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Yield Response of Novel Wheat Mutant Lines to Water Deficit and Nitrogen Use Efficiency under Smart Agriculture Practices

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Abstract: Drought and sub-optimal nitrogen (N) availability severely threaten wheat production, which is a cornerstone of global food security. Developing climate-resilient wheat varieties is therefore a critical priority. In this study, two field experiments were conducted to assess the performance of novel bread and durum wheat mutant lines as well as two local varieties under varying levels of drought stress and N fertilization, applied at different growth stages according to plant N requirements as climate-smart agricultural (CSA) practices to enhance nitrogen use efficiency (NUE). The findings indicated considerable genotypic variation in response to both stresses. Under severe drought (D2), the mutant lines M34 and M160 exhibited the highest tolerance with the lowest grain yield reductions of 12.5% and 12.9%, respectively, which was further supported by drought tolerance indices. M34 recorded the lowest TOL average of −75.0 and a high STI of 0.95, while M160 demonstrated a balanced STI of 0.90 with competitive MP and GMP values, collectively confirming the resilience and sustained productivity of both mutant lines across moderate and severe drought conditions. Mutant line M160 and the check variety, BS6, showed high NUE, which contributed to increasing grain yield over 25% at the low N level (230 kg N/ha) in climate-smart agriculture practices compared to the recommended level (260 kg N/ha). The mutant line M160 was found to be a unique and valuable genotype because it had both high drought tolerance and high NUE. Consequently, the climate-resilient mutant lines M34 and

M160 demonstrated remarkable potential to sustain economically viable wheat production under drought and low-nitrogen conditions, reducing crop losses and supporting farmer livelihoods in arid and semi-arid systems. CSA practices, through optimized N fertilization timing and reduced chemical inputs, effectively enhanced NUE while mitigating soil degradation, nitrogen leaching, and agrochemical pollution. Collectively, the integration of climate-resilient mutants with CSA practices provided a comprehensive, sustainable, and scalable strategy for improving wheat grain yield and resource use efficiency in water-limited and nitrogen-deficient environments.

Key words: Wheat, mutants, water deficiency, N use efficiency, and climate-smart agriculture practices.

1. Introduction

Wheat (*Triticum aestivum* L.) is the staple diet for more than 2.5 billion people in 89 countries and therefore plays a key role in global food security. It provides approximately 20% of the total caloric and protein intake for a significant portion of the global population, making its production indispensable to human sustenance. With the world population projected to reach 10 billion by 2050, increasing wheat yields is a critical challenge that requires immediate and sustained attention **(Sharma and Sharma, 2025)**. In Egypt, average farm-level wheat yields remain relatively low compared to the national potential of 6.8–7.9 t/ha under optimal management conditions **(Wasti *et al.*, 2024)**. This yield gap is primarily attributed to limited adoption of improved crop varieties, suboptimal nutrient and water management, and low soil fertility in arid and semi-arid production regions **(Sheahan and Barrett, 2017)**.

Research has consistently demonstrated that approximately 60% of the increase in crop productivity is achieved through strategic nutrient and water management, while 40% is attributed to improved crop varieties **(Stewart *et al.*, 2005 and Tilman *et al.*, 2011)**. Therefore, to increase wheat productivity, enhancing the genetic potential of wheat as well as developing climate-smart agricultural practices to optimize nutrient and water use efficiency on farms is essential, particularly in the context of rising global demand and changing climate conditions that threaten traditional farming methods.

Climate change is increasingly contributing to higher temperatures, prolonged drought periods, uneven rainfall distribution, and accelerated soil fertility decline, all of which severely threaten wheat production in arid and semi-arid environments. Therefore, drought stress is a major limiting factor in wheat cultivation, capable of reducing grain yield by up to 50-60% depending on its timing and intensity **(Nyaupane *et al.*, 2024 and Zhao *et al.*, 2020)**. Water shortages negatively impact wheat at all growth stages, from reducing seed germination and plant height to impairing photosynthesis and disrupting the grain-filling process, which ultimately contribute to lower yield and quality **(Mutanda *et al.*, 2025 and Nyaupane *et al.*, 2024)**.

To quantify and compare the drought tolerance of the evaluated genotypes, several yield-based drought tolerance indices have been widely adopted in wheat breeding programs. The drought susceptibility index (DSI), developed by Fischer and Maurer **(Fischer and Maurer, 1978)**, quantifies the proportional yield reduction of a genotype relative to the mean reduction of all tested genotypes under stress conditions. The tolerance index (TOL) and mean productivity index (MP), proposed by Rosielle and Hamblin **(Rosielle, 1981)**, measure the absolute yield difference between stressed and non-stressed environments and the average yield across both conditions, respectively. Fernandez subsequently introduced the geometric mean productivity (GMP) and the stress tolerance index (STI), the latter of which is particularly effective for simultaneously identifying genotypes with high yield under both stressed and non-stressed conditions **(Fernandez, 1992)**. These indices are divided into two groups that work together: susceptibility indices (DSI and TOL), where lower values mean higher drought tolerance, and productivity indices (MP, GMP, and STI), where higher values mean better and more stable yield performance. The combined use of both classes has been consistently recommended for a more reliable and comprehensive screening of drought-tolerant genotypes, as relying on a single index may yield inconclusive rankings **(Farshadfar *et al.*, 2013 and Eid and Sabry, 2019)**.

In addition to water scarcity, wheat production is highly dependent on nutrient availability, especially nitrogen. Nitrogen (N) is the most critical input for achieving high yields and adequate grain protein content. However, applying N fertilizer during inappropriate growth stages and under unsuitable climatic conditions poses a significant threat to the environment, including surface and groundwater pollution from nitrate, emissions of ammonia and greenhouse gases (GHG), and reduced crop productivity **(Hawkesford, 2017)**.

Mutation breeding, utilizing physical mutagens such as gamma irradiation, has proven to be one of the most effective and widely applied strategies for generating novel genetic variability in crop plants, particularly for improving tolerance to abiotic stresses such as drought **(Jankowicz-Cieslak, 2016; Mba, 2013)**. Gamma rays induce random mutations across the genome, creating a broad spectrum of phenotypic variation that can be screened for desirable traits including enhanced water use efficiency, deeper root systems, osmotic adjustment, and improved stomatal regulation under water deficit conditions **(Esnault, 2010 and Sikora, 2011)**. In wheat specifically, mutation breeding has successfully generated genotypes with significantly improved drought tolerance, as gamma-irradiated mutant lines have demonstrated superior performance in terms of grain yield stability, reduced yield loss under water stress, and enhanced physiological adaptation to arid environments **(El-Degwy, 2013 and Esnault, 2010)**. The International Atomic Energy Agency (IAEA) and the Food and Agriculture Organization (FAO) have jointly supported mutation breeding programs globally, resulting in the release of over 3,000 officially registered mutant crop varieties, many of which exhibit improved tolerance to drought and other abiotic stresses **(FAO/IAEA, 2021)**. These advances point out the importance of mutation breeding as a complementary tool to conventional and molecular breeding approaches in the development of climate-resilient wheat varieties capable of sustaining productivity under the increasingly challenging conditions imposed by climate change **(Nazarenko, 2023 and OlaOlorun *et al.*, 2021)**.

A comprehensive assessment of novel wheat mutant lines under varying levels of both drought stress and N fertilization is crucial to identify robust genotypes suitable for release in diverse agricultural systems. This study was conducted to evaluate the performance of novel high-yielding wheat mutants under varying drought and nitrogen levels using climate-smart agricultural (CSA) practices and to validate the application of CSA practices in wheat production under drought stress and different nitrogen fertilization regimes.

2. Materials and Methods

2.1. Experimental site and plant material

The field experiment was carried out at the farm of the Nuclear Research Center, Egyptian Atomic Energy Authority, Inshas, Egypt, during the winter growing season of 2023/2024. The site has an arid climate with a long-term average of 17.8°C and total rainfall (46 mm) (Fig. 1), making crop production reliant on irrigation. The soil had a sandy loam texture, and the soil at a depth of 0–30 cm before wheat sowing was slightly alkaline, with low fertility, a pH of 8.2, organic matter content of 1.1%, total nitrogen (N) of 0.5 g/kg, available phosphorus (P) of 7.0 mg/kg, and potassium (K) of 150 mg/kg.

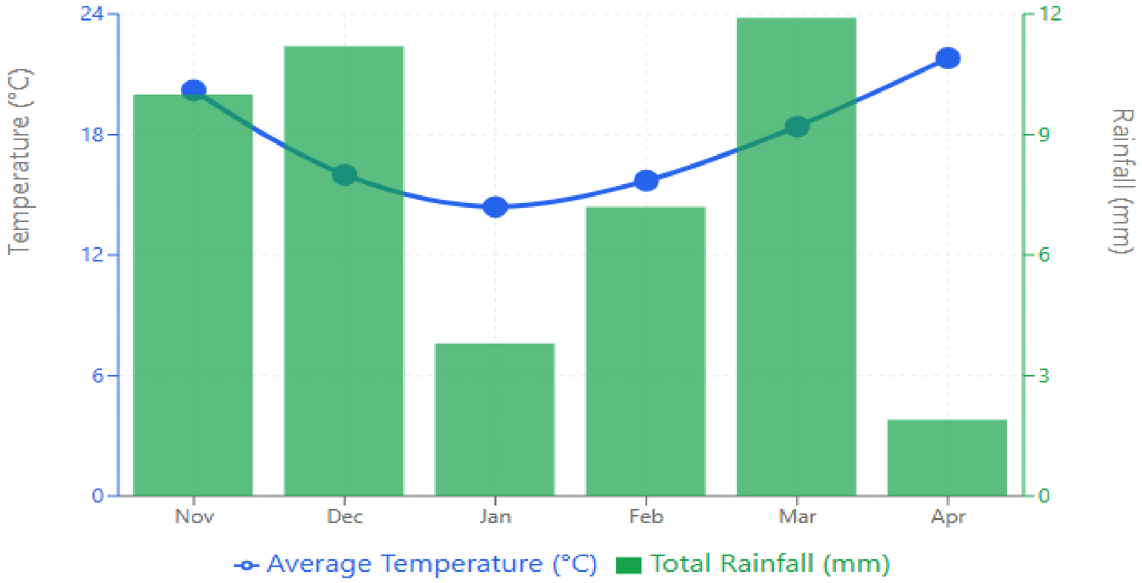

Fig. (1). Average monthly temperature (°C) and total monthly rainfall (mm) during the 2023-2024 wheat growing season.

Table (1). The characteristics of wheat genotypes in this study

Name	**Type**	**Pedigree**	**Main traits**
Taqa 14	Mutant	[Aseel-5/γ-ray 350 Gy]	Rust resistance, long spike, high yield, TGW
Taqa 59	Mutant	[Sakha 93/γ-ray 350 Gy]	Rust resistance, high tillers, high yield
Taqa 152	Mutant	[Sakha 93/γ-ray 350 Gy]	Rust resistance, too early, high yield
M34	Mutant	[Aseel 5/γ-ray 350 Gy]	Rust resistance, high tillers, high yield, drought tolerance
M154-2	Mutant	[Giza 168/γ-ray 350 Gy]	Rust resistance, early heading, high yield
M160	Mutant	[Aseel 5/γ-ray 350 Gy]	Rust resistance, high yield, drought tolerance
Giza 171 (Gz171)	Local variety	[Sakha 93/Gemmiza 9]	Rust resistance, high yield, high quality
Taqa 4	Mutant	[Sohag 3/γ-ray 350 Gy/M5/S4] × [Beni Sueif 3/γ-ray 250 Gy/M5/B2]	Rust resistance, early heading, high yield, high quality
Taqa 9	Mutant	[Beni Sueif 3/γ-ray 350 Gy]	Rust resistance, moderate heading, high yield, high quality
Beni Suef 6 (BS6)	Local variety	BOOMER-21 / BUSCA-3	Rust resistance, high yield, high quality

Ten wheat genotypes, seven bread wheat (*Triticum aestivum* L.) genotypes (Taqa14, Taqa59, Taqa152, M34, M154-2, M160, and local variety Giza171); and three durum wheat (*Triticum durum* Desf.) genotypes (Taqa 4, Taqa9, and local variety Beni Suef6) were selected for this study. The wheat mutant lines were developed by the Egyptian Atomic Energy Authority using gamma irradiation, and they were selected for their high yield potential and rust resistance.

2.2. Field experiments

Two field experiments were established to assess the performance of the ten wheat genotypes under varying levels of drought stress and N fertilization using a drip irrigation system. The total area of each experimental plot was 6 m², and it was made up of 10 rows, each 3 meters long. The grains were grown on 10*20 cm plots within and between rows. Each plot received P and K at a rate equivalent to 70 and 60 kg ha^{-1}, respectively before sowing the wheat crop. The grain of the wheat genotypes was sown on the 15th of November, 2023, at a seed rate of 140 kg/ha. The treatments were applied with two replications in a randomized complete block design (RCBD). In the drought stress experiment, three treatments were conducted: well-watered (control), moderate stress (D1), and severe stress (D2), in which the irrigation was applied every 7, 14 and 21 days, respectively. In the nitrogen fertilization experiment, three treatments were applied as urea (46% N), where each treatment was divided into three doses, with the first dose applied in the growth stage (GS) GS-32, followed by the second and third doses in the growth stages GS-39 and GS-59, respectively. The three levels were as follows:

- Recommended dose: 260 kg N ha^{-1}, applied in splits of 85, 85, and 90 kg N ha^{-1}.
- Low dose (T1): 230 kg N ha^{-1}, applied in splits of 95, 105, and 30 kg N ha^{-1}.
- High dose (T2): 290 kg N ha^{-1}, applied in splits of 110, 130, and 50 kg N ha^{-1}.

2.3. Data measurements and statistical analysis

At physiological maturity, the agronomic and yield-related traits were collected. The following parameters were measured from each experimental plot, such as plant height, spike length, number of spikelets/spike, spike number/m², biological yield/m², and grain yield/m².

Analysis of variance (ANOVA) was carried out to determine if the different treatments had any significant effect on wheat grain yield using the MSTATC software package (version 2.4). Duncan's multiple range test values were calculated only when the treatment effect was significant at $P \leq 0.05$.

2.4. Calculation of Drought Tolerance Indices

To evaluate and compare the drought tolerance of the ten wheat genotypes across the two drought levels (D1 and D2), five yield-based drought tolerance indices were calculated using grain yield data recorded under well-watered (Yp) and drought-stressed (Ys) conditions, following the formulae of Fischer and Maurer (1978), Rosielle and Hamblin (1981), and Fernandez (1992), as summarized in Table X:

1. Drought Susceptibility Index (DSI) = $1-(Ys/Yp)/1-(\bar{Y}s/\bar{Y}p)$, **(Fischer and Maurer, 1978)**.
2. Tolerance Index (TOL) = $Ys-Yp$ **(Rosielle, 1981)**.
3. Mean Productivity Index (MP) = $(Ys+Yp)/2$ **(Rosielle, 1981).**
4. Geometric Mean Productivity (GMP) = $(Yp*Ys)^{0.5}$ **(Fernandez, 1992).**
5. Stress Tolerance Index (STI) = $(Ys*Yp)/(\bar{Y}p)^2$ **(Fernandez, 1992).**

Where Yp and Ys are the grain yield means of individual genotypes under well-watered and drought-stressed conditions, respectively, and $\bar{Y}p$ and $\bar{Y}s$ are the grand means of all genotypes under well-watered and drought-stressed conditions, respectively. Each index was calculated separately for D1 and D2, and the average across both drought levels was used for final genotypic comparisons and classification **(Eid and Sabry, 2019)**.

3. Results

3.1. Effect of drought stress on wheat genotypes

All wheat genotypes exhibited significant variations at $P \leq 0.05$ in agro-morphological and yield traits in response to drought stress, with the adverse effects of water deficit clearly observed in grain yield, which declined as the stress intensified from moderate (D1) to severe (D2) levels (Table 2).

3.1.1. Grain yield performance under drought stress

All wheat genotypes produced the highest grain yield under the well-watered control treatment, followed by a gradual decline under the D1 and D2 treatments, as shown in Figure 1 and Table 2. The bread wheat mutant lines Taqa152 and Taqa14 exhibited the highest grain yield (1.072 and 1.040 t/ha, respectively) among all evaluated wheat genotypes under well-watered conditions. Also, the mutant line Taqa152 gave the highest mean harvest index (48.6) across all drought treatments. In bread wheat genotypes under severe drought treatment (D2), the mutant lines M34 and M160 recorded the highest grain yields of 8.72 and 8.56 g/m^2, respectively, compared to the local variety Giza 171, which yielded 7.11 t/ha. This corresponds to significant grain yield increases of 22.7% and 20.4% for M34 and M160, respectively, over the local variety. The performance of durum wheat mutant lines varied by water regime. The mutant line Taqa 9 exhibited the maximum grain yield under well-watered conditions (1.05 t/ha), significantly exceeding the local check BS6 (8.23 t/ha) by 27.7%. Under drought treatments D1 and D2, the mutant line Taqa 4 recorded the highest grain yield among all durum wheat genotypes, with values of 8.54 and 8.12 t/ha, respectively. Across both well-watered and drought treatments, all bread and durum wheat mutant lines outperformed their respective local varieties (Giza 171 and BS6) in grain yield, with recorded increases ranging from 4% to 20%, except for mutant line Taqa 59 under severe drought, which did not exhibit a yield advantage.

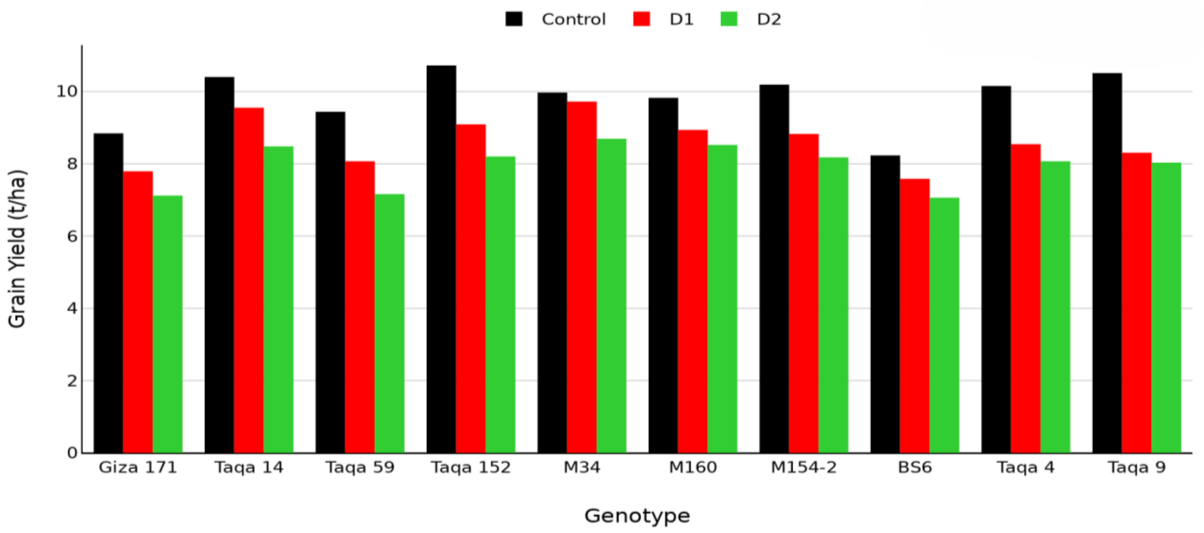

Fig. (1). Grain yield of ten wheat genotypes under control, moderate drought (D1), and severe drought (D2) conditions.

3.1.2. Yield reduction under drought stress

To compare the drought tolerance of the genotypes, the percentage of reduction in grain yield relative to the control was calculated (Fig. 2). Under moderate and severe drought treatments, the mutant line M34 was exceptionally tolerant, exhibiting the lowest yield reduction of only 2.5 and 12.5%, respectively, as compared with local variety Giza171 (11.6% and 19.6%, respectively). Also, the mutant M160 demonstrated strong tolerance with a yield loss of only 12.9% under severe drought. In contrast, the mutant lines Taqa 59 and Taqa 9 were the most drought-sensitive, suffering the greatest yield losses of 24.4% and 23.4%, respectively.

Table (2). Effect of drought stress treatments on the agronomic and yield traits of ten wheat genotypes

Genotype	Treatment	Plant Height (cm)	Spike Length (cm)	Spikelets No./Spike	Spikes No./m²	Biological Yield (g/m²)	Grain Yield (g/m²)	Harvest index	Yield increases %
Giza171	Control	110.0	12.0	22	438.0	2019	883.5	43.8	
	D1	107.5	12.0	23	398.5	1901	780.5	41.1	
	D2	105.5	10.5	21	369.5	1751	710.5	40.6	
	Mean	107.7^{ab}	11.5^{e}	22.0^{e}	402.0^{f}	1890^{ef}	791.5^{e}	41.8^{de}	
Taqa14	Control	108.5	23.5	29	510.0	2473	1040.0	42.1	17.7%
	D1	109.5	22.5	28	448.5	2157	955.5	44.3	22.4%
	D2	109.0	20.5	28	438.0	2017	851.0	42.2	19.8%
	Mean	109.0^{a}	22.2^{a}	28.3^{a}	465.5^{cd}	2215^{b}	948.7^{a}	42.9^{cd}	19.9%
Taqa59	Control	95.0	13.0	20	563.5	2073	944.5	45.6	6.9%
	D1	85.0	11.5	19	491.5	1856	811.5	43.7	4.0%
	D2	91.5	11.0	19	470.0	1698	714.0	42.1	0.5%
	Mean	90.5^{f}	11.8^{e}	19.3^{f}	508.3^{b}	1875^{f}	823.3^{d}	43.8^{c}	4.0%
Taqa152	Control	101.5	14.0	24	476.0	2078	1072	51.6	21.3%
	D1	96.0	13.5	22	417.0	1910	909.0	47.6	16.5%
	D2	89.5	12.5	21	399.0	1775	827.5	46.7	16.5%
	Mean	95.7^{def}	13.3^{d}	22.3^{de}	430.7^{e}	1921d^{ef}	936.2^{ab}	48.6^{a}	18.3%
M34	Control	112.0	13.5	23	587.0	2558	997.0	39.0	12.8%
	D1	103.0	13.0	24	507.5	2195	972.0	44.3	24.5%
	D2	100.0	12.5	23	483.0	2057	872.0	42.4	22.7%
	Mean	105.0^{abc}	13.0^{d}	23.3^{d}	525.8^{a}	2270^{a}	947.0^{a}	41.9^{de}	19.6%
M160	Control	106.0	16.0	28	438.5	2120	982.5	46.4	11.2%
	D1	106.5	14.5	27	410.0	1917	893.5	46.7	14.5%
	D2	96.5	13.5	25	389.5	1870	855.5	45.8	20.4%
	Mean	103.0^{abcd}	14.7^{c}	26.7^{b}	412.7^{f}	1969^{d}	910.5^{bc}	46.3^{b}	15.0%
M154-2	Control	104.0	19.0	26	456.0	2124	1019	48.0	15.3%
	D1	100.5	16.5	25	400.0	1882	882.5	46.9	13.1%
	D2	98.5	15.0	25	369.0	1813	817.5	45.2	15.1%
	Mean	101.0^{bcde}	16.8^{b}	25.3^{c}	408.3^{f}	1939de	906.3^{c}	46.7^{b}	14.5%
BS6	Control	98.5	9.0	20	489.0	2096	823.0	39.3	
	D1	96.0	7.5	19	422.5	1880	758.5	40.4	
	D2	90.5	7.0	18	375.5	1741	706.0	40.6	
	Mean	95.0^{ef}	7.8^{g}	19.0^{f}	429.0^{e}	1905^{ef}	762.5^{f}	40.1^{e}	
Taqa4	Control	100.0	11.0	20	488.5	2225	1015.0	45.6	23.3%
	D1	98.5	9.5	20	454.5	1971	854.0	43.4	12.6%
	D2	100.5	8.5	18	413.0	1862	812.0	43.7	15.0%
	Mean	99.7^{cde}	9.7^{f}	19.3^{f}	452.0^{d}	2019^{c}	893.5^{c}	44.2^{c}	17.2%
Taqa9	Control	106.0	13.5	24	535.0	2489	1051.0	42.3	27.7%
	D1	92.5	11.5	23	458.0	2119	830.5	39.3	9.5%
	D2	82.5	10.5	22	419.0	1912	805.5	42.2	14.1
	Mean	93.7^{ef}	11.8^{e}	23.0^{de}	470.7^{c}	2173^{b}	895.7^{c}	41.2^{de}	17.5%
Overall Mean	Control	104.2^{a}	14.5^{a}	NS	498.1^{a}	2225^{a}	982.7^{a}	44.4^{a}	
	D1	99.5^{ab}	13.2^{b}	NS	440.8^{b}	1978^{b}	864.8^{b}	43.7^{ab}	
	D2	96.4^{b}	12.2^{b}	NS	412.5^{c}	1849^{c}	797.2^{c}	43.1^{b}	

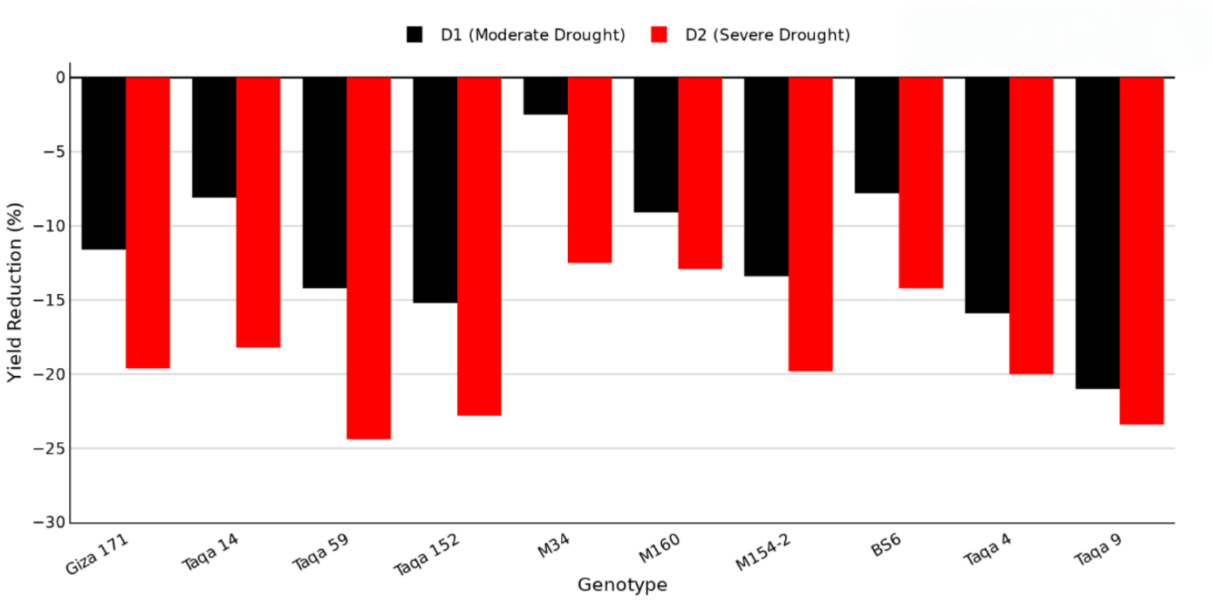

Fig. (2). Percentage of reduction in grain yield for ten wheat genotypes under D1 and D2 of drought stress relative to the well-watered (control) conditions.

3.1.3. Drought Tolerance Indices

The five drought tolerance indices were evaluated under two levels of drought stress, moderate and severe drought (D1 and D2), and the average across both levels was used for final genotypic comparison of susceptibility and productivity indices (Tables 2 and 3).

3.1.3.1. Susceptibility Indices (DSI and TOL)

For the DSI index, all genotypes recorded negative average values across both drought levels, confirming universal yield suppression under water deficit. However, the degree of susceptibility varied considerably among genotypes. Taqa 59 recorded the lowest DSI average of -0.77 across D1 and D2, followed by Taqa 152 and Taqa 9 with averages of -0.78 each. In contrast, M34 showed the highest DSI average of -0.84, while M154-2 and BS6 recorded -0.83, and GZ171, M160 and Taqa 4 recorded -0.80, indicating the greatest proportional yield reduction across both drought levels among all tested genotypes.

Table (3). The susceptibility Indices (DSI and TOL) of ten wheat genotypes under two levels of water regime

Genotypes	DSI1	DSI2	Average	TOL1	TOL2	Average
Gz171	-0.76	-0.83	**-0.80**	-103.0	-173	**-138**
Taqa 14	-0.80	-0.81	**-0.81**	-84.0	-188.5	**-136.3**
Taqa 59	-0.74	-0.80	**-0.77**	-133.0	-230.5	**-181.8**
Taqa 152	-0.73	-0.83	**-0.78**	-163.0	-244.5	**-203.8**
M34	-0.85	-0.82	**-0.84**	-25.0	-125	**-75**
M154-2	-0.79	-0.88	**-0.83**	-89.0	-127	**-108**
M160	-0.75	-0.85	**-0.80**	-136.5	-201.5	**-169**
BS6	-0.80	-0.85	**-0.83**	-64.5	-117	**-90.8**
Taqa 4	-0.72	-0.87	**-0.80**	-160.5	-202.5	**-181.5**
Taqa 9	-0.67	-0.89	**-0.78**	-220.5	-245.5	**-233**

Regarding the TOL index, M34 recorded the lowest average of -75.0 across D1 and D2, indicating the smallest absolute yield loss under both moderate and severe drought, followed by BS6 (-90.8) and M154-2 (-108.0). In contrast, Taqa 9 and Taqa 152 recorded the highest absolute TOL averages of -233.0 and -203.8, respectively, reflecting the largest absolute yield reductions across both drought levels.

3.1.3.2. Productivity Indices (MP, GMP, and STI)

The productivity indices, averaged across D1 and D2, revealed a clear ranking of genotypes in terms of sustained yield capacity under drought. Taqa 14 recorded the highest averages for all three productivity indices, MP of 971.4, GMP of 968.6, and STI of 0.97, followed closely by Taqa 152 with MP of 970.1 and STI of 0.96, and M34 with MP of 959.5 and STI of 0.95. Similarly, M160 demonstrated a balanced STI average of 0.90 combined with competitive mean productivity (MP) and geometric mean productivity (GMP) values, further validating its stable yield performance under both moderate and severe drought conditions. On the other hand, BS6 consistently recorded the lowest productivity averages across both drought levels, with MP of 777.6, GMP of 776.2, and STI of 0.62. Giza 171 also showed relatively low STI (0.68) and MP (814.5), reflecting limited productivity across D1 and D2.

Table (3). The productivity indices (MP, GMP, and STI) of ten wheat genotypes under two levels of water regime

Genotypes	MP1	MP2	Average	GMP1	GMP2	Average	STI1	STI2	Average
Gz171	832.0	797.0	**814.5**	830.4	792.3	**811.3**	0.71	0.65	**0.68**
Taqa 14	997.5	945.3	**971.4**	996.6	940.5	**968.6**	1.03	0.92	**0.97**
Taqa 59	878.0	829.3	**853.6**	875.5	821.2	**848.3**	0.79	0.70	**0.75**
Taqa 152	990.5	949.8	**970.1**	987.1	941.8	**964.5**	1.01	0.92	**0.96**
M34	984.5	934.5	**959.5**	984.4	932.4	**958.4**	1.00	0.90	**0.95**
M154-2	938.0	919.0	**928.5**	936.9	916.8	**926.9**	0.91	0.87	**0.89**
M160	950.8	918.3	**934.5**	948.3	912.7	**930.5**	0.93	0.86	**0.90**
BS6	790.8	764.5	**777.6**	790.1	762.3	**776.2**	0.65	0.60	**0.62**
Taqa 4	934.3	913.3	**923.8**	930.8	907.6	**919.2**	0.90	0.85	**0.88**
Taqa 9	940.8	928.3	**934.5**	934.3	920.1	**927.2**	0.90	0.88	**0.89**

3.2. Effect of nitrogen fertilization levels on wheat genotypes

Nitrogen fertilization level had a significant ($P \leq 0.05$) effect on the agronomic performance and grain yield of the wheat genotypes. The way different genotypes reacted to both low (T1) and high (T2) N applications, compared to the recommended control, was quite different (Table 4).

3.2.1. Grain yield performance at varying nitrogen levels

Most studied wheat genotypes produced significantly higher grain yield at low (T1) and high (T2) levels of N compared to the control level (Fig. 3), indicating that the control level may be suboptimal for these genotypes under the experimental conditions. Under low nitrogen treatment, the durum wheat mutant Taqa 9 and bread wheat mutant M160 achieved the highest grain yields (1250 and 1229 g/m², respectively) relative to the control N level among all wheat genotypes, reflecting their high nitrogen use efficiency (NUE). Furthermore, mutant lines M160 and M154-2 exhibited the strongest positive response to increasing nitrogen fertilization, producing the highest grain yields (1251 and 1226 g/m², respectively) under the high N level (T2). Similarly, the durum wheat mutant Taqa4 showed a marked positive response, with its yield increasing from 1015 g/m² under control conditions to 1238 g/m² at the high N level. Overall, both climate-smart N fertilizer treatments (T1 and T2) outperformed the nationally recommended N level.

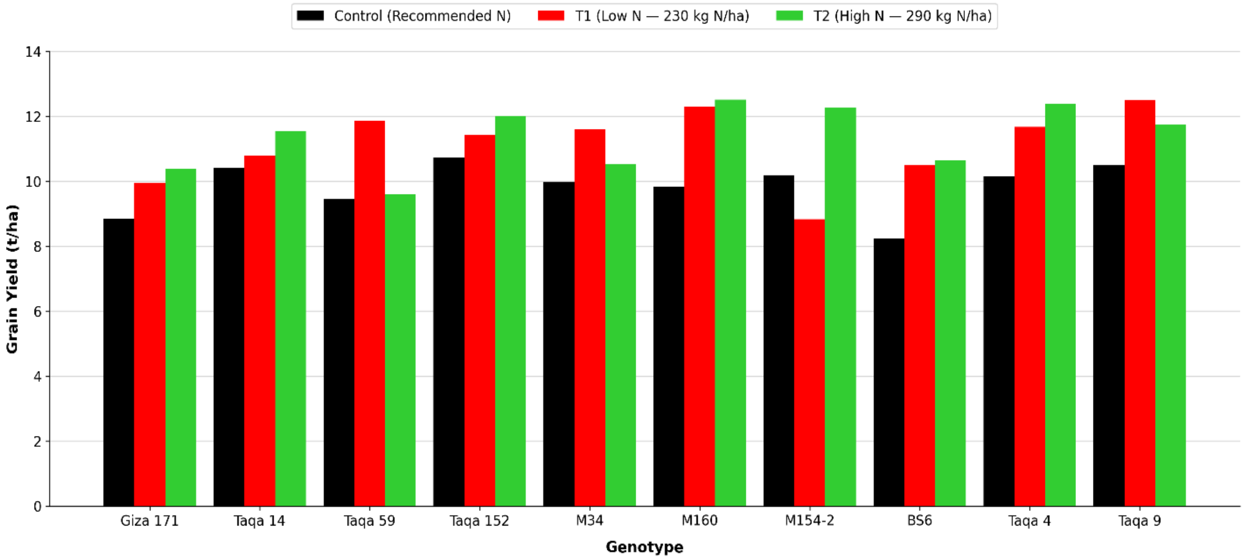

Fig. (3). Grain yield of ten wheat genotypes under recommended (control), low N (T1), and high N (T2) fertilization levels.

3.2.2. Climate-Smart Agriculture Practices of Nitrogen Use Efficiency and Responsiveness

The change percentage in grain yield relative to the control dose offers perspectives on both N use efficiency (positive response to low N) and responsiveness to high N inputs (Figure 4). The local variety BS6 and the mutant line M160 were highly efficient and responsive, showing the largest yield increases of 27.0% and 25.1%, respectively, even at the low N (N1) level. They further increased their yield under high N (N2). This suggests these genotypes can utilize N very effectively. The mutant Taqa59 showed a strong yield increase (25.7%) under the low N treatment but did not respond further to the high N treatment, suggesting it is highly efficient at a low N level but may have a lower yield potential limitation. These results showed that Giza 171, Taqa 152, M160, M154-2, BS6, and Taqa 4 are the best types for using nitrogen efficiently.

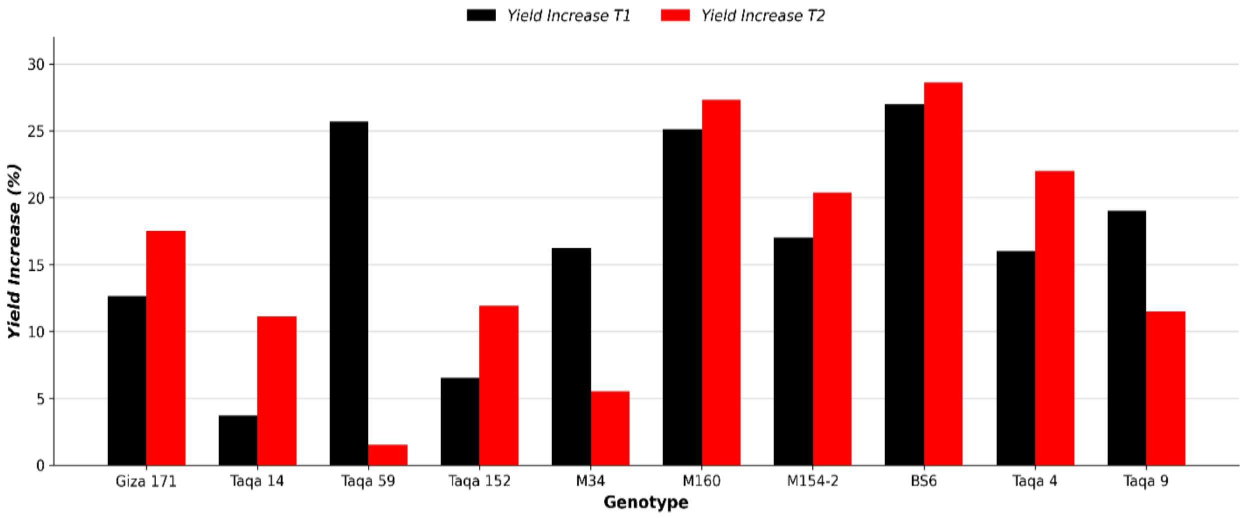

Fig. (4). The change percentage in grain yield for ten wheat genotypes under low N (T1) and high N (T2) treatments relative to the recommended control.

Table (4). How different N fertilization treatments affect the growth and yield of ten wheat genotypes compared to the recommended control

Genotypes	Treatments	Plant Height (cm)	Spike Length (cm)	Spikelets No./Spike	Spikes No./m²	Biological Yield (g/m²)	Grain Yield (g/m²)	Harvest Index (%)	Yield increases %
Giza171	Control	110.0	12.0	22	438.0	2019	884	43.8	
	T1	111.0	12.5	23	510.5	2105	995	47.3	12.6%
	T2	104.5	10.5	23	576.0	2220	1038	46.8	4.3%
	Mean	108.5^{ab}	11.7^{g}	22.7^{d}	508.2^{g}	2114^{d}	972^{d}	45.9^{c}	
Taqa14	Control	108.5	23.5	29	510.0	2473	1040	42.1	
	T1	110.0	22.5	30	564.0	2283	1078	47.2	3.7%
	T2	106.5	24.0	29	576.5	2390	1155	48.3	11.1%
	Mean	108.3^{ab}	23.3^{a}	29.3^{a}	550.2^{d}	2382^{b}	1091^{b}	35.8^{f}	
Taqa59	Control	95.0	13.0	20	563.5	2073	944.5	45.6	
	T1	96.5	13.0	21	610.5	2190	1187	54.2	25.7%
	T2	92.5	12.0	19	643.0	2068	959	46.4	1.5%
	Mean	94.7^{e}	12.7^{f}	20.0^{e}	605.7^{b}	2110^{d}	1030^{c}	48.8^{b}	
Taqa152	Control	101.5	14.0	24	476.0	2078	1072	51.6	
	T1	95.0	15.0	25	552.5	2151	1142	53.1	6.5%
	T2	95.5	15.0	25	572.5	2190	1200	54.8	11.9%
	Mean	97.3^{d}	14.7^{d}	24.7^{c}	533.7^{e}	2140^{d}	1138^{a}	53.2^{a}	
M34	Control	112.0	13.5	23	587.0	2558	997	39.0	
	T1	110.0	14.5	24	618.0	2678	1159	43.3	16.2%
	T2	107.5	14.0	23	660.5	2874	1052	36.6	5.5%
	Mean	109.8^{de}	14.0^{de}	23.3^{d}	621.8^{a}	2703^{a}	1069^{b}	39.6^{e}	
M160	Control	106.0	16.0	28	438.5	2120	982.5	46.3	
	T1	98.5	16.5	28	474.5	2168	1229	56.7	25.1%
	T2	101.5	16.5	29	516.0	2396	1251	52.2	27.3%
	Mean	102.0^{c}	16.3^{c}	28.3^{a}	476.3^{h}	2228^{c}	1154^{a}	51.8^{a}	
M154-2	Control	104.0	19.0	26	456.0	2124	1019	48.0	
	T1	107.0	18.5	27	495.5	2142	1193	55.7	17.1%
	T2	100.5	19.0	26	517.0	2479	1226	49.5	20.3%
	Mean	103.8^{b}	18.8^{b}	26.3^{b}	489.5^{h}	2248^{c}	1146^{a}	51.1^{a}	
BS6	Control	98.5	9.0	20	489.0	2096	823	39.3	
	T1	101.5	9.5	20	517.5	2303	1045	45.4	27.0%
	T2	92.5	9.0	21	550.0	2305	1058	45.9	28.6%
	Mean	97.5^{h}	9.2^{h}	20.3^{e}	518.8^{fg}	2234^{c}	975^{d}	43.5^{d}	
Taqa4	Control	100.0	11.0	20	488.5	2225	1015	45.6	
	T1	107.5	11.5	21	531.0	2215	1177	53.1	16.0%
	T2	97.5	11.0	22	553.0	2656	1238	46.6	22.0%
	Mean	101.7^{g}	11.2^{g}	21.0^{e}	524.2^{ef}	2365^{b}	1143^{a}	48.5^{b}	
Taqa9	Control	106.0	13.5	24	535.0	2489	1051	42.2	
	T1	100.5	14.0	25	578.5	2663	1250	46.9	18.9%
	T2	95.0	14.0	25	595.5	2829	1168	41.3	11.1%
	Mean	100.5^{e}	13.8^{e}	24.7^{c}	569.7^{c}	2660^{a}	1156^{a}	43.5^{d}	
Overall Mean	Control	NS	NS	23.6^{b}	498.1^{c}	2252^{c}	982.7^{b}	43.6^{b}	
	T1	NS	NS	24.4^{a}	545.3^{b}	2290^{b}	1145^{a}	50.0^{a}	16.5%
	T2	NS	NS	24.2^{ab}	576.0^{a}	2440^{a}	1134^{a}	46.5^{b}	15.4%

4. Discussion

This study provides a comprehensive evaluation of novel wheat mutants under drought stress and varying N fertilization levels, which are primary constraints on crop production in arid and semi-arid regions. The results demonstrate significant genotypic variation in response to these stresses, highlighting the success of the mutation breeding program in developing resilient and efficient germplasm.

4.1. Genotypic performance and tolerance under drought stress

The drought stress led to a predictable decline in growth and yield parameters across all genotypes (Table 1), the findings consistent with **(Fahad *et al.*, 2017 and Zhao *et al.*, 2020)**. The decrease in grain yield in water-limited conditions results directly from adverse effects on essential yield components, including the number of spikes per unit area and biomass production. However, the key finding of this experiment was the differential response among the genotypes, which is crucial for identifying stress-tolerant genetic material. The mutant lines M34 and M160 were the best varieties for being able to survive in drought stress. Their superior performance was visually evident in their significantly lower percentage of yield reduction compared to other genotypes, especially under severe stress (Figure 2). The tolerance of M34 was exceptional; its yield under severe drought was higher than the yield of several other genotypes under only moderate stress (Figure 1). This yield stability is a sign of drought tolerance and is often linked to the ability to keep important physiological processes going in water deficit, such as maintaining photosynthesis and nutrient uptake, which are crucial for plant survival during drought conditions **(Barnabás *et al.*, 2008)**. The identification of mutant lines M34 and M160 provides valuable genetic resources that can be used in breeding programs to improve drought resilience in modern wheat cultivars.

4.2. Drought Tolerance Indices

The two-level drought stress approach adopted in this study provides a more comprehensive assessment of genotypic stability across a range of water deficit intensities, as recommended by Fernandez, and Eid **(Fernandez, 1992 and Eid and Sabry, 2019).** The contrasting rankings observed between susceptibility and productivity indices highlight the importance of using complementary indices rather than relying on a single measure, as emphasized by Farshadfar, Eid and Zahedi **(Farshadfar *et al.*, 2013; Eid and Sabry, 2019 and Zahedi MB, 2026)**, who demonstrated that individual indices could produce misleading genotypic classifications when applied in isolation.

The high DSI average recorded for M34 (-0.84) may initially suggest susceptibility; however, this must be interpreted alongside the TOL index, where M34 recorded the lowest absolute yield reduction of -75.0 across both drought levels. This apparent contradiction is well documented in the literature, as Fischer and Maurer **(Fischer and Maurer, 1978)** noted that DSI values reflect proportional sensitivity relative to the mean performance of all genotypes, and thus a high-yielding genotype performing consistently well under stress may record a higher DSI without being truly susceptible. The consistently low TOL value of M34, combined with its high STI of 0.95, confirms its status as the most drought-resilient genotype in this study, capable of minimizing yield reduction while sustaining high productivity under both moderate and severe drought, a highly desirable trait profile for breeding programs targeting arid and semi-arid environments **(Blum, 2011)**.

Taqa 14 emerged as the most productive genotype under drought conditions, excelling across all productivity indices with the highest STI (0.97), MP (971.4), and GMP (968.6) averages. According to Fernandez (Fernandez, 1992), the STI is the most reliable index for simultaneously identifying genotypes with high yield under both stressed and non-stressed conditions, as it integrates performance across both environments into a single value. The strong performance of Taqa 14 and Taqa 152 in the productivity indices aligns with their high grain yield recorded under well-watered and drought-stressed conditions (Table 2), further validating their suitability for cultivation in variable water availability environments.

The large absolute TOL values recorded for Taqa 9 (-233.0) and Taqa 152 (-203.8) should not be misinterpreted as indicators of poor drought tolerance. Rosielle and Hamblin **(Rosielle and Hamblin, 1981)** cautioned that high-yielding genotypes naturally tend to exhibit larger absolute yield differences between stressed and non-stressed conditions, as their yield potential under well-watered conditions is substantially higher. This observation is consistent with the high grain yields recorded for both genotypes under well-watered conditions (Table 2), confirming that their large TOL values are a consequence of their superior yield potential rather than drought susceptibility.

Conversely, BS6 and Giza 171 were identified as the least productive genotypes across both drought intensities, recording the lowest STI values of 0.62 and 0.68, respectively. These results suggest that both local varieties are limited in their ability to sustain acceptable yield levels under water deficit conditions, limiting their direct suitability for drought-prone environments without further genetic improvement **(Blum, 2011)**. The combined classification of genotypes across both index classes, therefore, identifies M34, Taqa 14 and M160 as the most promising genotypes, exhibiting complementary profiles of drought resilience and high productivity, respectively, making them valuable genetic resources for climate-smart wheat breeding programs in water-limited environments.

M34 stands out as the most drought-resilient genotype based on its consistently low TOL average across D1 and D2, combined with a high STI of 0.95, confirming its ability to minimize yield reduction under both moderate and severe droughts while sustaining high productivity. Taqa 14 and M160 are identified as the most productive genotypes under drought, excelling in all productivity indices across both levels. Conversely, BS6 and Giza 171 are the most susceptible and least productive genotypes, respectively, across the two drought intensities, limiting their direct suitability for drought-prone environments without further improvement **(Blum, 2011)**.

4.3. Genotypic response to climate-smart agriculture practices of nitrogen fertilization and nitrogen use efficiency

Nitrogen is the most critical nutrient for wheat yield, but its optimal application rate is highly dependent on both the genotype and the environment. A striking result from the N experiment was that most genotypes, including the local varieties, produced higher yields under the low N (T1) (230 kg N/ha) and high N (T2) (290 kg N/ha) treatments than under the recommended (control) dose (260 kg N/ha) (Fig. 3). This suggests that the standard recommendation may not be optimal for achieving the maximum genetic potential of these specific genotypes in the sandy-loam soil of the experimental site.

Nitrogen Use Efficiency (NUE) is a critical trait for sustainable agriculture and can be assessed by a genotype's ability to produce high yield with limited N input **(Hawkesford, 2017 and Masclaux-Daubresse *et al.*, 2010)**. As depicted in Figure 4, the yield percentage increase over the control treatment provides a meaningful assessment of genotypic NUE. The mutant line M160 and local variety Bs6 emerged as the top-performing genotypes, both recording remarkable yield increases of more than 25% under low nitrogen supply (T1), underscoring their potential as nitrogen-efficient genotypes for low-input cropping systems. This indicates they possess superior NUE and are highly efficient at converting available N into grains. Furthermore, their yield continued to increase at the high N (T2) treatment, showing they are also highly responsive to increased N fertilizer application. In contrast, the mutant line Taqa59 showed a high grain yield at the low N level, and its yield declined at the high N level, suggesting it is highly efficient but adapted to low-input systems and less responsive to high fertilization rates **(Le Gouis *et al.*, 2000)**. The decline in yield at the T2 level is due to the high number of spikes/m² and the weak stem architecture as compared to the strong stem architecture of the mutant line M160, which resulted in lodging and affected the yield potential **(Berry *et al.*, 2004)**. This diversity in response is invaluable for tailoring variety selection to specific farm management strategies, as it allows farmers to choose varieties that can better withstand lodging and optimize yield potential under varying conditions.

4.4. Implications for Breeding Climate-Resilient Wheat Varieties

The main outcome of this research is identifying genotypes that exhibit tolerance to multiple combined stresses. The mutant line M160 stands out as a particularly valuable asset. It has not only exhibited strong drought tolerance and low yield reduction (Fig. 2), but it was also one of the most N-efficient (nitrogen-efficient) and responsive genotypes (Fig. 4). This combination of traits is the ideal profile for climate-smart varieties, where crops must perform reliably across variable water and nutrient conditions. The successful development of such a genotype through mutation breeding validates this approach as a powerful tool for generating novel, adaptive genetic variation to meet the challenges of climate change **(Kharkwal and Shu, 2009)**.

5. Conclusions

This study successfully evaluated the performance of novel wheat mutant lines under critical abiotic stresses drought and suboptimal N supply. The results indicated that mutation breeding is a very effective way to create useful genetic diversity for climate resilience. Under severe drought conditions, the mutant lines M34 and M160 were identified as exceptionally tolerant, exhibiting significantly lower yield reductions compared to the other genotypes. The bread wheat mutant line M160 and the local variety BS6 showed better N use efficiency in the low N (T1) and high N (T2) treatments compared to the national recommendation procedure. The mutant lines produced high yields even with low N input and were very responsive to increased N fertilization when it was added during the optimal growth stages through CSA. It is stated whether using CSA technology is better than regular transactions, particularly in terms of yield efficiency and responsiveness to nutrient inputs in agricultural practices.

According to susceptibility and productivity indices, M34 stands out as the most drought-resilient genotype based on its consistently low TOL average across D1 and D2, combined with a high STI of 0.95, confirming its ability to minimize yield reduction under both moderate and severe droughts while sustaining high productivity. M34, Taqa 14 and M160 are identified as the most productive genotypes under drought, excelling in all productivity indices across both levels. Conversely, BS6 and Giza 171 are the most susceptible and least productive genotypes, respectively, across the two drought intensities, limiting their direct suitability for drought-prone environments without further improvement.

The use of climate-resilient mutant lines, particularly M34 and M160, demonstrated remarkable potential to sustain wheat productivity under drought and low-nitrogen conditions, ensuring economically viable grain production even under severe water deficit, thereby reducing crop losses and supporting the livelihoods of farmers in arid and semi-arid agricultural systems. Adopting climate-smart agricultural practices, including optimized N fertilization timing and reduced N input levels, proved effective in enhancing nitrogen use efficiency and maintaining high grain yield with lower chemical fertilizer inputs, which in turn mitigates soil degradation, minimizes nitrogen leaching, and reduces the environmental pollution associated with excessive agrochemical application.

Collectively, the integration of climate-resilient mutants with CSA practices showed the greatest synergistic potential, contributing to a substantial improvement in wheat grain yield and resource use efficiency while simultaneously delivering economic and environmental co-benefits, and thus providing a comprehensive, sustainable, and scalable strategy for securing wheat production in water-limited and nitrogen-deficient environments.

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Authors' Contributions

M. Ayaad, H.M. Mansour, and O.M. Saleh were responsible for manuscript preparation, writing, and editing. I.O. Hassan, M.A.E. Basyouny, M.F. Kassab, M.A. Afify, M.A. Othman, A. Hegazy, and M. Salem conducted all field experiments, collected data, and performed the statistical analysis. M. Zaman provided scientific guidance on climate-smart agricultural practices and nitrogen use efficiency protocols. S.E.S. Sobieh, K.F. Al-Azab, I.O. Hassan, and M. Ayaad conceptualized and designed the study, supervised its implementation, and critically revised the manuscript for intellectual content.

All authors have read and approved the final version of the manuscript.

Declaration of Competing Interest

The authors declare that none of the work described in this study could have been influenced by any known competing financial interests or personal relationships.

References

Barnabás, B., Jäger, K. and Fehér, A. (2008). The effect of drought and heat stress on reproductive processes in cereals. Plant, Cell and Environment, 31(1), 11–38. https://doi.org/10.1111/j.1365-3040.2007.01727.x

Berry, P. M., Sterling, M., Spink, J. H., Baker, C. J., Bradley, R. S., Mooney, S. J., Tams, A. R. and Ennos, A. R. (2004). Understanding and reducing lodging in cereals. Advances in Agronomy, 84, 217–271., 217–271.

Blum, A. (2011). Plant Breeding for Water-Limited Environments. Springer, New York.

El-Degwy, I. S. (2013). Performance and genotypic variability of three bread wheat cultivars under stress irrigation regimes. Egypt. J. Agron., 35(2), 211–225.

Esnault, M. A., Legue, F. and Chenal, C. (2010). Ionizing radiation: advances in plant response. Environmental and Experimental Botany, 68(3), 231–237.

Fahad, S., Bajwa, A. A., Nazir, U., Anjum, S. A., Farooq, A., Zohaib, A., Sadia, S., Nasim, W., Adkins, S., Saud, S., Ihsan, M. Z., Alharby, H., Wu, C., Wang, D. and Huang, J. (2017). Crop production under drought and heat stress: Plant responses and management options. In Frontiers in Plant Science (Vol. 8). Frontiers Media S.A. https://doi.org/10.3389/fpls.2017.01147

FAO/IAEA. (2021). Mutant Variety Database (MVD). Joint FAO/IAEA Centre of Nuclear Techniques in Food and Agriculture, Vienna, Austria. https://Mvd.Iaea.Org.

Farshadfar, E., Mohammadi, R., Farshadfar, M. and Dabiri, S. (2013). Relationships and repeatability of drought tolerance indices in wheat-rye disomic addition lines. Australian Journal of Crop Science, 7(1), 130–138. https://search.informit.org/doi/10.3316/informit.142936078536528

Fernandez, G. C. J. (1992). Effective selection criteria for assessing plant stress tolerance. Proceedings of the International Symposium on Adaptation of Vegetables and Other Food Crops in Temperature and Water Stress. AVRDC, Tainan, Taiwan, 257–270.

Fischer, R. A. and Maurer, R. (1978). Drought resistance in spring wheat cultivars. I. Grain yield responses. Australian Journal of Agricultural Research, 29(5), 897–912.

Eid, M. H. and Sabry, S. A. (2019). Assessment of variability for drought tolerance indices in some wheat (Triticum aestivum L.) genotypes. Egyptian Journal of Agronomy, 41(2), 79–91. doi:10.21608/agro.2019.10401.1153**.**

Hawkesford, M. J. (2017). Genetic variation in traits for nitrogen use efficiency in wheat. Journal of Experimental Botany, 68(10), 2627–2632.

Jankowicz-Cieslak, J. and Till, B. J. (2016). Forward and reverse genetics in crop breeding. In: Al-Khayri, J.M., Jain, S.M. and Johnson, D.V. (Eds.), Advances in Plant Breeding Strategies: Breeding, Biotechnology and Molecular Tools. Springer, Cham, pp. 215–240.

Kharkwal, M. C. and Shu Q. Y. (2009). The Role of Induced Mutations in World Food Secuity.

Le Gouis, J., Béghin, D., Heumez, M., and Pluchard, P. (2000). Genetic differences for nitrogen uptake and nitrogen utilisation efficiencies in winter wheat. European Journal of Agronomy. 12 (3-4), 163-173.

Masclaux-Daubresse, C., Daniel-Vedele, F., Dechorgnat, J., Chardon, F., Gaufichon, L. and Suzuki, A. (2010). Nitrogen uptake, assimilation and remobilization in plants: Challenges for sustainable and productive agriculture. In Annals of Botany (Vol. 105, Number 7, pp. 1141–1157).

Mba, C. (2013). Induced mutations unleash the full potential of plant genetic resources for food and agriculture. Agronomy, 3(1), 200–231.

Mutanda, M., Shimelis, H., Chaplot, V. and Figlan, S. (2025). Managing drought stress in wheat (Triticum aestivum L.) production: strategies and impacts. In South African Journal of Plant and Soil (Vol. 42, Numbers 1–3, pp. 1–12). Taylor and Francis Ltd.

Nazarenko, M., Izhboldin, O., Liadska, I. and Pashchenko, N. (2023). Optimal doses and concentrations of mutagens for winter wheat breeding purposes. Grain quality. Scientific Papers. Series A. Agronomy, 66(2), 324-329.

Nyaupane, S., Poudel, M. R., Panthi, B., Dhakal, A., Paudel, H. and Bhandari, R. (2024). Drought stress effect, tolerance, and management in wheat–a review. Cogent Food and Agriculture, 10(1), 2296094.

OlaOlorun, B. M., Shimelis, H., Laing, M., and Mathew, I. (2021). Development of Wheat (Triticum aestivum L.) Populations for Drought Tolerance and Improved Biomass Allocation Through Ethyl Methanesulphonate Mutagenesis. Frontiers in Agronomy, 3:655820.

Rosielle, A. A. and H. J. (1981). Theoretical aspects of selection for yield in stress and non-stress environments. Crop Science, 21(6), 943-946.

Sharma, K. and Sharma, P. K. (2025). Wheat as a Nutritional Powerhouse: Shaping Global Food Security. https://doi.org/10.5772/intechopen.1009499

Sheahan, M. and Barrett, C. B. (2017). Ten striking facts about agricultural input use in Sub-Saharan Africa. Food Policy. 67, 12–25.

Sikora, P., C. A., L. M., O. J. and O. O. (2011). Mutagenesis as a tool in plant genetics, functional genomics, and breeding. International Journal of Plant Genomics, 314829.

Stewart, W. M., Dibb, D. W., Johnston, A. E. and Smyth, T. J. (2005). The Contribution of Commercial Fertilizer Nutrients to Food Production. Agronomy Journal, 97(1), 1-6.

Tilman, D., Balzer, C., Hill, J. and Befort, B. L. (2011). Global food demand and the sustainable intensification of agriculture. Proceedings of the National Academy of Sciences of the United States of America, 108(50), 20260–20264.

Wasti, M. K. D., Omar, M., Attaher, S., Govind, A., Devkota, K., Tesfaye, K. and Nangia, V. (2024). Yield gaps and their determinates for wheat production in irrigated drylands for Egypt. CGIAR (preprint/report).

Zahedi MB, Tahmasebi, S., Salami, M., Sukumaran, S. and Heidari, B. (2026). Identification of drought-tolerant ideotype in wheat using multi-trait genotype-ideotype distance index (MGIDI) and comprehensive evaluation value. *Sci Rep*. https://doi.org/10.1038/s41598-026-46140-6

Zhao, W., Liu, L., Shen, Q., Yang, J., Han, X., Tian, F. and Wu, J. (2020). Effects of water stress on photosynthesis, yield, and water use efficiency in winter wheat. Water (Switzerland), 12(8). https://doi.org/10.3390/W12082127