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Evaluation of salt stress tolerance in wheat varieties cultivated in the 1 polders of lake chad at the germination stage. 2 Abstract 3 Soil salinity is one of the major abiotic stresses that severely limits agricultural productivity, 4 particularly in arid and semi-arid regions. This study evaluated the effects of salt stress on 5 germination and early seedling growth of five wheat varieties subjected to five sodium 6 chloride (NaCl) concentrations: 0, 75, 150, 225, and 300 mM. Key germination and growth 7 parameters, including germination percentage, germination speed index, root and shoot 8 length, and salt tolerance index, were measured. Analysis of variance revealed highly 9 significant differences ($p < 0.001$) among treatments for most variables. Mexipack and Soms 10 90 showed strong tolerance, maintaining relatively high germination and growth performance 11 even at elevated NaCl concentrations, while Marzak was highly sensitive, with substantial 12 reductions in germination and seedling growth at lower salt levels. These findings highlight 13 the critical importance of selecting wheat varieties adapted to saline conditions. They also 14 emphasize the strategic role of salt-tolerant genotypes in sustaining agricultural productivity 15 in the polders of Lake Chad, where soil salinization is progressively increasing. The results 16 provide valuable insights for breeding programs targeting salt tolerance and offer practical 17 guidance for improving the resilience of local wheat production systems under salinity stress. 18 Keywords: Salinity, NaCl, Germination, Lake Chad, Wheat, Tolerance, Abiotic Stress. 19 20 21 Introduction 22 Soil salinity is widely recognized as one of the major abiotic stresses that drastically limit 23 global agricultural productivity, particularly in arid and semi-arid regions (Farooq et al. 2024). 24 This phenomenon is primarily driven by the accumulation of sodium chloride (NaCl) in the 25 rhizosphere, often exacerbated by the use of irrigation water rich in dissolved salts. Excess 26 **2 salinity imposes a dual constraint** on plants, osmotic stress and ionic stress, negatively 27 affecting key physiological processes such as germination, seedling establishment, and overall 28 growth (Ilyess et al. 2013; Zhang et al. 2024). **1 At the global scale,** salinity and sodicity impact 29 approximately 1.38 billion hectares, representing 10.7% of the Earth's land surface (FAO 30

2024), with particularly devastating consequences in irrigated systems of the western Sahel, 31 where substantial yield losses are frequently reported (Thiam et al. 2021; Smaoui et al. 2024). 32 Wheat (*Triticum* spp.) is a staple cereal essential for global food security, cultivated on nearly 33 217 million hectares worldwide (Diakite et al. 2023). Despite its importance, wheat is 34 considered moderately sensitive to salinity, with vulnerability most pronounced during the 35 early developmental stages, notably germination and initial seedling growth (Rehman et al. 36 2025). The response of a given genotype to salt stress depends on both the applied salt 37 concentration and the phenological stage, making the assessment of early-stage tolerance 38 particularly critical (Ben Naceur et al. 2001). In the polders of Lake Chad, wheat plays a 39 significant agronomic and socio-economic role. However, its yield potential under optimal 40 management is increasingly compromised by progressive soil salinization. Although 41 historically fertile (Bouquet 1969), these areas are now confronted with salt accumulation 42 driven by irrigation without adequate drainage, capillary rise of saline groundwater, and 43 intense surface evaporation (Harter and Motis 2016). This process has led to reduced 44 cultivable land and declining yields, positioning salinization as the primary obstacle to 45 achieving the full productive potential of wheat in this region (Alladjaba et al. 2025). Given 46 the urgency of this situation, the identification and selection of salt-tolerant wheat varieties 47 represent the most effective and sustainable mitigation strategy to ensure the resilience of 48 local agricultural production (Wu et al. 2010; Khan and Gulzar 2003). The present study 49 therefore aims to evaluate the variability in the response of five wheat varieties to salt stress 50 induced by different NaCl concentrations. The main objective is to identify the most tolerant 51 genotypes based on their germination performance and early growth traits. 52 Materials and Methods 53 Plant Material 54 The experiments were conducted on five wheat (*Triticum* spp.) varieties (Table 1). Four of 55 these varieties are officially registered in the national catalogue of plant species and varieties 56 of Chad, while the fifth, Marzak, is an introduced variety that is widely cultivated and 57

disseminated in the Lake Province. 58 Experimental Site 59

The study was carried out under controlled laboratory conditions at the Support Unit of the 60 Chadian Institute of Agronomic Research for Development (ITRAD), located in Bol, Lake 61 Province. The experimental site is geographically positioned at 13°30'13.35" N latitude and 62 14°41'33.95" E longitude (Figure 1). 63 Methods 64 Preparation of Salt Stress Solutions 65 Salt stress solutions were prepared using analytical-grade sodium chloride (NaCl). The NaCl 66 was dissolved in sterile distilled water to obtain five distinct concentrations: 0 mM (control), 67 75 mM, 150 mM, 225 mM, and 300 mM. These concentrations were selected to simulate a 68 progressive gradient of salinity stress intensity. 69 Experimental Design and Germination Conditions 70 The experiment was conducted using a completely randomized design in Petri dishes. For 71 each wheat variety, twenty seeds were carefully rinsed with distilled water and uniformly 72 placed in 9 cm diameter Petri dishes. Salt treatments were applied by adding 5 mL of the 73 corresponding NaCl solution to each dish. After treatment application, the Petri dishes were 74 hermetically sealed to minimize evaporation and incubated in a growth chamber under 75 controlled environmental conditions with a 12 h light / 12 h dark photoperiod. 76 Germination Monitoring 77 Germination was monitored daily for seven consecutive days. The emergence of the radicle 78 through the seed coat was adopted as the criterion for germination. The number of germinated 79 seeds was recorded every 24 hours. To evaluate the 1 effect of salinity stress on the performance 80 of the five wheat varieties, several parameters were assessed at the end of the experiment. 81 Germination Parameters 82 Germination Percentage (GP): Calculated as the percentage of germinated seeds at day i 83 (NG_i) relative to the total number of seeds sown (S): 84 $GP = (NG_i/S) \times 100$ (1) 85 Germination Speed Index (GSI): Determined according to Maguire (1962), reflecting the 86 rapidity and uniformity of germination. A higher GSI indicates faster germination: 87

$GSI = \sum(G_i/d_i)$ (2) 88 where G_i is the number of seeds germinated on day d_i . 89 Growth and Tolerance Parameters 90 Radicle and Shoot Length (mm): Measured on seedlings at day 7 to assess inhibition of early 91 growth under salt stress. Salt Tolerance Index (STI, %): Based on the methodology of Slama 92 (1982), expressed as the relative performance of a variety under stress compared to its 93 performance under control conditions: 94 $STI = (X_{stress}/X_{control}) \times 100$ (3) 95 STI was calculated for all germination and growth parameters, enabling classification of 96 varieties according to their physiological tolerance to salinity. 97 Statistical Analyses 98 Descriptive statistics, including mean, standard error (SE), minimum and maximum values, 99 and coefficient of variation (CV, %), were computed to characterize variability and 100 homogeneity of the data under different salinity levels. A one-way analysis of variance 101 (ANOVA) was performed to evaluate the main effects and interactions of salinity levels and 102 wheat varieties on all measured parameters. All statistical analyses and graphical 103 representations were conducted using R software. 104 Results 105 The analysis of variance (ANOVA) conducted to evaluate the effects of the factors Variety 106 and NaCl concentration revealed that Variety had a highly significant effect on the Salt 107 Tolerance Index (STI) ($p < 0.01$), and a very highly significant effect on both the Germination 108 Speed Index (GSI) ($p < 0.001$) and the Germination Percentage (GP) ($p < 0.001$). In contrast, 109 the effect of Variety was not significant for Shoot Growth (SG) and Root Growth (RG). 110 **1 On the other hand,** NaCl concentration exerted a very highly significant effect on all 111 parameters studied (SG, RG, STI, GSI, and GP) ($p < 0.001$), clearly indicating that increasing 112 salinity stress strongly inhibited seedling growth and negatively affected germination (Table 113 2). 114 Germination Percentage 115

The analysis of germination data collected over a seven-day period revealed a progressive 116 reduction in Germination Percentage (GP) in response to increasing NaCl concentrations. 117 However, the magnitude of this inhibition was strongly genotype-dependent. The varieties 118 Mexipack and Somsps 90 demonstrated resilience,

maintaining relatively high germination rates up to 150 mM NaCl. In contrast, Duilio and Marzak exhibited a sharp decline in germination as early as 75 mM NaCl. These findings confirm the substantial genetic variability among wheat varieties in their response to salinity stress at the germination stage (Figure 2).

Root Growth

Root growth of wheat seedlings exhibited a general and significant reduction correlated with increasing NaCl concentrations, starting as early as 75 mM. Under control conditions (0 mM NaCl), the variety Duilio, which initially developed roots of 13.1 cm, experienced a drastic inhibition, dropping to 1 cm at 150 mM NaCl. In contrast, the varieties Soms 90 and Mexipack, although showing moderate initial root growth, demonstrated the highest tolerance by maintaining relatively stable root lengths of approximately 2 cm up to 225 mM NaCl, indicating a superior ability to sustain root elongation under severe salinity stress. Conversely, the varieties Marzak and Penjamo displayed very low average values and were strongly affected even at the lowest salt concentrations tested (Figure 3).

Shoot Growth

Shoot growth, measured as shoot length (SL), revealed an overall inhibitory trend similar to that observed for root growth. The varieties Soms 90 and Duilio exhibited the greatest shoot lengths under control conditions (8.1 cm and 8.2 cm, respectively), but both declined sharply to less than 2 cm at 75 mM NaCl. Mexipack showed relative stability up to 150 mM NaCl, although shoot growth remained weak beyond this concentration. The variety Penjamo displayed a heterogeneous and irregular response. Finally, Marzak was distinguished by the earliest and most severe inhibition, with shoot length drastically reduced to only 0.2 cm at 300 mM NaCl (Figure 4).

Germination Speed Index

The Germination Speed Index (GSI), which quantifies the rapidity and uniformity of the germination process, varied significantly among wheat varieties in response to salinity stress. The varieties Mexipack and Penjamo stood out by maintaining relatively high and stable GSI values up to 150 mM NaCl. The variety Soms 90 exhibited a moderate and slightly

irregular 147 dynamic, with a slight decrease at 150 mM, followed by an unexpected increase at 300 mM 148 NaCl. In contrast, the varieties Marzak and Duilio consistently displayed low GSI values, 149 reflecting an intrinsically reduced germination speed and marked sensitivity regardless of the 150 applied salt concentration (Figure 5). 151 Salt Tolerance Index 152 The Salt Tolerance Index (STI) proved to be a key parameter in highlighting notable 153 differences among wheat varieties under varying NaCl concentrations. The varieties Somps 154 90 and Mexipack distinguished themselves by maintaining the highest mean STI values, 155 showing tolerance up to 150 mM NaCl. In contrast, the varieties Duilio and Marzak exhibited 156 a sharp decline, with STI values dropping below 50% as early as 225 mM NaCl (Figure 6). 157 Discussion 158 The results of this study unequivocally confirm that salinity exerts a significant inhibitory 159 effect on the processes of germination and early growth of wheat seedlings. The progressive 160 reduction in germination percentage, 1 as well as in root and shoot length, observed with 161 increasing NaCl concentrations is in full agreement with the findings of Mahboob et al. 2023 162 and Wu et al. 2010. This inhibition is primarily attributed to the dual effect of salt stress: the 163 initial osmotic constraint, which hinders water uptake required for imbibition, and ionic 164 toxicity resulting from Na^+/K^+ imbalance, which disrupts enzymatic activity and early 165 physiological processes in wheat. 166 The study clearly highlights pronounced inter-varietal variability in response to salinity stress. 167 Among the five genotypes tested, Mexipack and Somps 90 emerged as the most tolerant, 168 maintaining high germination and growth performance up to 150 mM NaCl. This resilience 169 suggests that these varieties possess more efficient adaptive mechanisms, potentially 170 including enhanced osmoregulatory capacity, increased accumulation of compatible solutes 171 such as proline, and/or reinforced antioxidant activity to neutralize salt-induced oxidative 172 stress, as emphasized by Ibrahimova et al. 2025 and Mrani et al. 2013. Conversely, the variety 173 Marzak proved particularly sensitive, showing significant reductions in germination and 174 growth even at low NaCl concentrations. This sensitivity reflects a limited osmotic adjustment 175 capacity and heightened vulnerability, consistent

with observations reported for salt-sensitive 176 genotypes (Zhang et al. 2024; El Sabagh et al. 2021). 177

The statistical analysis, which effectively distinguished tolerant from sensitive varieties, 178 validates the phenotypic approach employed in this study. The use of composite indicators 179 such as the Salt Tolerance Index (STI), combined with the analysis of morpho-physiological 180 traits, is widely recognized in the literature as a robust strategy for assessing and ranking 181 salinity tolerance (Dadshani et al. 2019; Ahmed et al. 2025). The variation observed in wheat 182 sensitivity across different NaCl concentrations further confirms the complex and polygenic 183 nature of salinity tolerance, as noted by Rehman et al. 2025. 184 In summary, this study confirms that salinity tolerance in wheat is an integrated trait governed 185 by a combination of physiological and genetic mechanisms. The varieties Mexipack and 186 Soms 90 are identified as promising genotypes and represent valuable genetic resources for 187 2 breeding programs aimed at improving wheat productivity in saline environments, particularly 188 in the polders of Lake Chad. 189

Conclusion 190 This study conclusively demonstrated that soil salinity exerts a significant inhibitory effect on 191 wheat seed germination and early seedling growth, with responses strongly differentiated 192 according to genotype. Increasing NaCl concentrations induced a progressive reduction in 193 germination percentage 1 as well as in root and shoot length. Phenotypic screening results 194 allowed the classification of varieties according to their level of tolerance. The tolerant 195 varieties Mexipack and Soms 90 maintained satisfactory agronomic performance up to 196 concentrations exceeding 150 mM NaCl, whereas the sensitive variety Marzak exhibited high 197 vulnerability at concentrations below 150 mM NaCl. Statistical analyses confirmed the 198 robustness of these observations and suggest that germination vigor and root growth are 199 reliable indicators of early tolerance to salt stress. To better exploit this tolerance, further 200 research integrating advanced molecular and physiological approaches is recommended to 201 unravel the genetic bases and underlying 1 mechanisms of salinity tolerance. Such

insights will 202 guide future wheat **2 breeding strategies aimed at** improving productivity under increasing soil 203 salinization, particularly in vulnerable agroecosystems such as the Lake Chad polders. 204 205 206 207 208

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297 298 Table 1. Wheat varieties studied. 299 Variety Wheat species Origin Mexico

Breadwheat (*Triticumaestivum*) Mexico Penjamo Breadwheat (*Triticumaestivum*) Mexico
 Duilio Durumwheat (*Triticumdurum*) Italy Somps 90 Durumwheat (*Triticumdurum*) Italy
 Marzak Durumwheat (*Triticumdurum*) Morocco 300 Table 2. Analysis of variance
 (ANOVA) for the effects of Variety and NaCl concentration on 301 germination and growth
 parameters (mean squares). 302 Source of variation DF SG RG STI GSI GP Varieties 4
 2.33 3.43 773.61 ** 245.80 *** 1326.00 *** NaCl concentration 4 19.75*** 41.86 ***
 2062.81 *** 128.19 *** 1298.50 *** Residuals 16 1.17 3.75 97.73 4.44 23.50 *** $p < 0,001$;
 ** $p < 0,01$; * $p < 0,05$ 303 304 305 306

307 Figure 1. 308 309 Figure 2. 310 311 312 313 314

315 Figure 3. 316 317 Figure 4. 318

319 Figure 5. 320 321 Figure 6. 322 323 324 325 Legend figure: 326

Figure 1. Location of the experimental site in the Lac Province, Chad. The left panel shows the Lac 327 Province with the experimental site indicated by a blue dot, while the right panel presents the 328 administrative map of Chad highlighting the Lac Province. 329
 Figure 2. Germination percentage (GP) of five wheat varieties under different NaCl concentrations, 330 measured on day 7 after sowing. Bars represent varieties Penjamo (light blue), Somps 90 (dark blue), 331 Mexipack (orange), Duilio (green) and Marzak (brown). 332 X: NaCl concentrations (mM) 333 Y: germination percentage (%) 334
 Figure 3. Effect of different NaCl concentrations on root growth of seedlings from five wheat varieties, 335 expressed as mean root length (cm) after seven days of experimentation. Bars represent varieties 336 Penjamo (light blue), Somps 90 (dark blue), Mexipack (orange), Duilio (green) and Marzak (brown). 337 X: NaCl concentrations (mM) 338 Y: Root growth (cm) 339
 Figure 4. Effect of different NaCl concentrations on shoot growth of seedlings from five wheat 340 varieties after seven days of exposure. Bars represent

varieties Penjamo (light blue), Somps 90 (dark 341 blue), Mexipack (orange), Duilio (green) and Marzak (brown). 342 X: NaCl concentrations (mM) 343 Y: Shoot growth (cm)

344 Figure 5. Variation in the Germination Speed Index (GSI) of five wheat varieties under different NaCl 345 concentrations. Bars represent varieties Penjamo (light blue), Somps 90 (dark blue), Mexipack 346 (orange), Duilio (green) and Marzak (brown). 347 X: NaCl concentrations (mM) 348 Y: Germination Speed Index (GSI) 349 Figure 6. Variation in the Salt Tolerance Index (STI) of five wheat varieties under different NaCl 350 concentrations. Bars represent varieties Penjamo (light blue), Somps 90 (dark blue), Mexipack 351 (orange), Duilio (green) and Marzak (brown). 352 X: NaCl concentrations (mM) 353 Y: Salt Tolerance Index STI (%) 354

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