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RESEARCH ARTICLE

EVALUATION OF SALT STRESS TOLERANCE IN WHEAT VARIETIES CULTIVATED IN THE POLDERS OF LAKE CHAD AT THE GERMINATION STAGE

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Abstract

Soil salinity is one of the major abiotic stresses that severely limits agricultural productivity, particularly in arid and semi-arid regions. This study evaluated the effects of salt stress on germination and early seedling growth of five wheat varieties subjected to five sodium chloride (NaCl) concentrations: 0, 75, 150, 225, and 300 mM. Key germination and growth parameters, including germination percentage, germination speed index, root and shoot length, and salt tolerance index, were measured. Analysis of variance revealed highly significant differences ($p < 0.001$) among treatments for most variables. Mexipack and Soms 90 showed strong tolerance, maintaining relatively high germination and growth performance even at elevated NaCl concentrations, while Marzak was highly sensitive, with substantial reductions in germination and seedling growth at lower salt levels. These findings highlight the critical importance of selecting wheat varieties adapted to saline conditions. They also emphasize the strategic role of salt-tolerant genotypes in sustaining agricultural productivity in the polders of Lake Chad, where soil salinization is progressively increasing. The results provide valuable insights for breeding programs targeting salt tolerance and offer practical guidance for improving the resilience of local wheat production systems under salinity stress.

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Introduction:-

Soil salinity is widely recognized as one of the major abiotic stresses that drastically limits global agricultural productivity, particularly in arid and semi-arid regions (Farooq et al. 2024). This phenomenon is primarily driven by the accumulation of sodium chloride (NaCl) in the rhizosphere, often exacerbated by the use of irrigation water rich

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in dissolved salts. Excess salinity imposes a dual constraint on plants, osmotic stress and ionic stress, negatively affecting key physiological processes such as germination, seedling establishment, and overall growth (Ilyess et al. 2013; Zhang et al. 2024). At the global scale, salinity and sodicity impact approximately 1.38 billion hectares, representing 10.7% of the Earth's land surface (FAO 2024), with particularly devastating consequences in irrigated systems of the western Sahel, where substantial yield losses are frequently reported (Thiam et al. 2021; Smaoui et al. 2024).

Wheat (*Triticum* spp.) is a staple cereal essential for global food security, cultivated on nearly 217 million hectares worldwide (Diakite et al. 2023). Despite its importance, wheat is considered moderately sensitive to salinity, with vulnerability most pronounced during the early developmental stages, notably germination and initial seedling growth (Rehman et al. 2025). The response of a given genotype to salt stress depends on both the applied salt concentration and the phenological stage, making the assessment of early-stage tolerance particularly critical (Ben Naceur et al. 2001). In the polders of Lake Chad, wheat plays a significant agronomic and socio-economic role. However, its yield potential under optimal management is increasingly compromised by progressive soil salinization. Although historically fertile (Bouquet 1969), these areas are now confronted with salt accumulation driven by irrigation without adequate drainage, capillary rise of saline groundwater, and intense surface evaporation (Harter and Motis 2016). This process has led to reduced cultivable land and declining yields, positioning salinization as the primary obstacle to achieving the full productive potential of wheat in this region (Alladjaba et al. 2025). Given the urgency of this situation, the identification and selection of salt-tolerant wheat varieties represent the most effective and sustainable mitigation strategy to ensure the resilience of local agricultural production (Wu et al. 2010; Khan and Gulzar 2003). The present study therefore aims to evaluate the variability in the response of five wheat varieties to salt stress induced by different NaCl concentrations. The main objective is to identify the most tolerant genotypes based on their germination performance and early growth traits.

Materials and Methods:-

Plant Material:-

The experiments were conducted on five wheat (*Triticum* spp.) varieties (Table 1). Four of these varieties are officially registered in the national catalogue of plant species and varieties of Chad, while the fifth, Marzak, is an introduced variety that is widely cultivated and disseminated in the Lake Province.

Experimental Site:-

The study was carried out under controlled laboratory conditions at the Support Unit of the Chadian Institute of Agronomic Research for Development (ITRAD), located in Bol, Lake Province. The experimental site is geographically positioned at 13°30'13.35" N latitude and 14°41'33.95" E longitude (Figure 1).

Methods:-

Preparation of Salt Stress Solutions:-

Salt stress solutions were prepared using analytical-grade sodium chloride (NaCl). The NaCl was dissolved in sterile distilled water to obtain five distinct concentrations: 0 mM (control), 75 mM, 150 mM, 225 mM, and 300 mM. These concentrations were selected to simulate a progressive gradient of salinity stress intensity.

Experimental Design and Germination Conditions:-

The experiment was conducted using a completely randomized design in Petri dishes. For each wheat variety, twenty seeds were carefully rinsed with distilled water and uniformly placed in 9 cm diameter Petri dishes. Salt treatments were applied by adding 5 mL of the corresponding NaCl solution to each dish. After treatment application, the Petri dishes were hermetically sealed to minimize evaporation and incubated in a growth chamber under controlled environmental conditions with a 12 h light / 12 h dark photoperiod.

Germination Monitoring:-

Germination was monitored daily for seven consecutive days. The emergence of the radicle through the seed coat was adopted as the criterion for germination. The number of germinated seeds was recorded every 24 hours. To evaluate the effect of salinity stress on the performance of the five wheat varieties, several parameters were assessed at the end of the experiment.

Germination Parameters:-

Germination Percentage (GP): Calculated as the percentage of germinated seeds at day i (NG_i) relative to the total number of seeds sown (S):

$$GP = (NG_i/S) \times 100 \quad (1)$$

Germination Speed Index (GSI): Determined according to Maguire (1962), reflecting the rapidity and uniformity of germination. A higher GSI indicates faster germination:

$$GSI = \sum(G_i/d_i) \quad (2)$$

where G_i is the number of seeds germinated on day d_i .

Growth and Tolerance Parameters:-

Radicle and Shoot Length (mm): Measured on seedlings at day 7 to assess inhibition of early growth under salt stress. Salt Tolerance Index (STI, %): Based on the methodology of Slama (1982), expressed as the relative performance of a variety under stress compared to its performance under control conditions:

$$STI = (X_{\text{stress}}/X_{\text{control}}) \times 100 \quad (3)$$

STI was calculated for all germination and growth parameters, enabling classification of varieties according to their physiological tolerance to salinity.

Statistical Analyses:-

Descriptive statistics, including mean, standard error (SE), minimum and maximum values, and coefficient of variation (CV, %), were computed to characterize variability and homogeneity of the data under different salinity levels. A one-way analysis of variance (ANOVA) was performed to evaluate the main effects and interactions of salinity levels and wheat varieties on all measured parameters. All statistical analyses and graphical representations were conducted using R software.

Results:-

The analysis of variance (ANOVA) conducted to evaluate the effects of the factors Variety and NaCl concentration revealed that Variety had a highly significant effect on the Salt Tolerance Index (STI) ($p < 0.01$), and a very highly significant effect on both the Germination Speed Index (GSI) ($p < 0.001$) and the Germination Percentage (GP) ($p < 0.001$). In contrast, the effect of Variety was not significant for Shoot Growth (SG) and Root Growth (RG).

On the other hand, NaCl concentration exerted a very highly significant effect on all parameters studied (SG, RG, STI, GSI, and GP) ($p < 0.001$), clearly indicating that increasing salinity stress strongly inhibited seedling growth and negatively affected germination (Table 2).

Germination Percentage:-

The analysis of germination data collected over a seven-day period revealed a progressive reduction in Germination Percentage (GP) in response to increasing NaCl concentrations. However, the magnitude of this inhibition was strongly genotype-dependent. The varieties Mexipack and Soms 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 dynamic, with a slight decrease at 150 mM, followed by an unexpected increase at 300 mM NaCl. In contrast, the varieties Marzak and Duilio consistently displayed low GSI values, reflecting an intrinsically reduced germination speed and marked sensitivity regardless of the applied salt concentration (Figure 5).

Salt Tolerance Index:-

The Salt Tolerance Index (STI) proved to be a key parameter in highlighting notable differences among wheat varieties under varying NaCl concentrations. The varieties Soms 90 and Mexipack distinguished themselves by maintaining the highest mean STI values, showing tolerance up to 150 mM NaCl. In contrast, the varieties Duilio and Marzak exhibited a sharp decline, with STI values dropping below 50% as early as 225 mM NaCl (Figure 6).

Table 1. Wheat varieties studied.

Variety	Wheat species	Origin
Mexipack	Breadwheat (<i>Triticum aestivum</i>)	Mexico
Penjamo	Breadwheat (<i>Triticum aestivum</i>)	Mexico
Duilio	Durumwheat (<i>Triticum durum</i>)	Italy
Soms 90	Durumwheat (<i>Triticum durum</i>)	Italy
Marzak	Durumwheat (<i>Triticum durum</i>)	Morocco

Table 2. Analysis of variance (ANOVA) for the effects of Variety and NaCl concentration on germination and growth parameters (mean squares).

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

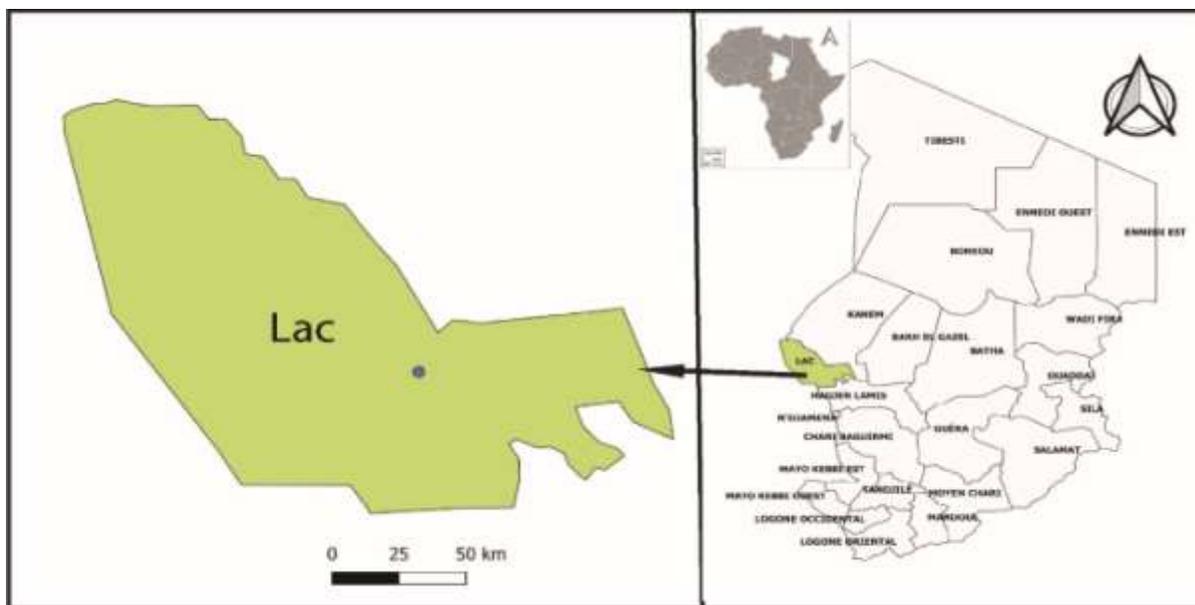


Figure 1.

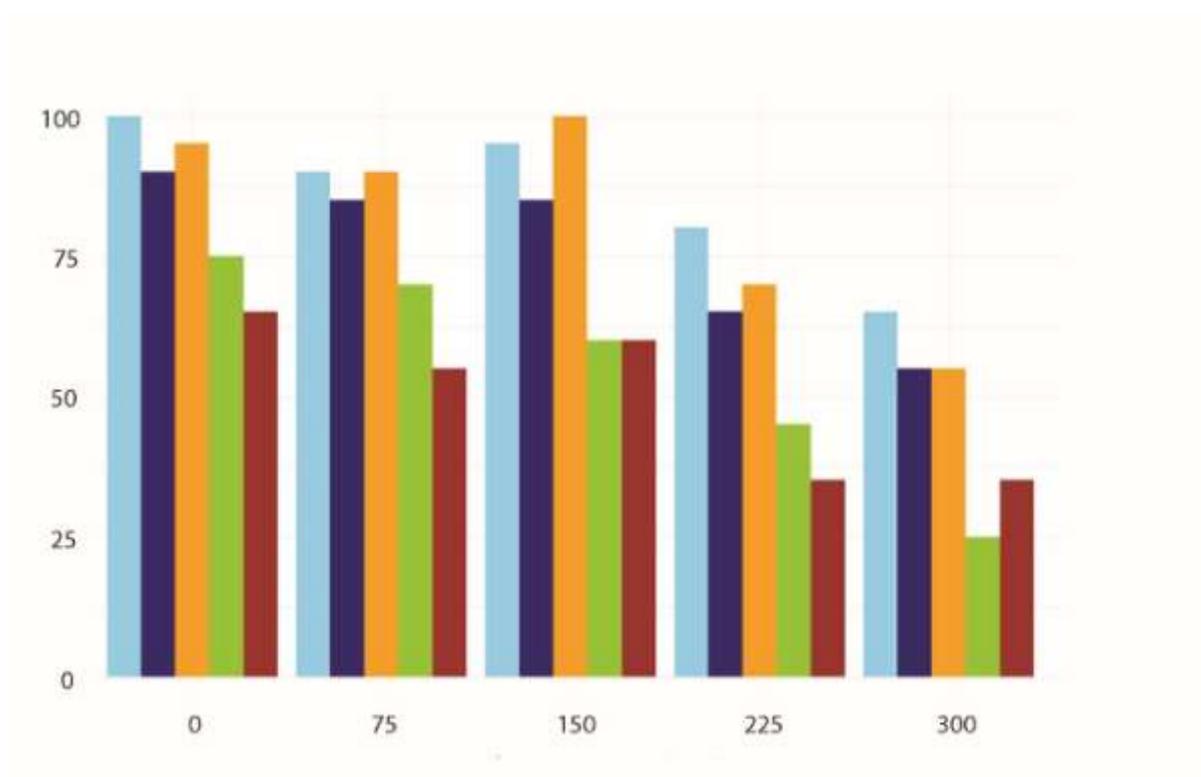


Figure 2.

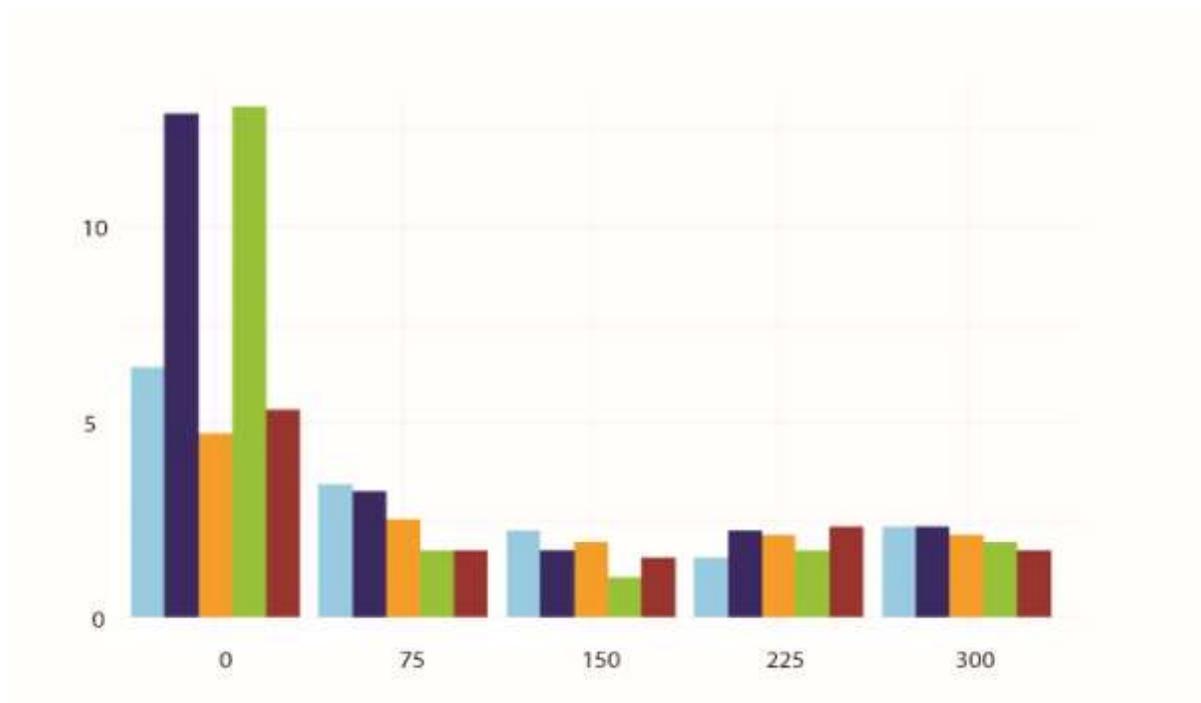


Figure 3.

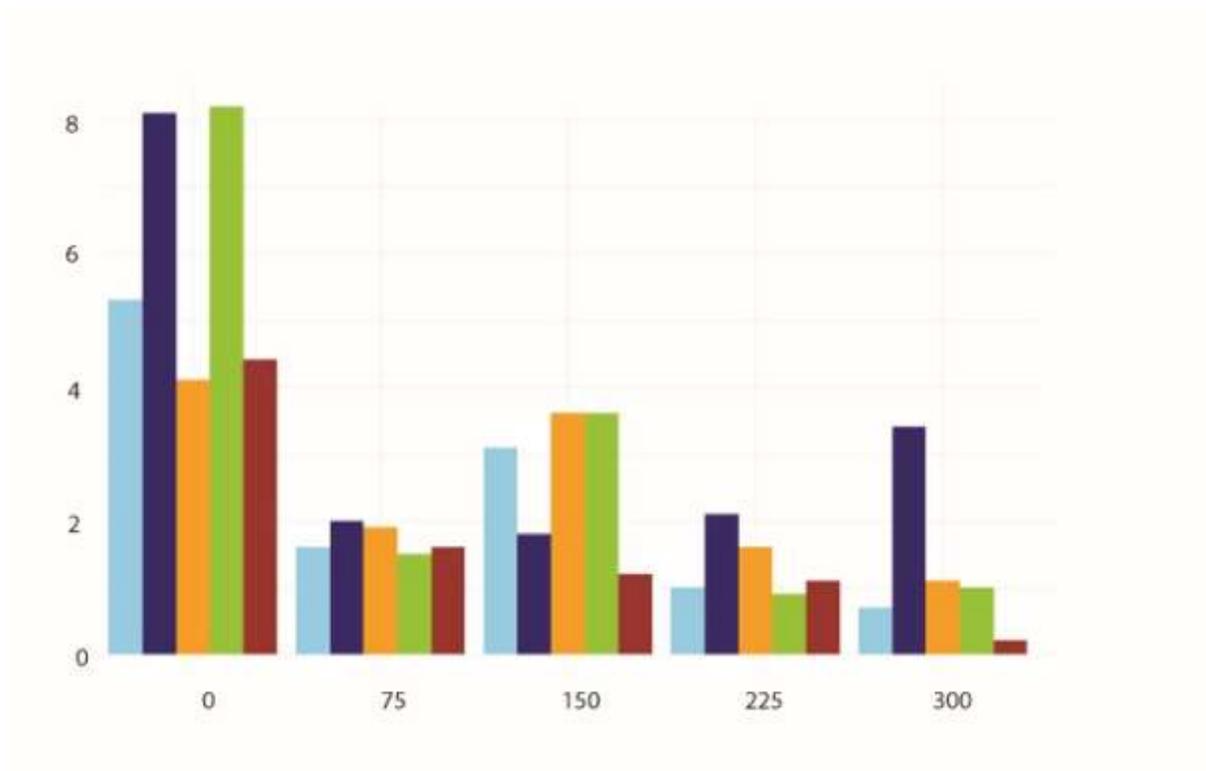


Figure 4.

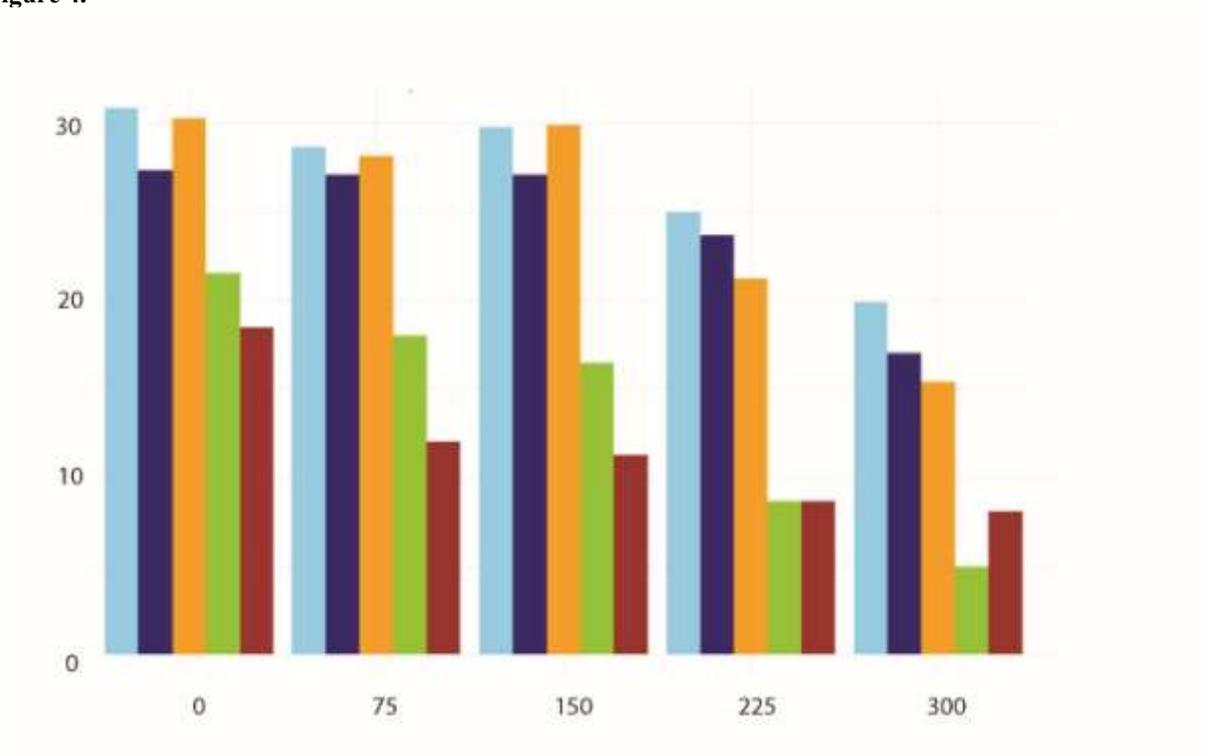


Figure 5.

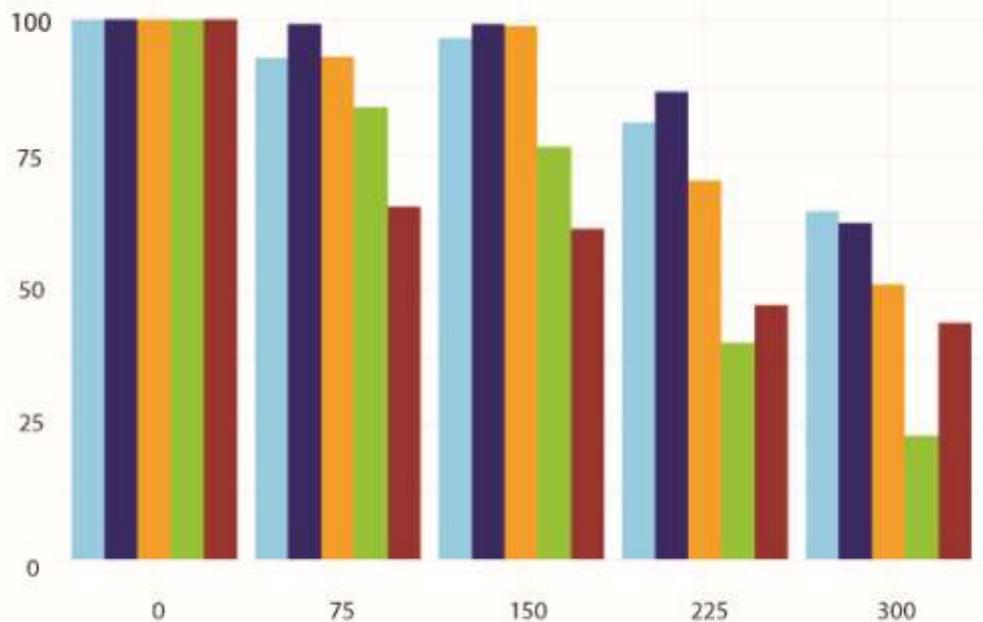


Figure 6.

Legend figure:

Figure 1. Location of the experimental site in the Lac Province, Chad. The left panel shows the Lac Province with the experimental site indicated by a blue dot, while the right panel presents the administrative map of Chad highlighting the Lac Province.

Figure 2. Germination percentage (GP) of five wheat varieties under different NaCl concentrations, measured on day 7 after sowing. Bars represent varieties Penjamo (light blue), Somsps 90 (dark blue), Mexipack (orange), Duilio (green) and Marzak (brown).

X: NaCl concentrations (mM)

Y: germination percentage (%)

Figure 3. Effect of different NaCl concentrations on root growth of seedlings from five wheat varieties, expressed as mean root length (cm) after seven days of experimentation. Bars represent varieties Penjamo (light blue), Somsps 90 (dark blue), Mexipack (orange), Duilio (green) and Marzak (brown).

X: NaCl concentrations (mM)

Y: Root growth (cm)

Figure 4. Effect of different NaCl concentrations on shoot growth of seedlings from five wheat varieties after seven days of exposure. Bars represent varieties Penjamo (light blue), Somsps 90 (dark blue), Mexipack (orange), Duilio (green) and Marzak (brown).

X: NaCl concentrations (mM)

Y: Shoot growth (cm)

Figure 5. Variation in the Germination Speed Index (GSI) of five wheat varieties under different NaCl concentrations. Bars represent varieties Penjamo (light blue), Somsps 90 (dark blue), Mexipack (orange), Duilio (green) and Marzak (brown).

X: NaCl concentrations (mM)

Y: Germination Speed Index (GSI)

Figure 6. Variation in the Salt Tolerance Index (STI) of five wheat varieties under different NaCl concentrations. Bars represent varieties Penjamo (light blue), Somsps 90 (dark blue), Mexipack (orange), Duilio (green) and Marzak (brown).

X: NaCl concentrations (mM)

Y: Salt Tolerance Index STI (%)

Discussion:-

The results of this study unequivocally confirm that salinity exerts a significant inhibitory effect on the processes of germination and early growth of wheat seedlings. The progressive reduction in germination percentage, as well as in root and shoot length, observed with increasing NaCl concentrations is in full agreement with the findings of Mahboob et al. 2023 and Wu et al. 2010. This inhibition is primarily attributed to the dual effect of salt stress: the initial osmotic constraint, which hinders water uptake required for imbibition, and ionic toxicity resulting from Na⁺/K⁺ imbalance, which disrupts enzymatic activity and early physiological processes in wheat. The study clearly highlights pronounced inter-varietal variability in response to salinity stress. Among the five genotypes tested, Mexipack and Soms 90 emerged as the most tolerant, maintaining high germination and growth performance up to 150 mM NaCl. This resilience suggests that these varieties possess more efficient adaptive mechanisms, potentially including enhanced osmoregulatory capacity, increased accumulation of compatible solutes such as proline, and/or reinforced antioxidant activity to neutralize salt-induced oxidative stress, as emphasized by Ibrahimova et al. 2025 and Mrani et al. 2013. Conversely, the variety Marzak proved particularly sensitive, showing significant reductions in germination and growth even at low NaCl concentrations. This sensitivity reflects a limited osmotic adjustment capacity and heightened vulnerability, consistent with observations reported for salt-sensitive genotypes (Zhang et al. 2024; El Sabagh et al. 2021).

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

Conclusion:-

This study conclusively demonstrated that soil salinity exerts a significant inhibitory effect on wheat seed germination and early seedling growth, with responses strongly differentiated according to genotype. Increasing NaCl concentrations induced a progressive reduction in germination percentage as well as in root and shoot length. Phenotypic screening results allowed the classification of varieties according to their level of tolerance. The tolerant varieties Mexipack and Soms 90 maintained satisfactory agronomic performance up to concentrations exceeding 150 mM NaCl, whereas the sensitive variety Marzak exhibited high vulnerability at concentrations below 150 mM NaCl. Statistical analyses confirmed the robustness of these observations and suggest that germination vigor and root growth are reliable indicators of early tolerance to salt stress. To better exploit this tolerance, further research integrating advanced molecular and physiological approaches is recommended to unravel the genetic bases and underlying mechanisms of salinity tolerance. Such insights will guide future wheat breeding strategies aimed at improving productivity under increasing soil salinization, particularly in vulnerable agroecosystems such as the Lake Chad polders.

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