessed using Levene's test and square-root or angular transformations were applied when necessary to address deviations from model assumptions. ANOVA and mean comparisons were performed using the agricolae package (de Mendiburu, 2023). Following significant ANOVA effects, Duncan's multiple range test ($P < 0.05$) was used for exploratory mean separation among treatments. Correlation analysis was conducted to examine relationships among measured traits. Principal component analysis (PCA) was performed on the 45×10 matrix of treatment-combination means using the FactoMineR package (Lê *et al.*, 2008). Variables were standardized to zero mean and unit variance and PCA was based on the correlation matrix. Components with eigenvalues greater than 1 were retained according to Kaiser's criterion. Figures were generated using ggplot2 (Wickham, 2016).

RESULTS AND DISCUSSION

Table 1 summarizes the treatment means and analysis of variance for ten germination and early seedling growth traits.

Germination responses

Acid scarification, genotype and their interaction significantly affected germination rate (GR), germination index (GI), mean germination time (MGT) and germination coefficient (GC; all $P < 0.001$). Salinity affected GI, MGT and GC ($P < 0.05$), but not GR (Table 1).

Overall GR increased from 17.1% (0 min) to 61.3% (5 min) and 59.3% (10 min), with no significant difference between scarification durations. Genotype 2 recorded the highest GR after scarification, whereas Genotype 3 declined significantly from 62.6% to 50.9% between 5 and 10 min (Fig 1A). Scarification increased GI from 1.4 to 12.0-12.2 and GC from 0.06 to 0.79-0.83, with comparable 5- and 10-min means. However, Genotype 1 showed significant increases in GI (7.7 to 10.4) and GC (0.45 to 0.70) between these durations (Fig 1B,D).

MGT declined from 7.5 to 4.5 and 4.2 days across 0, 5 and 10 min, respectively; all three means differed significantly. The additional reduction between 5 and 10 min was significant in Genotype 1 but not Genotypes 2 or 3 (Fig 1C). At 100 mM NaCl, GI (7.4) and GC (0.48) were significantly lower than at 0-50 mM, but not 75 mM; MGT (5.7 days) exceeded values at 0 and 25 mM only.

Seedling vigor and elongation

Acid scarification and salinity affected vigor index (VI), root length (RL) and shoot length (SL; $P < 0.001$). Genotype affected VI and RL ($P < 0.001$) and SL ($P < 0.05$). Scarification $\times$ genotype interactions were significant for all three traits ($P < 0.001$), scarification $\times$ salinity for VI and SL ($P < 0.01$) and RL ($P < 0.05$) and salinity $\times$ genotype for SL ($P < 0.01$; Table 1).

Across 0, 5 and 10 min, VI increased (54.2, 401.1, 449.6), RL (0.96, 2.25, 2.53 cm) and SL (1.70, 4.06, 4.80 cm), with significant differences among all durations. Increasing NaCl reduced all three traits (Table 1).

Genotype 2 recorded the highest VI after scarification (583.7 and 621.0 at 5 and 10 min), but these durations

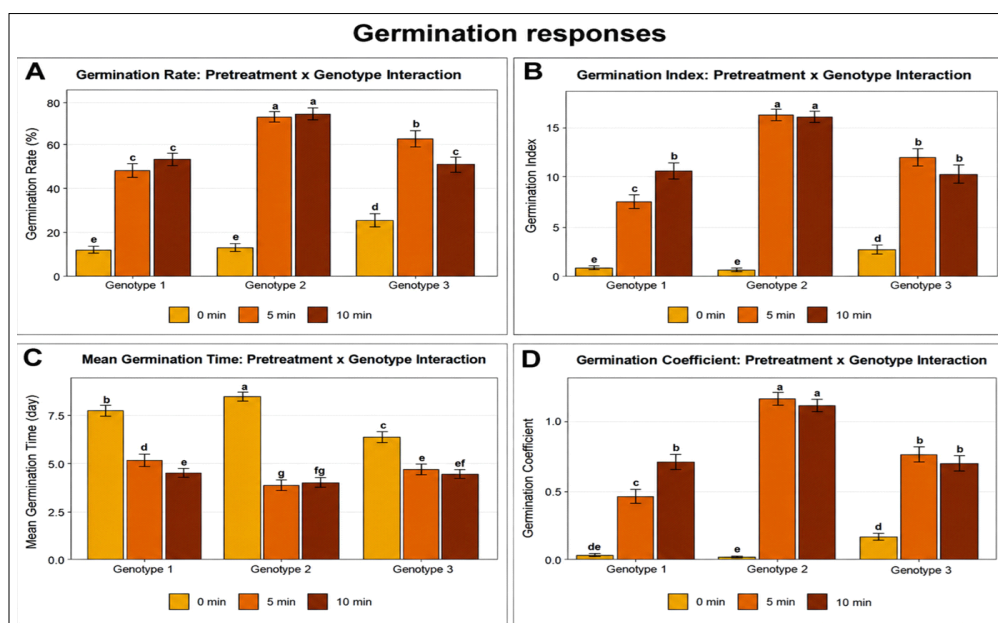


Fig 1: Effects of scarification $\times$ genotype on (A) germination rate, (B) germination index, (C) mean germination time and (D) germination coefficient. Error bars: SE; shared letters: no significant difference (Duncan's test, $P < 0.05$).

Table 1: Mean values and analysis of variance for germination and early seedling growth traits of wild soybean genotypes as affected by acid scarification and salinity treatments.

Measurements	GR (%)	GI	MGT (days)	GC	VI	RL (cm)	SL (cm)	TFW (mg seedling ⁻¹)	RDW (mg seedling ⁻¹)	SDW (mg seedling ⁻¹)
Acid scarification (min)										
0 min.	17.1b	1.4b	7.5a	0.06b	54.2c	0.96c	1.70c	50.3c	0.86c	8.0c
5 min.	61.3a	12.0a	4.5b	0.79a	401.1b	2.25b	4.06b	86.3b	1.09b	13.6b
10 min.	59.3a	12.2a	4.2c	0.83a	449.6a	2.53a	4.80a	95.6a	1.36a	15.9a
Salinity (mM)										
0	49.4	9.4a	5.2bc	0.61a	450.7a	2.72a	4.88a	92.3a	1.35a	17.4a
25	46.6	8.9a	5.1c	0.59a	382.3b	2.48a	4.44b	87.9ab	1.24a	15.7ab
50	45.8	8.7a	5.4a-c	0.58a	305.3c	2.04b	3.55c	82.8b	1.21a	12.9b
75	46.4	8.5ab	5.5ab	0.50ab	230.7d	1.42c	2.79d	69.3c	0.94b	9.3c
100	41.4	7.4b	5.7a	0.48b	139.2e	0.90d	1.93e	54.6d	0.77b	7.1d
Genotypes										
Genotype 1	37.9b	6.3c	5.8a	0.39c	246.8b	2.03a	3.33b	73.4b	1.21a	13.3a
Genotype 2	53.7a	11.1a	5.3b	0.77a	410.5a	2.16a	3.87a	73.4b	0.94b	10.9b
Genotype 3	46.2a	8.2b	5.0b	0.53b	247.5b	1.55b	3.37ab	85.3a	1.16a	13.1a
Source of variation										
Acid scarification	***	***	***	***	***	***	***	***	***	***
Salinity	ns	*	*	*	***	***	***	***	***	***
Genotypes	***	***	***	***	***	***	*	***	**	***
A × S	ns	ns	ns	ns	**	*	**	ns	***	ns
A × G	***	***	***	***	***	***	***	***	*	***
S × G	ns	ns	ns	ns	ns	ns	**	*	ns	**
A × S × G	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Means followed by different lowercase letters within the same factor and trait differ significantly according to Duncan's multiple range test at * P<0.05, **; P<0.01, ***; P<0.001, ns: not significant (P>0.05), A: Acid scarification, S: Salinity, G: Genotypes, GR: Germination rate, GI: Germination index, MGT: Mean germination time, GC: Germination coefficient, VI: Vigor index, RL: Root length, SL: Shoot length, TFW: Total fresh weight, RDW: Root dry weight, SDW: Shoot dry weight.

were statistically comparable (Fig 2A). Scarification benefits for VI declined with increasing salinity (Fig 2B). The highest numerical RL occurred in Genotype 2 after 10 min (3.08 cm), although 5 and 10 min were comparable in Genotypes 1 and 2; Genotype 3 showed no significant duration effect (Fig 2C). At 100 mM, only 10-min scarification increased RL significantly over the unscarified control (Fig 2D).

For SL, 5 and 10 min were comparable in Genotypes 1 and 2, whereas 10 min exceeded the unscarified control in Genotype 3 (Fig 3A). Ten minutes exceeded 5 min only at

75 mM (Fig 3B). Genotype 2 had the highest numerical SL at 0 mM (5.95 cm), comparable to Genotype 3; genotypes did not differ at 100 mM (Fig 3C).

Seedling biomass

Acid scarification and salinity significantly affected total fresh weight (TFW), root dry weight (RDW) and shoot dry weight (SDW; $P < 0.001$). Genotype affected TFW and SDW ($P < 0.001$) and RDW ($P < 0.01$). Scarification $\times$ genotype interactions occurred for all three traits (TFW and SDW,

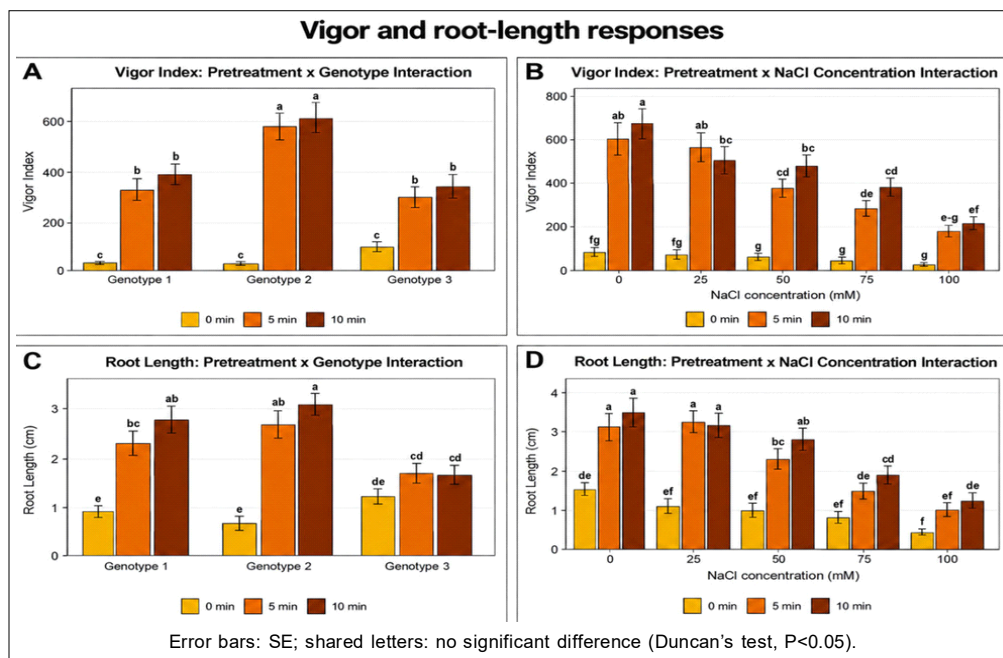


Fig 2: Vigor index (A, B) and root length (C, D) under scarification $\times$ genotype (A, C) and scarification $\times$ NaCl (B, D).

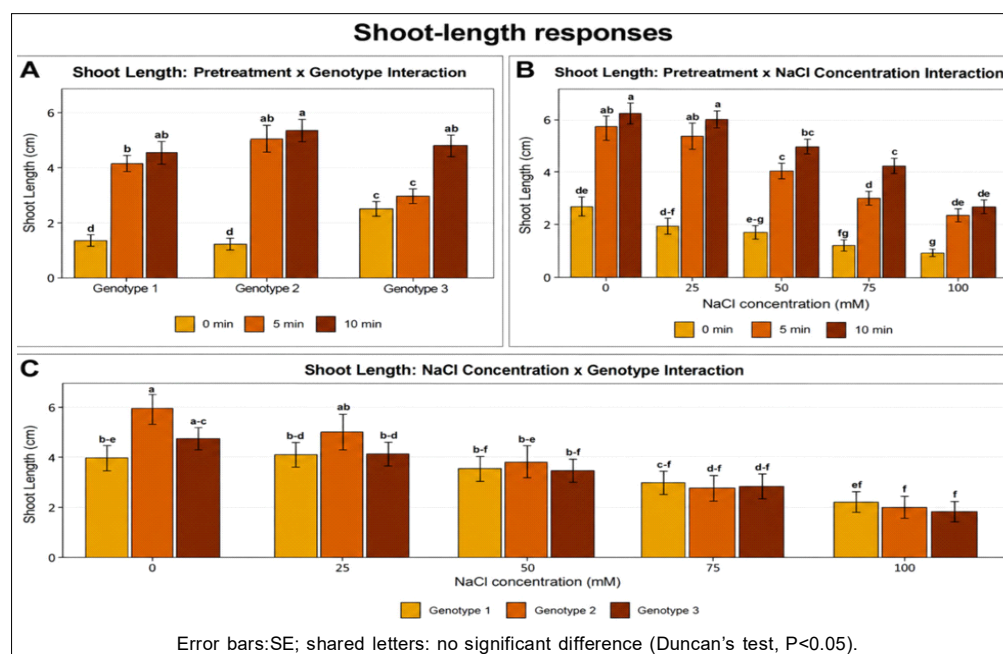


Fig 3: Shoot length under (A) scarification $\times$ genotype, (B) scarification $\times$ NaCl and (C) NaCl $\times$ genotype.

$P < 0.001$; RDW, $P < 0.05$), scarification $\times$ salinity for RDW ($P < 0.001$) and salinity $\times$ genotype for TFW ($P < 0.05$) and SDW ($P < 0.01$; Table 1).

TFW increased significantly across scarification durations (50.3, 86.3 and 95.6 mg seedling⁻¹) but declined from 92.3 to 54.6 mg seedling⁻¹ between 0 and 100 mM NaCl. The 5- and 10-min treatments were comparable in Genotypes 1 and 2; in Genotype 3, 10 min increased TFW over the unscarified control (Fig 4A). At 0 mM, Genotype 3 recorded the highest numerical TFW but was comparable to Genotype 2; genotypes did not differ at 100 mM (Fig 4B). RDW rose significantly with scarification duration (0.86, 1.09 and 1.36 mg seedling⁻¹). Ten minutes increased RDW in Genotype 1 relative to 0 and 5 min; both scarification durations exceeded the control in Genotype 2, whereas Genotype 3 showed no significant differences (Fig 4C). RDW declined at higher salinity and scarification durations were comparable at 100 mM (Fig 4D).

SDW increased significantly across durations (8.0, 13.6 and 15.9 mg seedling⁻¹), but declined from 17.4 to 7.1 mg seedling⁻¹ between 0 and 100 mM NaCl. Both scarification durations increased SDW in Genotypes 1 and 2 without differing from each other; Genotype 3 showed no significant response (Fig 4E). Genotype 3 had the highest numerical SDW at 0 mM, whereas Genotype 1 was numerically higher at 75-100 mM without significant superiority (Fig 4F).

Trait correlations and principal component analysis

Across 45 treatment-combination means, germination rate correlated with germination index ($r = 0.98$) and coefficient ($r = 0.96$), which were nearly perfectly correlated with each

other ($r = 1.00$, rounded; $P < 0.001$). Mean germination time correlated negatively with other traits ($r = -0.91$ to -0.54). Vigor index correlated with root and shoot lengths ($r = 0.92$ and 0.94). Dry weights showed weaker correlations with germination traits ($r = 0.40$ - 0.56) but strong intercorrelation ($r = 0.90$) and associations with total fresh weight ($r = 0.81$ - 0.90 ; Fig 5A).

PC1 (72.3%) and PC2 (12.1%) jointly explained 84.4% of variation. Germination indices and vigor aligned positively with PC1, opposite to mean germination time; dry weights contributed more to positive PC2. Scarified treatments tended toward positive PC1, higher NaCl concentrations toward negative PC1, with genotype-dependent patterns (Fig 5B).

Low germination in unscarified wild soybean and its improvement following acid scarification are consistent with a water-impermeable seed coat (Gong *et al.*, 2025). Physical dormancy is associated with seed-coat structure and loci including *qHS1* and *GmHs1-1* (Wen *et al.*, 2024; Yan *et al.*, 2024). Sulfuric acid may facilitate imbibition by disrupting this barrier (Uzun and Aydin, 2004). Effective exposure durations vary considerably among legumes: 10-15 min was most effective in annual *Medicago* species (Kir, 2019), whereas *Medicago falcata* exceeded 94% germination after 40 min in 98% H₂SO₄ (Wang *et al.*, 2024). The significant decline in Genotype 3 germination between 5 and 10 min indicates a duration-dependent response; possible embryo injury was not examined.

Although salinity did not significantly affect final germination rate, it prolonged mean germination time and reduced germination index, germination coefficient, vigor, seedling elongation and biomass (Phang *et al.*, 2008; Han

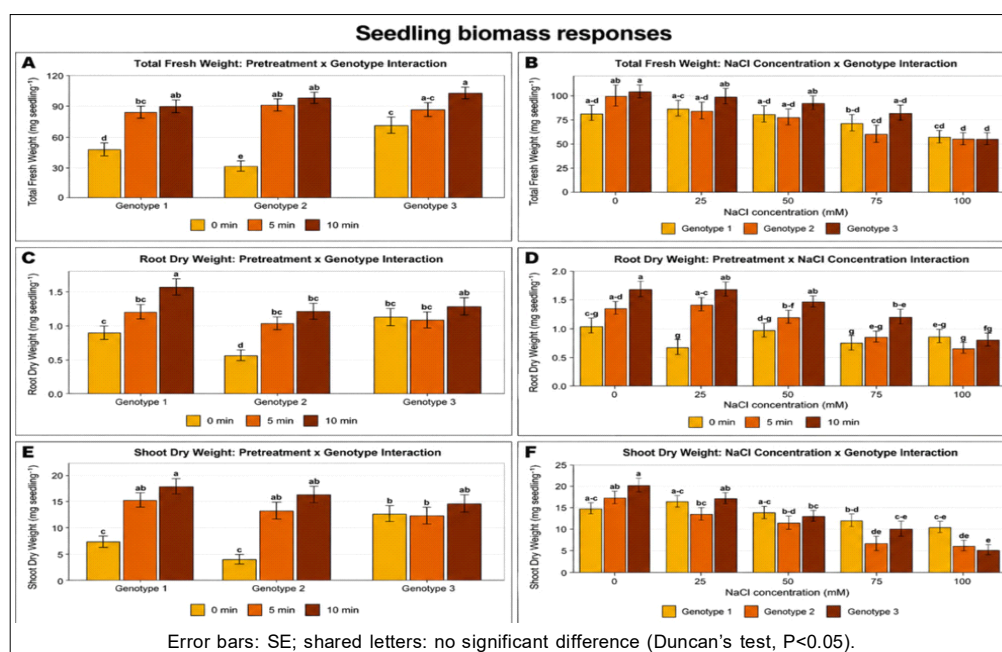


Fig 4: Total fresh weight (A, B), root dry weight (C, D) and shoot dry weight (E, F) under scarification $\times$ genotype (A, C, E), scarification $\times$ NaCl (D) and NaCl $\times$ genotype (B, F).

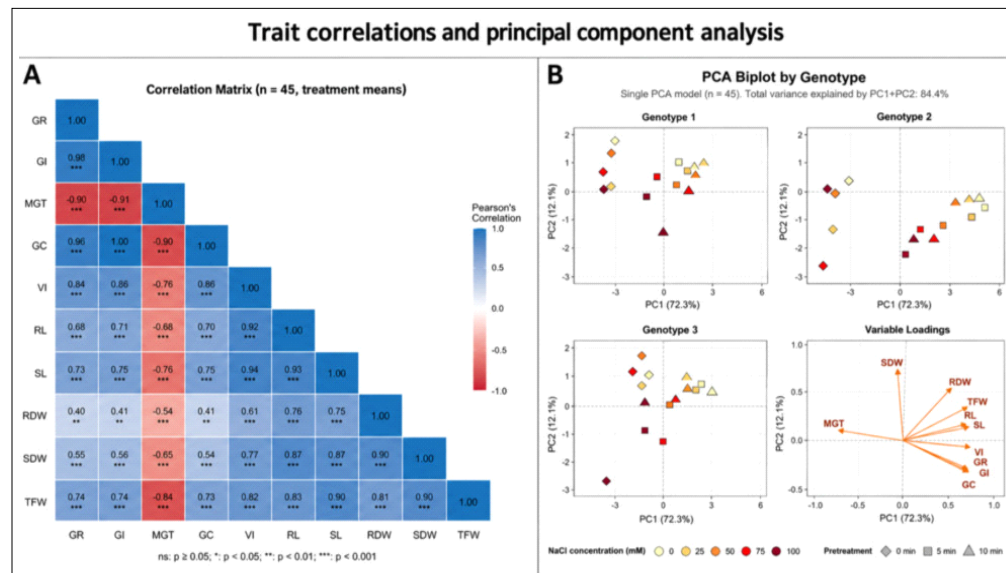


Fig 5: (A) Pearson correlations among 45 treatment-combination means and (B) PCA scores and loadings by genotype. Colors indicate NaCl concentrations and symbols indicate scarification durations in panel B.

et al., 2025). These responses may reflect osmotic limitations on water uptake and ionic effects associated with Na^+ and Cl^- accumulation (Munns and Tester, 2008). Changes in gibberellin and abscisic acid regulation may also delay germination (Shu *et al.*, 2017), although these physiological mechanisms were not directly examined.

Final germination percentage alone inadequately characterizes early-stage salinity responses. Although vigor index responded to NaCl, its correlations with germination and growth partly reflect shared mathematical components rather than independent physiological evidence (Finch-Savage and Bassel, 2016). Because trait discrimination may vary with salinity (Gobade *et al.*, 2025), combining germination percentage, timing, seedling elongation and dry-matter accumulation supports broader assessment without overinterpreting correlated indices.

Significant scarification $\times$ salinity interactions for vigor index, root length, shoot length and root dry weight indicated NaCl-dependent responses (Table 1). Scarification improved early growth, but benefits generally diminished at higher salinity, indicating persistent salt-related constraints (Munns and Tester, 2008; Nazih *et al.*, 2024). Thus, dormancy breaking should not be equated with physiological salt tolerance. Whether scarification alters salt entry through the seed coat remains untested; standardized pretreatment is needed for reliable genotype comparisons.

No accession was consistently superior. Genotype 2 had significantly higher germination index, coefficient and vigor index, but its numerically highest germination rate and shoot length did not significantly exceed Genotype 3. Genotype 3 had greater total fresh weight; Genotypes 1 and 3 exceeded Genotype 2 in root and shoot dry weights (Table 1). Such patterns align with reported wild soybean

diversity (Hyten *et al.*, 2006; Luo *et al.*, 2005). Despite salt-tolerance-associated loci of breeding interest (Guo *et al.*, 2021; Shi *et al.*, 2022), three accessions tested during early development cannot establish whole-plant salt tolerance or breeding superiority.

Correlation analysis and PCA provided exploratory summaries of treatment-associated variation. Strong correlations among germination indices and dry-weight variation suggest that favorable germination need not imply greater biomass. Multivariate approaches have informed soybean salinity research (Shelke *et al.*, 2017); MGIDI-based selection was examined separately (Patil *et al.*, 2025). These analyses neither establish genotype superiority nor test genotype $\times$ environment interactions. Further evaluation requires larger germplasm panels and less-redundant trait sets.

Three accessions were tested under controlled Petri-dish conditions, using NaCl alone and two scarification durations beyond the control. Assessments covered germination and early seedling growth, not ion accumulation, osmotic adjustment, antioxidant or hormonal responses, or embryo injury. Consequently, mechanisms cannot be established or field performance predicted. Future work should include more accessions and scarification durations, physiological measurements and later-stage greenhouse and field trials.

CONCLUSION

Scarification improved wild soybean germination and early seedling growth, consistent with alleviated physical dormancy. Overall germination was comparable after 5 and 10 min, although Genotype 3 germination was significantly lower after 10 than 5 min. Salinity delayed germination and reduced seedling vigor, elongation and biomass without

significantly affecting final germination percentage. Genotype 2 had higher germination index, germination coefficient and vigor index, whereas Genotypes 1 and 3 accumulated more root and shoot dry matter; none was consistently superior. Dormancy breaking does not establish physiological salt tolerance. Broader germplasm evaluation and later-stage greenhouse and field validation are required before breeding recommendations.

Disclaimers

The views and conclusions expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated institutions. The authors are responsible for the accuracy and completeness of the information provided, but do not accept any liability for any direct or indirect losses resulting from the use of this content.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

REFERENCES

- Abdul-Baki, A.A. and Anderson, J.D. (1973). Vigor determination in soybean seed by multiple criteria. *Crop Science*. **13**: 630-633.
- Avcı, S., Kaya, M.D., İleri, O. and Özaşık, İ. (2013). Effect of dormancy breaking treatments and salinity on germination of *Mellilotus alba* and *M. officinalis*. *Journal of Applied Sciences Research*. **9(3)**: 1293-1297.
- Bouzrout, S., Henkrar, F., Fahr, M. and Smouni, A. (2023). Salt stress responses and alleviation strategies in legumes: A review of the current knowledge. *Biotech*. **13**: 287.
- Çirka, M., Kaya, A.R. and Eryiğit, T. (2021) Influence of temperature and salinity stress on seed germination and seedling growth of soybean (*Glycine max* L.). *Legume Research*. **44(9)**: 1053-1059. doi: 10.18805/LR-628.
- Çirka, M., Tunçtürk, R., Kulaz, H. and Tunçtürk, M. (2022). Effects of salt stress on some growth parameters and biochemical changes in bean (*Phaseolus vulgaris* L.). *Acta Scientiarum Polonorum, Hortorum Cultus*. **21(3)**: 53-63.
- de Mendiburu, F. (2023). *Agricolae: Statistical Procedures for Agricultural Research*. <https://CRAN.R-project.org/package=agricolae>.
- Dönmez, H.B. (2025). Effect of salt stress on germination and seedling growth of pearl millet [*Pennisetum glaucum* (L.) R. Br.] cultivars. *Mustafa Kemal University Journal of Agricultural Sciences*. **30(2)**: 657-667.
- Ertekin, İ., Yılmaz, Ş. and Can, E. (2022). Determination of responses to salt stress of some fescue (*Festuca* spp.) species at germination and seedling stages. *Mustafa Kemal University Journal of Agricultural Sciences*. **27(2)**: 266-271.
- Finch-Savage, W.E. and Bassel, G.W. (2016). Seed vigour and crop establishment: extending performance beyond adaptation. *Journal of Experimental Botany*. **67(3)**: 567-591.
- Gobade, A., Arathi, S., Gijare, S., Pawar, D. and Patil, A.S. (2025). Evaluating salt tolerance in soybean core collection: Germination response under salinity stress. *Genetic Resources and Crop Evolution*. **72**: 2059-2076.
- Gong, Y., Zhang, D., Lv, J., Lv, P., Zhao, X., Sha, Q., Zhou, W. and Sun, Y. (2025). Breaking wild soybean seed physical dormancy: Optimal methods and seed coat structural changes. *Genetic Resources and Crop Evolution*. **72**: 8533-8545.
- Guo, X., Jiang, J., Liu, Y., Yu, L., Chang, R., Guan, R. and Qiu, L. (2021). Identification of a novel salt tolerance-related locus in wild soybean (*Glycine soja* Sieb. and Zucc.). *Frontiers in Plant Science*. **12**: 791175.
- Han, L., Ge, L., Fei, L., Huang, C., Li, Y., Fan, W., Zhu, D. and Zhao, L. (2025). A comprehensive evaluation of soybean germplasm resources for salt tolerance during germination. *Plants-Basel*. **14**: 791.
- Hyten, D.L., Song, Q., Zhu, Y., Choi, I.Y., Nelson, R.L., Costa, J.M., Specht, J.E., Shoemaker, R.C. and Cregan, P.B. (2006). Impact of genetic bottlenecks on soybean genome diversity. *Proceedings of the National Academy of Sciences of the United States of America*. **103(45)**: 16666-16671.
- Irik, H.A. and Bıkmaz, G. (2024). Effect of different salinity on seed germination, growth parameters and biochemical contents of pumpkin (*Cucurbita pepo* L.) seeds cultivars. *Scientific Reports*. **14**: 6929.
- ISTA (2018). International Rules for Seed Testing. Intorduction to the ISTA Rules, The International Seed Testing Association (ISTA) Zürichstr. 50, CH-8303 Bassersdorf, Switzerland.
- Javaid, M.M., Mahmood, A., Alshaya, D.S., Alkahtani, M.D.F., Waheed, H., Wasaya, A., Khan, S.A., Naqve, M. et al. (2022). Influence of environmental factors on seed germination and seedling characteristics of perennial ryegrass (*Lolium perenne* L.). *Scientific Reports*. **12**: 9522.
- Kader, M.A. (2005). A comparison of seed germination calculation formulae and the associated interpretation of resulting data. *Journal and proceedings of the Royal Society of New South Wales*. **138**: 65-75.
- Khan, M.A., Fawad, M., Jamal, A., Ali, A. and Ahmad, R. (2025). Influence of varying salinity on germination indices and threshold of salt tolerance in Alfalfa (*Medicago sativa* L.). *Sarhad Journal of Agriculture*. **41(2)**: 528-537.
- Kir, B. (2019). Effect of seed coating on germination of ciliate medick [*Medicago ciliaris* (L.) All.] and Snail Medick [*Medicago scutellata* (L.) Mill.]. *Legume Research*. **42(3)**: 375-378. doi: 10.18805/LR-426.
- Lê, S., Josse, J. and Husson, F. (2008). FactoMineR: A package for multivariate Analysis. *Journal of Statistical Software*. **25(1)**: 1-18.
- Luo, Q., Yu, B. and Liu, Y. (2005). Differential sensitivity to chloride and sodium ions in seedlings of *Glycine max* and *G. soja* under NaCl stress. *Journal of Plant Physiology*. **162**: 1003-1012.
- Munns, R. and Tester, M. (2008). Mechanisms of salinity tolerance. *Annual Review of Plant Biology*. **59**: 651-681.
- Nazih, A., Baghour, M., Maatougui, A., Aboukhalid, K., Chiboub, B. and Bazile, D. (2024). Effect of gibberellic acid and mechanical scarification on the germination and seedling stages of *Chenopodium quinoa* Willd. under Salt Stress. *Plants-Basel*. **13**: 1330.

- Patil, V., Joshi, M.A., Chaitra, K. and Singh, D. (2025). Integrating seed quality traits and salt tolerance indices for efficient screening of salinity-tolerant soybean [*Glycine max* (L.) Merrill] Genotypes. *Legume Research*. **49(10)**: 1666-1676. doi: 10.18805/LR-5512.
- Phang, T.H., Shao, G. and Lam, H.M. (2008). Salt tolerance in soybean. *Journal of Integrative Plant Biology*. **50(10)**: 1196-1212.
- R Core Team (2024). A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. <https://www.r-project.org/>.
- Rice, W.N. (1960). Development of the cold test for seed evaluation. *Proceedings of the Association of Official Seed Analysts*. **50(1)**: 118-123.
- Shelke, D.B., Pandey, M., Nikalje, G.C., Zaware, B.N., Suprasanna, P. and Nikam, T.D. (2017). Salt responsive physiological, photosynthetic and biochemical attributes at early seedling stage for screening soybean genotypes. *Plant Physiology and Biochemistry*. **118**: 519-528.
- Shi, M., Liao, X., Ye, Q., Zhang, W., Li, Y., Bhat, J.A., Kan, G. and Yu, D. (2022). Linkage and association mapping of wild soybean (*Glycine soja*) seeds germinating under salt stress. *Journal of Integrative Agriculture*. **21(10)**: 2833-2847.
- Shu, K., Qi, Y., Chen, F., Meng, Y., Luo, X., Shuai, H., Zhou, W. *et al.* (2017). Salt stress represses soybean seed germination by negatively regulating GA biosynthesis while positively mediating ABA biosynthesis. *Frontiers in Plant Science*. **8**: 1372.
- Uzun, F. and Aydin, I. (2004). Improving germination rate of *Medicago* and *Trifolium* species. *Asian Journal of Plant Sciences*. **3(6)**: 714-717.
- Wang, S., Shi, F., Shi, R. and Zhang, Y. (2024). Seed dormancy and germination in alfalfa (*Medicago falcata* L.). *Legume Research*. **47(2)**: 234-241. doi: 10.18805/LRF-758.
- Wen, Z., Lu, X., Wen, J., Wang, Z. and Chai, M. (2024). Physical Seed Dormancy in Legumes: Molecular Advances and Perspectives. *Plants-Basel*. **13**: 1473.
- Wickham, H. (2016). ggplot2: Elegant Graphics for Data Analysis, Springer-Verlag New York. Tarihinde adresinden erişildi <https://ggplot2.tidyverse.org>
- Yan, H., Tian, D., Zhang, Q., Wen, J., Wang, Z.Y. and Chai, M. (2024). GmHs1-1 and GmqHS1 simultaneously contribute to the domestication of soybean hard-seededness. *Plants-Basel*. **13**: 2061.