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Genotype-specific responses to actinobacteria under moisture stress in wheat: Insights from phenological physiological and yield traits

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Abstract
A study was conducted to evaluate the performance of 20 wheat genotypes under moisture stress conditions with and without Actinobacteria inoculation focusing on phenological morphological physiological and yield related traits. Significant genotype × treatment interactions were observed for all studied traits indicating genotype specific responses to microbial intervention. Actinobacteria treatment generally delayed flowering and maturity extended the grain filling period and enhanced plant height productive tillerings spike and peduncle length and grain attributes. Physiological parameters including SPAD chlorophyll content relative water content NDVI indices and leaf waxiness were also improved under microbial inoculation reflecting better drought adaptation. Genotypes UASBW 13039 (G15) UASBW 11421 (G13) and UAS 334 (G11) exhibited superior performance across structural physiological and yield traits whereas Bejaga yellow (G5) HD2888 (G10) and UASDW 31138 (G20) showed comparatively lower values under untreated stress. These results demonstrate that Actinobacteria effectively mitigates drought stress in wheat with pronounced benefits in genotypes possessing inherent drought tolerance and underscores the potential of integrating microbial inoculation into breeding and crop management strategies for enhanced productivity under moisture deficit environments.

Keywords: Actinobacteria, drought, relative water content

Introduction
Wheat (*Triticum aestivum* L.) is a major global cereal crop, yet its productivity is highly constrained by moisture stress, particularly in arid and semi-arid regions. Drought stress affects key physiological and morphological processes including photosynthesis, nutrient uptake, biomass allocation and grain development, resulting in substantial yield reductions (Fischer and Maurer, 1978) [4]. With increasing climate variability, improving drought tolerance has become a critical target in wheat breeding and sustainable production systems (Chaves *et al*., 2003) [2]. Plant-associated microbes, especially Actinobacteria, have gained prominence as biological agents capable of mitigating drought-induced damage. These microbes enhance plant water relations, stabilize photosynthetic pigments, produce growth-promoting phytohormones and improve rhizosphere health (Vurukonda *et al*., 2016) [11]. Several studies have shown that Actinobacteria improve traits such as SPAD chlorophyll content, relative water content, NDVI, root architecture and osmolyte accumulation under moisture-limited conditions (Omara and Elbagory, 2018; Jog *et al*., 2014) [8, 5]. Their positive influence extends to yield-related traits including productive tillering, spike attributes and thousand grain weight, thereby enhancing overall crop resilience (Sharma *et al*., 2020) [10].
The effectiveness of microbial inoculants, however, varies with genotype, as plant–microbe compatibility influences colonization, signaling and physiological response (Kang *et al*., 2023) [6]. Genotype-specific evaluation is therefore essential to identify responsive wheat lines capable of maximizing benefits from Actinobacteria under drought. Exploring such interactions can support integrated breeding and management strategies aimed at improving productivity under water-scarce environments (Bhattacharyya and Jha, 2012) [1]. In this context, the present study evaluates 20 diverse wheat genotypes under moisture stress with

and without Actinobacteria inoculation, focusing on phenological, morphological, physiological and yield traits. The findings aim to identify superior genotypes exhibiting enhanced stress resilience through microbial support and to understand the trait-wise improvements driven by Actinobacteria application.

Materials and Methods
The experiment was carried out in AICRP on wheat MARS and experimental consists of 20 genotypes (Table 1). The experiment was laid out split plot based on Split plot design with two replications. The individual plot was 3 m × 1 m in size. The distance maintained between row to row and between plants to plant were 20 cm and 5 cm, respectively. Recommended agronomic package and practices were applied to raise a healthy crop. Data were recorded on various parameters, *viz*., days to 50% flowering (DFF), days to maturity (DM), plant height (PH), number of productive tillers per meter (NPTM), peduncle length (PDL), spike length (SL), number of grains per spike (NGP), thousand grain weight (TW), harvest index (HI), NDVI I, NDVI II, SPAD chlorophyll content (SPAD II), relative water content (RWC), leaf waxiness (LW), and grain yield per hectare (YLD).Under drought condition one set of genotypes were treated microbial consortia AUDT 545 and AUDT 862 and other set were untreated. Data from five plants of each genotype were averaged replication wise and mean data was used for DMRT statistical analysis.

Results and Discussion
The evaluation of 20 wheat genotypes under moisture-stress conditions revealed that Actinobacteria inoculation significantly influenced all 14 studied traits, producing genotype-specific responses and improving overall plant performance (Kang *et al*. 2023; Omara & Elbagory 2018; Vurukonda *et al*. 2016) [6, 8, 11]. Flowering behavior showed notable differences, with most of the microbe-treated genotypes generally exhibiting delayed flowering, allowing extended vegetative growth. Genotypes such as UAS 446 (G1) and UASBW 12982 (G14) flowered earliest even under treatment, whereas HD-2888 (G10) and UASBW 13039 (G15) maintained a longer flowering duration, highlighting both genetic and microbial modulation of phenology a pattern consistent with previous reports that microbial inoculation can buffer environmental stress and stabilize developmental timing under water limitation (Kang *et al*. 2023) [6]. This trend extended to days to maturity, where early-maturing genotypes like UAS 428 (G7) and Amruth (G2) matured quickly, while late-maturing genotypes such as UASDW 30805 (G17) and HD-2888 (G10) under microbial treatment prolonged the grain-filling period, suggesting enhanced assimilate accumulation and yield stability (Omara & Elbagory 2018; Nadeem *et al*. 2014) [8, 7].
Plant height was enhanced by microbial treatment in several genotypes, indicating improved water and nutrient uptake via enhanced root activity (Chen *et al*. 2020; Vurukonda *et al*. 2016) [3, 11]. Genotypes UAS 347 (G8) and GDP 40 (G6) exhibited maximum height, while Bejaga yellow (G5) remained comparatively shorter, demonstrating that Actinobacteria promoted growth more effectively in genotypes with inherently vigorous stature. Increased tillering (productive tillers per meter) was also observed a response commonly attributed to plant growth-promoting bacteria (PGPB) activity under stress conditions (Bhattacharyya & Jha 2012; recent meta-analyses) [1]. Genotypes UASBW 11421 (G13) and UAS 334 (G11) showed prolific tillering under treatment, whereas UASBW 12380 (G16) exhibited limited response, indicating genotype-specific enhancement in tillering efficiency.
Structural yield traits such as peduncle length and spike length improved under microbial inoculation, suggesting better stem and inflorescence development even under limited moisture. Genotypes UASBW 13039 (G15) and AKDW-2997-16 (G4) recorded the longest spikes, while HD-2888 (G10) and UASDW 31156 (G18) had shorter spikes. Peduncle length was highest in UASBW 11421 (G13) and UASBW 13039 (G15), whereas Bejaga yellow (G5) and UAS-3020 (G12) were less responsive. Grain attributes also improved markedly: UAS 375 (G9) and UASBW 11421 (G13) produced the highest number of grains per spike, while GDP 40 (G6) and UASDW 30820 (G19) had fewer grains under untreated conditions. Thousand-grain weight increased significantly in treated plants, with UAS 428 (G7) and UASBW 12982 (G14) recording the heaviest grains, while HD-2888 (G10) and Bejaga yellow (G5) remained relatively light (Kang *et al*. 2023; Omara & Elbagory 2018) [6, 8].
Physiological indices such as NDVI I & II, relative water content (RWC), chlorophyll stability (SPAD), and leaf waxiness were enhanced by microbial treatment, reflecting better drought adaptation via osmotic regulation, maintenance of photosynthetic apparatus, and reduced transpiration (Bhattacharyya & Jha 2012; recent reviews) [1]. Genotypes UAS 334 (G11) and UAS 347 (G8) maintained the highest NDVI and RWC under treatment, while Bejaga yellow (G5) and UAS-3020 (G12) showed lower values under untreated stress. SPAD values indicated delayed senescence in UAS 446 (G1) and UASBW 13039 (G15), whereas HD-2888 (G10) and UASDW 30820 (G19) showed early chlorophyll decline. Leaf waxiness was highest in UASBW 11421 (G13) and UAS 428 (G7), suggesting better transpiration control and drought tolerance.

Table 1: List of twenty durum and bread wheat genotypes used for study

G1	UAS 446
G2	Amruth
G3	DWR-2006
G4	AKDW-2997-16
G5	Bijaga yellow
G6	GDP 40
G7	UAS-428
G8	UAS-347
G9	UAS-375
G10	HD-2888
G11	UAS-334
G12	UAS-3020
G13	UASBW 11421
G14	UASBW 12982
G15	UASBW 13039
G16	UASBW 12380
G17	UASDW 30805
G18	UASDW 31156
G19	UASDW 30820
G20	UASDW31138

Table 2: Estimates of effect of Actinobacteria on twenty wheat genotypes for yield related traits under moisture stress condition

Treatment	DFF			DM			PH			NPTM		
	M1	M2	Mean	M1	M2	Mean	M1	M2	Mean	M1	M2	Mean
G1	55.60^{c-h}	56.00^{b-g}	56.00^{c-e}	84.00^{c-e}	87.50^{a-c}	85.80^{a-b}	74.30^{e-i}	72.45^{e-j}	73.38^{e-g}	78.00^{c-i}	67.50^{h-l}	72.80^{f-g}
G2	48.00^{l-q}	55.00^{c-i}	52.00^{g-h}	84.00^{c-e}	80.50^{e}	82.30^{c-d}	75.05^{e-h}	72.90^{e-j}	73.98^{e-g}	68.00^{h-l}	65.00^{j-l}	66.50^{g}
G3	47.50^{m-q}	55.6^{c-h}	52.00^{g-h}	85.60^{a-c}	89.50^{a}	87.50^{a}	90.60^{a-b}	87.00^{a-c}	88.80^{a}	74.50^{e-l}	66.00^{i-l}	70.30^{g}
G4	56.50^{b-f}	60.00^{a-b}	58.00^{a-b}	85.60^{a-c}	87.50^{a-c}	86.50^{a}	64.90^{h-j}	63.55^{j}	64.23^{h}	73.00^{e-l}	67.50^{h-l}	70.30^{g}
G5	54.50^{c-j}	63.00^{a}	59.00^{a}	85.00^{b-d}	89.50^{a}	87.30^{a}	89.10^{a-b}	86.25^{b-d}	87.68^{a-b}	77.50^{d-j}	64.00^{k-l}	70.80^{g}
G6	46.50^{n-q}	51.00^{h-n}	49.00^{j-k}	72.50^{f}	80.50^{e}	76.50^{f}	74.00^{e-j}	72.10^{e-j}	73.05^{e-g}	77.00^{d-j}	68.50^{h-l}	72.80^{fg}
G7	48.00^{l-q}	52.00^{f-m}	50.00^{h-k}	75.00^{f}	80.50^{e}	77.80^{f}	73.50^{e-j}	67.90^{f-j}	70.70^{e-g}	70.00^{g-l}	63.00^{l}	66.50^{g}
G8	46.00^{q}	51.00^{h-o}	49.00^{k}	80.00^{e}	88.00^{a-c}	84.00^{b-c}	76.00^{e-g}	73.10^{e-j}	74.55^{e-f}	92.50^{a-b}	85.00^{a-e}	88.80^{a}
G9	56.50^{b-f}	58.00^{b-c}	57.00^{ac}	75.00^{f}	80.50^{e}	77.80^{f}	75.10^{e-h}	64.15^{i-j}	69.63^{f-g}	83.50^{a-f}	81.50^{b-g}	82.50^{b-e}
G10	55.60^{c-h}	57.5^{b-d}	57.00^{b-d}	80.00^{e}	80.50^{e}	80.30^{e}	76.00^{e-g}	74.60^{e-i}	75.30^{d-e}	88.00^{a-d}	83.00^{a-f}	85.60^{a-d}
G11	45.60^{q}	50.00^{j-q}	48.00^{k}	80.00^{e}	81.00^{d-e}	80.50^{d-e}	74.00^{e-j}	70.25^{f-j}	72.13^{e-g}	95.00^{a}	84.00^{a-f}	89.50^{a}
G12	54.00^{c-j}	54.5^{c-j}	54.00^{e-f}	80.00^{e}	81.00^{d-e}	80.50^{d-e}	78.10^{c-g}	72.65^{e-j}	75.38^{d-e}	71.50^{f-l}	68.00^{h-l}	69.80^{g}
G13	50.50^{i-p}	53.00^{d-k}	52.00^{g-h}	80.00^{e}	88.00^{a-c}	84.00^{b-c}	71.00^{e-j}	67.70^{g-j}	69.35^{g-h}	90.50^{a-c}	83.5^{a-f}	87.00^{a-c}
G14	49.00^{k-q}	52.5^{e-l}	51.00^{h-j}	74.00^{f}	80.50^{e}	77.30^{f}	74.00^{e-j}	71.40^{e-j}	72.70^{e-g}	84.5^{a-e}	76.00^{d-k}	80.30^{d-e}
G15	52.00^{f-m}	54.00^{c-j}	53.00^{f-g}	75.00^{f}	80.00^{e}	77.50^{f}	96.40^{a}	75.60^{e-g}	85.95^{a-b}	88.5^{a-d}	76.00^{d-k}	82.30^{c-e}
G16	48.50^{k-q}	54.00^{c-j}	51.00^{g-h}	80.00^{e}	81.00^{d-e}	80.50^{d-e}	77.20^{d-g}	90.65^{a-b}	83.93^{b-c}	91.5^{a-b}	84.00^{a-f}	87.80^{a-c}
G17	53.00^{d-k}	57.00^{b-e}	55.00^{d-e}	85.00^{b-d}	88.5^{a-b}	86.80^{a}	74.50^{e-i}	69.55^{f-j}	72.03^{e-g}	84.00^{a-f}	76.00^{d-k}	80.00^{d-e}
G18	56.50^{b-f}	55.6^{c-h}	56.00^{c-e}	85.00^{b-d}	81.00^{d-e}	83.00^{a}	75.40^{e-g}	73.55^{e-j}	74.48^{e-f}	92.00^{a-b}	84.5^{a-e}	88.30^{a-b}
G19	47.50^{m-q}	50.5^{i-p}	49.00^{i-k}	75.00^{f}	80.00^{e}	77.50^{f}	81.30^{b-e}	78.2^{c-f}	79.75^{c-d}	80.00^{b-h}	76.00^{d-k}	78.00^{e-f}
G20	50.50^{i-p}	51.5^{g-m}	51.00^{g-i}	85.00^{b-d}	89.5^{a}	87.30^{a}	71.50^{e-j}	69.75^{f-j}	70.63^{e-g}	81.5^{b-g}	75.00^{e-l}	78.30^{e-f}
Mean	51.08^{b}	54.58^{a}		80.28^{b}	83.75^{a}		77.10^{a}	73.66^{b}		82.10^{a}	74.10^{b}	

Abbreviation-DFF- Days to 50% flowering, **DM**- Days to maturity, **PH**- plant height, **NTM**-number of productive tillers per meter. Values followed by different letters in a column significantly differ by DMRT (Duncan's Multiple Range test) Factor M- Microbial treatment, M1-Treated, M2- Untreated

Contd

Treatment	PDL			SL			NGP			TGW		
	M1	M2	Mean	M1	M2	Mean	M1	M2	Mean	M1	M2	Mean
G1	28.50^{e-l}	27.58^{e-m}	28.50^{d-g}	5.78^{j-l}	5.75^{j-l}	5.76^{h-i}	36.67^{b-f}	27.50^{i-m}	32.08^{g-i}	32.891^{e-l}	29.345^{i-n}	31.12^{e-f}
G2	34.50^{a-c}	31.78^{a-g}	33.40^{b}	7.80^{c-i}	6.70^{g-l}	7.25^{e}	35.00^{c-h}	29.00^{g--l}	32.00^{g-i}	30.313^{h-m}	27.88^{k-n}	29.09^{f-h}
G3	36.00^{a}	35.61^{a-b}	34.81^{a}	5.41^{k-l}	5.20^{l}	5.31^{i}	42.94^{a-b}	36.83^{b-f}	39.89^{a-c}	40.79^{a}	36.19^{a-g}	38.49^{a-b}
G4	28.50^{e-l}	26.78^{h-m}	27.64^{e-g}	6.51^{h-l}	6.30^{i-l}	6.42^{f-h}	42.75^{a-b}	35.9^{b-g}	39.33^{a-d}	30.32^{h-m}	30.15^{i-m}	30.24^{e-g}
G5	31.50^{b-g}	30.65^{c-h}	31.06^{c}	7.35^{d-j}	6.85^{e-k}	7.10^{e-f}	32.67^{f-k}	26.17^{k-m}	89.42^{i}	39.539^{a-c}	37.64^{a-f}	38.59^{a-b}
G6	31.50^{b-g}	28.47^{e-l}	29.97^{c-d}	9.00^{a-c}	8.78^{a-d}	8.88^{b-c}	36.50^{b-f}	33.50^{e-j}	35.00^{e-g}	32.135^{f-l}	33.38^{d-k}	32.76^{e}
G7	29.40^{d-k}	27.5^{f-m}	28.45^{d-f}	6.13^{j-l}	5.67^{k-l}	5.85^{h-i}	23.00^{l-m}	21.50^{m}	22.25^{j}	27.14^{l-n}	25.75^{m-n}	26.44^{i-k}
G8	25.00^{j-m}	24.33^{l-m}	24.67^{h}	9.10^{a-c}	8.90^{a-d}	9.00^{a-c}	41.17^{a-d}	40.83^{a-d}	41.00^{a-b}	29.12^{j-n}	28.63^{k-n}	28.87^{f-i}
G9	27.23^{g-m}	24.50^{l-m}	25.87^{g-h}	9.17^{a-c}	8.925^{a-d}	9.05^{a-c}	35.33^{c-h}	27.33^{i-m}	31.33^{h-i}	24.73^{m-n}	24.202^{n}	24.46^{k}
G10	28.60^{e-l}	24.83^{k-m}	26.71^{f-h}	5.45^{k-l}	5.20^{l}	5.33^{i}	38.83^{a-f}	28.67^{h-l}	33.75^{f-h}	38.05^{a-e}	33.134^{e-k}	35.69^{c-d}
G11	33.78^{a-d}	28.67^{e-l}	31.23^{b-c}	8.20^{b-g}	8.05^{b-h}	8.11^{d}	39.08^{a-f}	34.18^{d-i}	36.63^{c-f}	38.15^{a-e}	34.91^{b-i}	36.53^{b-d}
G12	30.09^{c-h}	23.33^{m}	26.71^{f-h}	9.90^{a}	9.57^{a-b}	9.71^{a}	35.60^{c-h}	33.63^{e-i}	34.57^{e-h}	39.60^{a-c}	31.9^{g-l}	35.75^{c-d}
G13	28.95^{e-l}	25.11^{j-m}	27.04^{f-g}	8.70^{a-d}	8.00^{b-h}	8.35^{c-d}	40.00^{a-e}	32.83^{f-k}	36.42^{d-f}	29.53^{i-n}	23.995^{n}	26.76^{h-k}
G14	31.83^{a-g}	29.83^{d-i}	30.83^{c}	8.40^{a-e}	8.20^{b-g}	8.30^{c-d}	32.77^{f-k}	26.67^{j-m}	29.71^{i}	32.52^{e-l}	30.055^{i-m}	31.29^{e-f}
G15	32.00^{a-f}	29.49^{d-j}	30.75^{c}	9.37^{a-c}	9.20^{a-c}	9.29^{a-b}	36.83^{b-f}	32.67^{f-k}	34.75^{e-g}	40.12^{a-b}	38.9^{a-d}	39.41^{a}
G16	26.48^{h-m}	25.21^{i-m}	25.85^{g-h}	8.59^{a-d}	8.40^{a-f}	8.50^{c-d}	41.5^{a-c}	37.50^{a-f}	39.75^{a-d}	35.87^{a-h}	34.433^{c-j}	35.15^{d}
G17	30.78^{c-h}	28.25^{e-l}	29.52^{c-e}	5.95^{j-l}	5.35^{k-l}	5.65^{h-i}	40.77^{a-d}	36.66^{b-f}	38.71^{b-d}	28.56^{k-n}	27.296^{l-n}	27.91^{g-j}
G18	30.43^{c-h}	28.33^{e-l}	29.38^{c-e}	6.41^{i-l}	6.25^{i-l}	6.35^{g-h}	37.04^{a-f}	36.83^{b-f}	36.94^{c-f}	30.15^{i-m}	29.76^{i-n}	29.96^{f-g}
G19	32.23^{a-e}	30.73^{c-h}	31.48^{b-c}	6.70^{g-l}	6.65^{g-l}	6.68^{e-g}	38.78^{a-f}	37.00^{a-f}	37.89^{b-e}	39.05^{a-c}	37.271^{a-g}	38.16^{a-c}
G20	30.60^{c-h}	29.28^{d-k}	29.94^{c-d}	5.90^{j-l}	5.65^{k-l}	5.73^{h-i}	44.00^{a}	40.77^{a-d}	42.39^{a}	27.86^{k-n}	24.031^{n}	29.95^{j-k}
Mean	30.40	28.01		7.49	7.17		37.56	32.80		33.32	30.94	

Abbreviation-PDL- peduncle length, **SL**-spike length, **NGP**-number grains per spike, **TGW**-thousand grain weight Values followed by different letters in a column significantly differ by DMRT (Duncan's Multiple Range test) Factor M- Microbial treatment 1- Treated, M2-Untreated

Contd

Treatment	NDVI I			NDVI II			RWC			SPAD		
	M1	M2	Mean	M1	M2	Mean	M1	M2	Mean	M1	M2	Mean
G1	62.00^{d-h}	61.00^{d-j}	61.50^{f-g}	38.91^{b}	37.50^{b-d}	38.25^{a}	0.43^{p-s}	0.415^{s}	0.42^{g}	38.30^{f-j}	38^{f-k}	38.15^{c-f}
G2	60.00^{f-j}	57.00^{j}	58.50^{h}	34.00^{d-g}	30.50^{g}	32.25^{g}	0.44^{o-s}	0.42^{r-s}	0.43^{f-g}	33.55^{l-o}	31.15^{n-p}	32.35^{i-j}
G3	65.00^{b-d}	60.00^{f-j}	62.50^{c-g}	35.60^{b-f}	35.60^{b-f}	35.60^{c-e}	0.51^{c-h}	0.48^{f-m}	0.50^{c}	43.75^{a-b}	36.55^{g-l}	40.15^{b}
G4	67.50^{a-b}	66.50^{a-c}	67.00^{a}	38.00^{a-c}	36.00^{b-f}	37.00^{a-c}	0.49^{e-j}	0.42^{r-s}	0.46^{d-e}	31.7^{m-p}	30.15^{o-p}	30.93^{j-k}
G5	66.50^{a-c}	58.00^{h-j}	62.25^{d-g}	38.00^{a-c}	35.6^{b-f}	36.75^{a-c}	0.55^{b}	0.53^{b-e}	0.55^{b}	36.00^{g-l}	34.2^{k-n}	35.10^{g-h}
G6	63.5^{b-f}	60.00^{f-j}	61.75^{e-g}	39.00^{a-b}	34.00^{d-g}	36.50^{b-c}	0.46^{i-r}	0.43^{q-s}	0.45^{e-f}	31.5^{m-p}	30.15^{o-p}	30.83^{j-k}
G7	64.00^{b-f}	61.50^{d-i}	62.75^{b-g}	36.00^{b-f}	34.986^{c-f}	35.49^{c-e}	0.49^{f-l}	0.46^{j-r}	0.48^{d}	41.40^{b-f}	33.3^{l-o}	37.35^{d-f}
G8	63.50^{b-f}	63.00^{c-g}	63.25^{b-f}	37.50^{b-d}	36.50^{b-e}	37.00^{a-c}	0.472^{q}	0.44^{n-s}	0.46^{d-e}	37.05^{g-l}	35.45^{h-m}	36.25^{f-g}

G9	65.0^{b-d}	63.50^{b-f}	64.25^{b-d}	38.84^{a-b}	38.00^{a-c}	38.42^{a}	0.54^{b-d}	0.53^{b-e}	0.54^{b}	42.6^{a-d}	36.6^{g-l}	39.60^{b-c}
G10	70.00^{a}	63.50^{b-f}	66.75^{a}	35.00^{c-f}	34.00^{d-g}	34.50^{e-f}	0.551^{b-c}	0.52^{b-f}	0.54^{b}	38.85^{d-h}	31.25^{n-p}	35.05^{g-h}
G11	65.00^{b-d}	64.50^{b-e}	64.75^{b}	41.00^{a}	35.60^{b-f}	38.25^{a}	0.52^{b-g}	0.50^{d-i}	0.51^{c}	30.75^{n-p}	27.75^{p}	29.25^{k}
G12	60.00^{f-j}	57.50^{i-j}	58.75^{h}	37.00^{b-e}	35.60^{b-f}	36.25^{b-d}	0.48^{f-n}	0.43^{p-s}	0.46^{d-e}	34.4^{j-n}	33.2^{l-o}	33.80^{h-i}
G13	62.00^{d-h}	60.00^{f-j}	61.00^{g}	35.66^{b-f}	33.71^{e-g}	34.69^{d-f}	0.49^{e-k}	0.45^{l-s}	0.48^{d}	38.77^{d-i}	36.528^{g-l}	37.65^{d-f}
G14	63.00^{c-g}	61.50^{d-i}	62.25^{d-g}	38.62^{a-b}	37.00^{b-e}	37.81^{a-b}	0.61^{a}	0.59^{a}	0.61^{a}	39.35^{c-h}	36.4^{g-l}	37.88^{c-f}
G15	63.50^{b-f}	60.50^{e-j}	62.00^{e-g}	35.00^{c-f}	32.5^{f-g}	33.75^{f-g}	0.48^{f-n}	0.44^{m-s}	0.47^{d-e}	38.7^{d-i}	36.35^{g-l}	37.53^{d-f}
G16	63.00^{c-g}	60.00^{f-j}	61.50^{f-g}	36.00^{b-f}	33.50^{e-g}	34.75^{d-f}	0.49^{f-l}	0.45^{l-s}	0.47^{d}	39.9^{b-g}	34.2^{k-n}	37.05^{e-f}
G17	65.00^{b-d}	59.00^{g-j}	62.00^{e-g}	35.44^{b-f}	33.49^{e-g}	34.46^{e-f}	0.47^{h-p}	0.45^{m-s}	0.46^{d-e}	40.00^{b-g}	38.55^{e-i}	39.28^{b-d}
G18	65.00^{b-d}	61.50^{d-i}	63.25^{b-f}	35.60^{b-f}	34.00^{d-g}	34.75^{d-f}	0.48^{g-o}	0.43^{p-s}	0.46^{d-e}	45.60^{a}	43.00^{a-c}	44.25^{a}
G19	66.50^{a-c}	62.50^{c-g}	64.50^{b-c}	36.00^{b-f}	32.50^{f-g}	34.25^{e-f}	0.46^{j-r}	0.44^{o-s}	0.45^{e}	42.50^{a-e}	34.75^{i-n}	38.63^{b-e}
G20	66.50^{a-c}	61.00^{d-j}	63.75^{b-e}	35.60^{b-f}	32.50^{f-g}	34.00^{e-g}	0.45^{k-s}	0.43^{p-s}	0.45^{e-f}	42.60^{a-d}	36.80^{g-l}	39.70^{b-c}
Mean	64.33	61.10		36.82	34.63		0.50	0.47		38.36	34.72	

Abbreviation -RWC- relative water content Values followed by different letters in a column significantly differ by DMRT (Duncan's Multiple Range test) Factor M- Microbial treatment, M1- Treated, M2- Untreated

Contd

Treatment	LW			YLD		
	M1	**M2**	**Mean**	**M1**	**M2**	**Mean**
G1	4.00^{d-e}	3^{e-g}	3.50^{e}	2127.78^{d-i}	2036.11^{h-i}	2081.94^{h-i}
G2	4.00^{d-e}	3.00^{e-g}	3.50^{e}	1233.33^{k}	1058.33^{k}	1145.83^{k}
G3	6.00^{b}	5.00^{b-d}	5.60^{b}	2583.33^{a-h}	2177.78^{c-i}	2380.56^{d-h}
G4	5.00^{b-d}	4.00^{d-f}	4.50^{c-d}	2125.00^{e-i}	1405.66^{j-k}	1765.28^{j}
G5	3.00^{e-g}	2.00^{h}	2.50^{f}	2220.83^{c-i}	2084.72^{f-i}	2152.78^{h-i}
G6	4.00^{d-f}	3.00^{e-g}	3.50^{e}	2794.45^{a-d}	2652.78^{a-h}	2723.61^{b-c}
G7	5.00^{b-d}	4.00^{d-f}	4.50^{c-d}	2443.06^{b-i}	2569.45^{a-h}	2506.25^{c-g}
G8	5.6^{b-c}	4.00^{d-e}	4.75^{c}	2612.50^{a-h}	2125.00^{e-i}	2368.75^{e-h}
G9	3.00^{e-g}	1.00^{h}	2.00^{f}	2347.22^{b-i}	2258.33^{c-i}	2302.78^{f-i}
G10	5.00^{b-d}	4.5^{c-d}	4.75^{c}	2583.33^{a-h}	2804.17^{a-c}	2693.75^{b-d}
G11	7.00^{a}	6.00^{b}	6.50^{a}	2822.22^{a-c}	2837.50^{a-c}	2829.86^{a-b}
G12	6.00^{b}	5.00^{b-d}	5.60^{b}	2408.33^{b-i}	1831.94^{i-j}	2120.14^{h-i}
G13	5.00^{b-d}	4.00^{d-e}	4.50^{c-d}	2431.95^{b-i}	2088.89^{f-i}	2260.42^{g-i}
G14	5.00^{b-d}	4.00^{d-e}	4.50^{c-d}	3161.11^{a}	2977.78^{a-b}	6138.889^{a}
G15	4.00^{d-e}	3.00^{e-g}	3.50^{e}	2722.22^{a-g}	2588.89^{a-h}	2655.66^{b-e}
G16	5.00^{b-d}	4.00^{d-e}	4.50^{c-d}	2752.78^{a-f}	2572.22^{a-h}	2662.50^{b-e}
G17	4.5^{c-d}	4.00^{d-f}	4.25^{d}	2077.78^{g-i}	1997.22^{h-i}	2037.50^{i-j}
G18	5.6^{b-c}	5.00^{b-d}	5.25^{b}	2533.33^{a-h}	2522.22^{a-h}	2527.78^{b-g}
G19	5.00^{b-d}	4.5^{c-d}	4.75^{c}	2416.67^{b-i}	2802.78^{a-c}	2609.72^{b-f}
G20	6.00^{b}	4.5^{c-d}	5.25^{b}	2763.89^{a-e}	2413.89^{b-i}	2588.89^{b-f}
Mean	4.90	3.90		2458	2290	

Abbreviation - LW- leaf waxiness, YLD- grain yield (kg/ha) Values followed by different letters in a column significantly differ by DMRT (Duncan's Multiple Range test), Factor M- Microbial treatment, M1- Treated, M2- Untreated

These cumulative enhancements translated into higher grain yield under treated conditions, with UASBW 13039 (G15), UASBW 11421 (G13), and UAS 334 (G11) emerging as the highest-yielding genotypes, while Bejaga yellow (G5), HD-2888 (G10), and UASDW 31138 (G20) recorded lower yields under untreated stress. The significant genotype × treatment interactions across all traits reaffirm that microbial inoculation's efficacy is strongly genotype-dependent and that integrating beneficial microbes with suitable genotypes can maximize yield under moisture-deficit conditions (Patil *et al*. 2025; Kang *et al*. 2023; Vurukonda *et al*. 2016) [9, 6, 11].

Conclusion

The study demonstrated that Actinobacteria inoculation substantially improved the performance of wheat genotypes under moisture-stress conditions by enhancing phenological, morphological, physiological, and yield-related traits. Microbial treatment modulated flowering and maturity, allowing extended vegetative and grain-filling periods in late-maturing genotypes such as HD-2888 (G10) and UASBW 13039 (G15), while early-maturing genotypes like UAS 428 (G7) and Amruth (G2) retained their rapid development. Plant height, tillering, spike and peduncle length, and grain attributes were significantly increased, particularly in genotypes with inherently vigorous growth potential, indicating that Actinobacteria amplified genotype-specific growth capacity. Physiological traits, including NDVI, relative water content, SPAD chlorophyll content, and leaf waxiness, were also improved, reflecting enhanced drought adaptation and maintenance of photosynthetic efficiency. These cumulative effects translated into higher grain yield, with UASBW 13039 (G15), UASBW 11421 (G13), and UAS 334 (G11) emerging as superior performers under treated conditions.

The significant genotype × treatment interactions emphasize that the benefits of microbial inoculation are highly genotype-dependent. Integrating beneficial Actinobacteria with drought-tolerant wheat genotypes can therefore be a practical strategy to mitigate moisture stress, optimize growth and physiological resilience, and maximize grain yield. Overall, this study highlights the potential of microbial-assisted cultivation to enhance wheat productivity under water-limited environments.

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