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Enhancing maize drought resilience through integrated fertilizer management: a study of two Iranian regions

Hamed Saljughian[1], Mohammadreza Yavarzadeh[2], Mohammad Mehdi Akbarian[3]

[1] Department of Agriculture, BAM.C., Islamic Azad University, Bam, Iran. PhD Candidate E-mail: saljoughian@iaubam.ac.ir
[2] Department of Agriculture, BAM.C., Islamic Azad University, Bam, Iran. Faculty Member E-mail: dr.yavarzadeh@iaubam.ac.ir (correspondence)
[3] Department of Agriculture, BAM.C., Islamic Azad University, Bam, Iran. Faculty Member E-mail: akbarian@iaubam.ac.ir

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Abstract

This study was developed in order to examinate the combined effects of drought stress and integrated fertilizer management on maize yield and physiological characteristics in Iran's Bam and Fahraj regions. The experiment used a split-plot design with randomized complete blocks in three replications. Drought stress treatments were applied at three levels: no stress (-0.3 MPa), mild drought stress (-0.7 MPa), and severe drought stress (-1.1 MPa). Six fertilizer treatments were evaluated: no fertilizer, chemical fertilizer (300 kg N ha^{-1} + 150 kg P_2O_5 ha^{-1}), phosphate biofertilizer, nitrogen biofertilizer, vermicompost (5 t ha^{-1}), and integrated fertilizer management, combining 50 % chemical fertilizer with both biofertilizers and vermicompost. Integrated fertilizer management under optimal irrigation conditions had the highest impact on crop performance. Grain yield in Bam region increased from 5640.6 kg ha^{-1} under no stress conditions to 12341.2 kg ha^{-1} with integrated fertilizer treatment; and in Fahraj region from 4140 kg ha^{-1} to 10840.6 kg ha^{-1}. The harvest index under no stress and integrated fertilizer treatment conditions reached the highest levels in Bam (45.94 %) and Fahraj (44.21 %). With increasing drought stress intensity, the harvest index decreased significantly, reaching 27.61 % in Bam under severe drought stress conditions. Therefore, integrated fertilizer management is an effective strategy for enhancing drought tolerance and improving maize performance in arid regions. The combination of chemical and biological fertilizers successfully mitigated the negative effects of drought stress and improved crop production efficiency.

Keywords: Sustainable agriculture. Water stress. Yield components. Nutrient management. Crop physiology. Semi-arid regions.

Introduction

Maize (*Zea mays* L.) stands as one of the most strategically important agricultural crops worldwide, serving critical roles in livestock and poultry feed production alongside numerous industrial applications. Despite this global significance, Iran faces a substantial production deficit, ranking among the world's largest maize importers. According to the Food and Agriculture Organization (FAO, 2018), Iran imported approximately 5.3 million tons of maize grain in 2018, highlighting the urgent need for enhanced domestic production efficiency.

With global forecasts projecting a doubling of maize demand (Aslam *et al.*, 2012), the convergence of increasing demand and limited water and soil resources presents unprecedented challenges for agricultural sustainability. Drought stress emerges as the primary constraint limiting maize productivity, particularly affecting photosynthetic efficiency and water use efficiency (Işik, Ortaş, 2024; Qiao *et al.*, 2024). This challenge is especially pronounced in Iran, where two-thirds of agricultural lands are located in semi-arid regions (Khuzestan, 2014).

Under water-deficit conditions, maize exhibits high sensitivity to water stress, with productivity declining dramatically when exposed to drought conditions (Daryanto *et al.*, 2016). Under drought stress, maize plants activate complex physiological adaptation mechanisms including stomatal closure to reduce water loss, osmotic adjustment through accumulation of compatible solutes like proline, and enhanced antioxidant defense systems to combat oxidative stress (Iqbal *et al.*, 2025; Rehan *et al.*, 2025). While these protective mechanisms help maintain cellular integrity, they simultaneously impair photosynthetic capacity and nutrient uptake efficiency, ultimately compromising yield potential through altered source-sink relationships and reduced assimilate translocation (Khan *et al.*, 2025).

To address these challenges, the integration of biological and organic fertilizers has emerged as a promising approach to mitigate drought stress impacts through multiple pathways. Vermicompost application enhances soil water-holding capacity while stimulating microbial activity and improving nutrient availability under water-limited conditions (Ahmad *et al.*, 2024; Malal *et al.*, 2024). At the plant level, these organic amendments increase chlorophyll content and support metabolic processes by maintaining cellular membrane stability (Tartoura, 2010). Integrated fertilizer systems combining chemical and biological components create synergistic effects that enhance plant tolerance to abiotic stress through improved root development, enhanced water uptake efficiency, and better nutrient mobilization (Jiang *et al.*, 2024; Shah *et al.*, 2023).

This integrated approach has demonstrated superior performance compared to individual fertilizer applications, with increased yields under drought conditions while reducing chemical fertilizer requirements by up to 50 % without compromising grain production (Nasrolahzadeh *et al.*, 2016). The effectiveness stems from complementary mechanisms: chemical fertilizers provide immediate nutrient availability, while biological components enhance long-term soil health and nutrient retention capacity.

The physiological basis for improved drought tolerance through integrated fertilizer management application involves enhanced antioxidant enzyme activity, particularly catalase, working synergistically with increased proline accumulation to maintain osmotic balance and protect cellular components from oxidative damage (Keya *et al.*, 2025)2025. Simultaneously, improved nutrient status supports continued photosynthetic activity and assimilate production, while enhanced root development increases the plant's capacity for water and nutrient acquisition under stress conditions (Sohrabi *et al.*, 2019).

Therefore, this study was developed in order to examinate the combined effects of drought stress and integrated fertilizer management on maize yield and physiological characteristics in Iran's Bam and Fahraj regions.

Materials and methods

This experiment was carried out during the 2019 growing season in two distinct arid regions of Kerman province, Iran: Bam (58°21' E, 29°06' N, elevation 1,067 m) and Fahraj (57°42' E, 28°54' N, elevation 1,045 m). These locations were selected to represent typical arid and semi-arid conditions prevalent across Iran's major agricultural zones, with contrasting climatic characteristics that allow for comprehensive evaluation of treatment effectiveness across different environmental contexts. The experiment employed a split-plot design based on randomized complete block design with three replications. Drought stress levels served as main plots, while fertilizer treatments were assigned as sub-plots. This experimental arrangement was chosen to accommodate the irrigation infrastructure requirements and minimize interference between different drought stress treatments.

Drought stress treatments

Drought stress levels were applied at three intensities based on soil water potential measurements:

1. No stress: irrigation applied when soil water potential reached -0.3 MPa;
2. Mild drought stress: irrigation applied when soil water potential reached -0.7 MPa;

3. Severe drought stress: irrigation applied when soil water potential reached -1.1 MPa.

Soil water potential was monitored using tensiometers installed at 20 cm depth in each main plot. Drought stress levels were initiated at the 6-8 leaf stage (V6-V8) and continued until physiological maturity (R6) to coincide with the most critical growth periods for drought sensitivity in maize.

Six fertilizer treatments were evaluated as sub-plot factors:

1. No fertilizer: no fertilizer application;
2. Chemical fertilizer: 300 kg N ha^{-1} + 150 kg P_2O_5 ha^{-1} (as triple superphosphate);
3. Phosphate biofertilizer: phosphate Barvar-2 applied at manufacturer's recommended rate of 2 kg ha^{-1} (phosphate-solubilizing bacteria);
4. Nitrogen biofertilizer: Nitroxin applied at manufacturer's recommended rate of 2 kg ha^{-1} (*Azotobacter chroococcum*);
5. Vermicompost: 5 t ha^{-1} applied 2 weeks before planting;
6. Integrated fertilizer management: 50 % chemical fertilizer (150 kg N + 75 kg P_2O_5 ha^{-1}) + phosphate biofertilizer at 2 kg ha^{-1} + nitrogen biofertilizer at 2 kg ha^{-1} + 2.5 t vermicompost ha^{-1}.

Composite soil samples were collected from multiple points across each experimental site from 0-30 cm depth, air-dried, and passed through a 2 mm sieve for physicochemical analysis. Soil analysis was conducted using standard methods as detailed in Table 1.

Soil fertility interpretation: both experimental soils exhibited alkaline pH (7.63-7.83), high salinity levels (EC > 3.5 dS m^{-1}), low nitrogen content (<0.1 %), low organic matter content (<1 %), medium potassium availability (150-200 mg kg^{-1}), and low phosphorus availability (<15 mg kg^{-1}). These characteristics are typical of arid region soils and indicate substantial nutrient limitations requiring fertilizer application for optimal crop production. Additionally, meteorological data collected in the regions are presented in Table 2.

Land preparation was initiated in July 2019 with deep plowing using a moldboard plow to 30 cm depth, followed by two perpendicular disk harrowings to break soil clods and achieve appropriate seedbed preparation. Plot layout was established according to the experimental design with 2-meter buffer zones between main plots to prevent lateral water movement and cross-contamination between drought stress levels. Each subplot measured 4.5 × 3.0 m (13.5 m^2) and consisted of six planting rows. Plant spacing was established at 16 cm within rows and 75 cm between rows, with a target population density of 8 plants m^{-2} and planting depth of

Table 1. Physicochemical properties of experimental soils

Parameter	Unit	Bam	Fahraj	Analysis Method
pH	-	7.83	7.63	1:2.5 soil:water suspension
EC	dS m^{-1}	3.83	3.63	Saturated paste extract
Total N	%	0.04	0.04	Kjeldahl method
Organic C	%	0.4	0.5	Walkley-Black method
Available K	mg kg^{-1}	170	171	1N NH_4OAc extraction, flame photometry
Available P	mg kg^{-1}	13.2	13.1	Olsen method, colorimetric
Texture	-	Sandy loam	Sandy loam	Hydrometer method

Source: Soil Science Department, Kerman Province Agricultural Organization, Kerman, Iran, 2019

Table 2. Meteorological characteristics of experimental locations during growing season.

Month	Mean Temperature (°C)	Maximum Temperature (°C)	Monthly Rainfall (mm)	Relative Humidity (%)
	Bam	Fahraj	Bam	Fahraj
January	25.0	28.0	30.7	34.7
February	29.7	32.1	35.6	39.6
March	36.1	38.1	42.4	45.4
April	35.0	38.0	40.7	44.7
May	33.3	36.8	39.0	44.0
June	29.8	32.8	36.0	40.0
July	27.6	29.6	34.1	36.1
August	22.0	24.0	28.4	30.4
September	13.7	13.7	19.4	24.4
October	14.8	16.6	21.2	23.2
November	14.9	16.4	21.0	23.0
December	21.5	20.5	27.6	23.6
Annual Total/Average	26.1	27.2	31.3	33.8

Source: Bam Meteorological Department, 2019; Fahraj Meteorological Department, 2019

4 cm. A 2-meter separation was maintained between all subplots and main plots to ensure treatment isolation.

The maize cultivar Single Cross 704 (SC704) was used throughout the experiment. This cultivar was selected for its adaptation to arid conditions and consistent performance across different environmental conditions in Iran. Seeds were pre-treated with fungicide (Captan 50 % WP at 3 g kg^{-1} seed) before planting to prevent soil-borne diseases.

Chemical fertilizer application: nitrogen was applied as urea (46 % N) in three split applications: one-third at planting, one-third at 8-leaf stage (V8), and one-third at tasseling stage (VT). Phosphorus was applied as triple superphosphate (46 % P_2O_5) entirely at planting and incorporated into the soil. Biofertilizer preparation and application: phosphate biofertilizer (Barvar-2) inoculation - seeds designated for phosphate biofertilizer treatments were coated with a suspension containing 10^8 CFU mL^{-1} of phosphate-solubilizing bacteria and dried in shade for 30 minutes according to manufacturer specifications. Nitrogen biofertilizer (Nitroxin) inoculation: seeds were treated with Nitroxin biofertilizer containing *Azotobacter chroococcum* (10^8 CFU mL^{-1}), dried in shade, and planted immediately to maintain bacterial viability. Vermicompost application: vermicompost was applied at 5 tons ha^{-1} (integrated treatment: 2.5 tons ha^{-1}) two weeks before planting and incorporated into the soil to 15 cm depth using rotary cultivation. No stress treatment: seeds for no stress and other non-biofertilizer treatments were soaked in distilled water for 30 minutes to maintain uniform seed moisture conditions across all treatments.

A drip irrigation system was installed with drip tapes spaced 75 cm apart (matching row spacing) and emitters spaced 20 cm apart along each tape. Water application was no stressled using calibrated volumetric flow meters for each main plot to ensure precise water delivery according to treatment specifications.

Irrigation scheduling was based on cumulative evaporation measurements from a Class A evaporation pan installed adjacent to each experimental site. Daily evaporation data were recorded at 08:00 h, and irrigation was applied when cumulative evaporation reached predetermined thresholds corresponding to target soil water potentials for each drought stress level. Water quality analysis showed electrical conductivity of 1.2 dS m^{-1} (Bam) and 1.4 dS m^{-1} (Fahraj), pH of 7.8 (both locations), and sodium adsorption ratio (SAR) of 2.1 (Bam) and 2.3 (Fahraj), indicating suitable quality for agricultural irrigation.

Weed control: pre-emergence herbicide (Atrazine 50 % SC at 2.5 L ha^{-1}) was applied immediately after planting. Hand weeding was performed as needed throughout the growing season to maintain weed-free conditions.

Pest management: integrated pest management practices were implemented, including regular scouting and targeted applications of approved insecticides when economic thresholds were reached. Plant density management: thinning was performed at the 4-leaf stage to achieve the target population density of 8 plants m^{-2}.

Physiological parameters

Chlorophyll content determination: chlorophyll *a* content was measured spectrophotometrically using the method of Arnon (1975) with modifications. Fresh leaf samples (0.5 g) were collected from the middle portion of the uppermost fully expanded leaf at grain filling stage (R2), extracted with 80 % acetone, and absorbance measured at 663 nm and 645 nm wavelengths. Chlorophyll content was calculated using the following equation:

Chlorophyll *a* (mg g^{-1} FW) = $[12.7(A_{663}) - 2.69(A_{645})] \times V/(1000 \times W)$:

Where: A_{663} and A_{645} are absorbances at respective wavelengths, V is the extract volume (mL), and W is the fresh weight (g).

Crop Growth Rate (CGR): CGR was calculated using Hunt's formula (1990): $CGR = (W_2 - W_1)/(t_2 - t_1) \times (1/GA)$; where W_1 and W_2 are dry weights at times t_1 and t_2, and GA is ground area. Measurements were taken at 10-day intervals from 30 to 80 days after emergence.

Agronomic parameters

The following yield components were evaluated: number of kernels per row (counted from five randomly selected ears per subplot); number of rows per ear (recorded from the same five ears); and thousand-grain weight (determined by weighing two 500-seed samples and calculating mean weight). Therefore, yield measurements were: grain yield (determined from a 2 m^2 harvest area in the center of each subplot, adjusted to 14 % moisture content); biological yield (total above-ground dry matter from 1 m^2 area at physiological maturity); and harvest index (calculated as grain yield/biological yield) × 100).

Statistical analysis

Data analysis was performed using SAS software version 9.4 (SAS Institute Inc., Cary, NC, USA). Analysis of variance (ANOVA) was conducted using the PROC GLM procedure for split-plot design.

For individual location analysis, main plots were considered as the drought stress levels (3 levels); sub-plots as the fertilizer treatments (6 levels); and three replications. For combined analysis across locations, there were considered two levels of locations (Bam and Fahraj); three levels of drought stress; six levels of fertilizer treatments; and three replications (blocks nested within locations).

Mean separation was performed using Duncan's Multiple Range Test at $P \leq 0.05$ probability level. Regression analysis was conducted to establish relationships between drought stress levels and measured parameters for each fertilizer treatment. Coefficient of variation (CV) was calculated to assess experimental precision, and homogeneity of variance was verified using Levene's test before conducting ANOVA. Statistical analysis followed the principles of split-plot design analysis as described by Montgomery (2017), with appropriate error terms used for testing main plot and sub-plot effects.

Results and discussion

The crop growth rate (CGR; g m^{-2} day^{-1}) serves as a fundamental physiological indicator for assessing maize performance under varying environmental conditions. Analysis of variance revealed significant effects ($p < 0.01$) of fertilizer treatments, drought stress levels, and their interactions on CGR in both Bam and Fahraj regions (Figure 1; Tables 3 and 4).

Under optimal irrigation conditions (no stress), the Integrated fertilizer management treatment reached superior performance in both regions. In Bam, CGR peaked at 120 g m^{-2} day^{-1} at 71 days after emergence, while the No stress treatment achieved only 60 g m^{-2} day^{-1}. Similarly, in Fahraj region, the combined treatment reached maximum values of 130 g m^{-2} day^{-1} compared to 70 g m^{-2} day^{-1} in the No stress treatment (Figure 1). This enhanced performance under optimal conditions reflects the synergistic effects of chemical and biological fertilizers in promoting nutrient availability and plant metabolism.

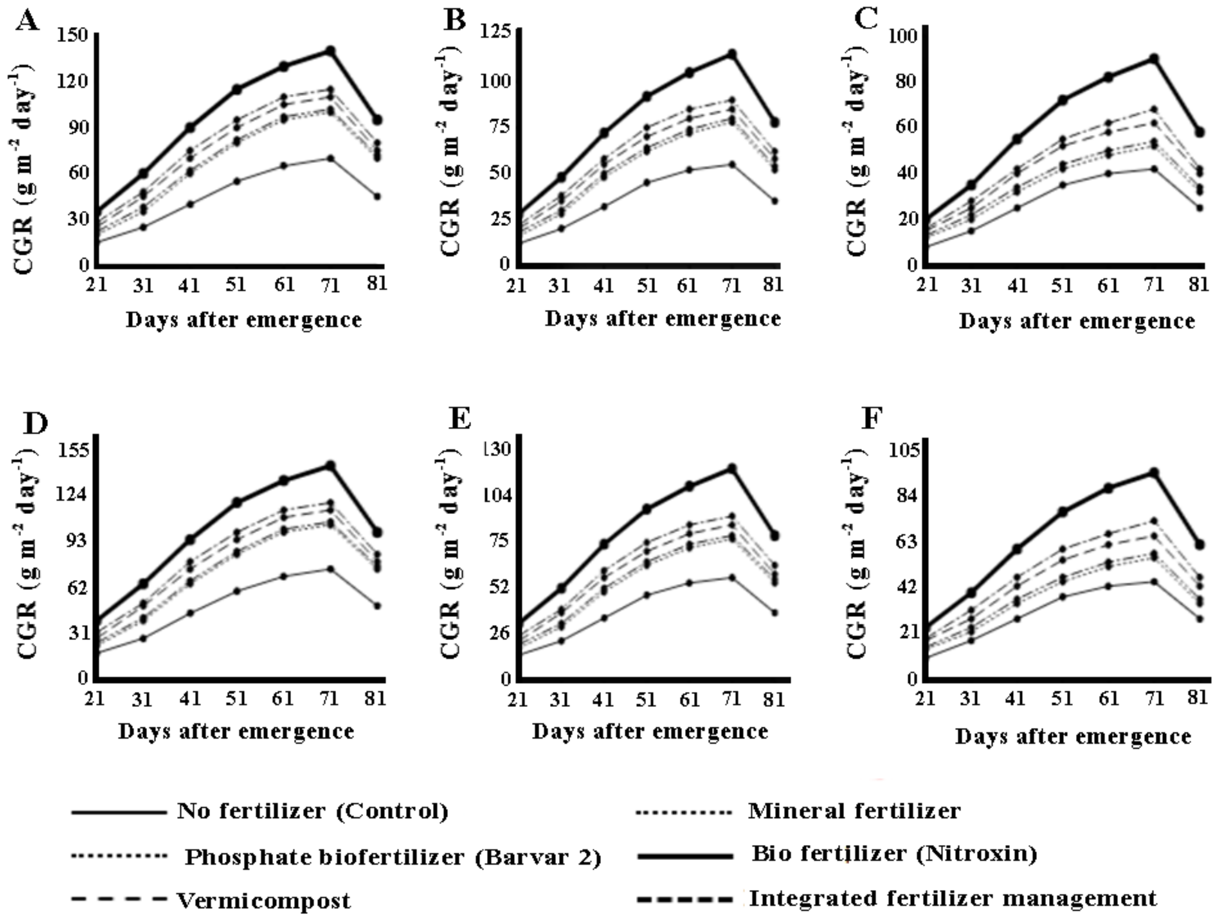
Under mild drought stress conditions, CGR values decreased substantially across all treatments. The Integrated fertilizer management treatment maintained relatively higher CGR values of 95 g m^{-2} day^{-1} in Bam and 102 g m^{-2} day^{-1} in Fahraj, representing reductions of 21 % and 22 % respectively compared to optimal conditions. No stress treatments exhibited more severe reductions, dropping to 42 g m^{-2} day^{-1} in Bam and 48 g m^{-2} day^{-1} in Fahraj, indicating 30 % and 31 % decreases respectively.

The most pronounced effects occurred under severe drought stress, where CGR declined dramatically across all treatments. The Integrated fertilizer management treatment maintained CGR values of 75 g m^{-2} day^{-1} in Bam and 82 g m^{-2} day^{-1} in Fahraj, representing 38 % and 37 % reductions from optimal conditions. No stress treatments showed the most severe responses, with CGR dropping to 32 g m^{-2} day^{-1} in Bam and 35 g m^{-2} day^{-1} in Fahraj, indicating reductions of 47 % and 50 % respectively.

The temporal pattern of CGR exhibited typical bell-shaped curves across all treatments, with gradual increases until day 71 followed by decline thereafter, corresponding to maize phenological development (Andrade *et al.*, 2002). The initial CGR increase coincided with rapid leaf area expansion and enhanced photosynthetic capacity, while the subsequent decline reflected leaf senescence and photoassimilate translocation to developing grains.

Drought stress significantly impaired CGR through multiple physiological mechanisms, including stomatal closure, reduced CO_2 assimilation, and decreased leaf water potential (Chaves *et al.*, 2009). However, the Integrated fertilizer management treatment effectively mitigated these adverse effects by enhancing root development, improving water uptake efficiency, and maintaining cellular osmotic adjustment (Wu *et al.*, 2005). The superior performance of biological fertilizers likely resulted from enhanced soil structure, increased water retention capacity, and promotion of beneficial microbial activity (Hungria *et al.*, 1997).

Figure 1. Interactive effects of fertilizer treatments and drought stress levels on crop growth rate of maize in Bam (A-B-C) and Fahraj (D-E-F) regions; where A and D represent no drought stress, B and E represent mild drought stress, and C and F represent severe drought stress.



Source: authors (2019)

Regional differences were evident, with Fahraj consistently showing higher CGR values than Bam across all stress levels, potentially attributed to more favorable climatic conditions and soil characteristics. These findings demonstrate that integrated fertilizer management represents an effective strategy for maintaining crop productivity under water-limited conditions, with implications for sustainable agricultural practices in semi-arid regions.

The combined analysis across Bam and Fahraj regions was essential to determine location effects and location × treatment interactions. This analysis was critical to establish whether fertilizer treatments and drought stress levels respond consistently across both locations or exhibit differential responses. Significant location × treatment interactions (such as Region × Fertilizer and Region × Drought Stress) indicate the necessity for location-specific recommendations rather than uniform applications. Furthermore, given the significant superiority of Bam region in grain yield (9687.4 vs. 8576.3 kg ha^{-1}) and number of seeds per row (31.2 vs. 26.3), this analysis enables direct comparison of regional performance and determination of relative advantages of each location under different treatment conditions (Table 5). The combined analysis provides critical information for scaling up research findings and developing region-appropriate agricultural management strategies.

Table 3. Interactive effects of fertilizer treatments and drought stress on corn characteristics in Bam region.

Treatment	Chlorophyll content	Kernel number per row	1000-grain weight	Biological yield	Grain yield	Harvest index
	(mg g^{-1} FW)	(number)	(g)	(kg ha^{-1})	(kg ha^{-1})	(%)
Simple effect - Drought stress levels						
No stress(C)	0.852a	31.2a	183.1a	16654.2a	12341.4a	45.2a
Mild drought stress(M)	0.631b	24.6b	171.2b	15973.2b	9854b	40.6b
Severe drought stress(S)	0.432c	15.2c	170.3b	11053.2c	4789c	27.3b
Simple effect - Fertilizer treatments						
No fertilizer(NF)	0.421c	28.5c	183.2d	16641.3e	4231d	28.35c
Integrated fertilizer(IF) management	0.821a	42.7a	272.3a	28994.4a	12515a	45.21a
Vermicompost(VC)	0.654b	39.2ab	220.7c	23147.6c	7857c	38.1b
Nitrogen biofertilizer(NB)	0.641b	38.0b	235.1c	19341.3d	7632c	38.3b
Phosphate biofertilizer(PB)	0.611b	37.2b	239.1c	19266.1d	7874c	38.2b
Chemical fertilizer(CF)	0.801a	38.7b	255.2b	25613.2b	9874b	36.3b
Interactive effects - Drought stress × Fertilizer treatments						
C×NF	0.772d	30.7d	183.3e	16640.6ed	5640.6d	28.3d
C×IF	0.931a	43.2a	299.2a	28994.4a	12341.2a	45.9 a
C×VS	0.832b	37.1b	221.7d	22613.4c	8613.4bc	38.2 b
C×NB	0.842b	38.2b	220.7d	19266.3d	7266.3c	38.8b
C×PB	0.812b	38.1b	220.7d	19266.3d	7266.3c	37.2 bc
C×CF	0.913b	38.7b	235.2c	25613.4b	9613.4b	36.8 c
M×NF	0.612e	25.6e	174.2 g	15973.2e	4532.1de	23.1e
M×IF	0.881b	40.6ab	269.3b	26994.2b	9632.1b	40.7 b
M×VS	0.742c	36.0bc	221.3d	21980.1c	5632.1d	31.7 d
M×NB	0.777d	34.7c	221.3d	17266.6d	5632.5d	31.7d
M×PB	0.726d	33.2c	221.3d	17266.6d	5421.2d	30.7d
M×CF	0.871b	36.2bc	232.1d	23280.1c	7452.3c	31.7d
S×NF	0.556f	18.3 g	171.3 g	7251.3 g	3687.2f	24.7e
S×IF	0.784c	26.7e	205.3e	13498.2e	7412.1c	27.6d
S×VS	0.611d	19.2fg	187.6 f	13328.1f	4563.1e	28.9d
S×NB	0.626d	19.2fg	188.4 f	9516.6f	4213.1e	28.3d
S×PB	0.632d	19.4fg	186.6 f	9511.4f	4132.5e	27.9d
S×CF	0.722d	21.9f	197.6ef	15328.1ec	5421.3d	22.8e

Source: authors (2019)

Table 4. Interactive effects of fertilizer treatments and drought stress on corn characteristics in Fahraj region.

Treatment	Chlorophyll content	Kernel number per row	1000-grain weight	Biological yield	Grain yield	Harvest index
	(mg g^{-1} FW)	(number)	(g)	(kg ha^{-1})	(kg ha^{-1})	(%)
Simple effect - Drought stress levels						
No stress(C)	0.921a	38.2a	253.4a	23989.2a	10840.3a	44.2a
Mild drought stress(M)	0.871b	35.6b	249.4 a	21144.3.2b	8131.2b	40.6b
Severe drought stress(S)	0.733c	21.3c	170.3b	10499.2c	5911.2c	28.1b
Simple effect - Fertilizer treatments						
No fertilizer(NF)	0.761c	26.7c	182.7d	16640.3e	3451e	27.4 c
Integrated fertilizer(IF) management	0.920a	38.2a	271.4a	23994.4a	10325a	44.2 a
Vermicompost(VC)	0.821b	32.4 b	221.7c	17610.6c	5767d	38.1b
Nitrogen biofertilizer(NB)	0.831b	33.1b	234.9c	14221.3d	6522c	38.3b
Phosphate biofertilizer(PB)	0.801b	33.1b	238.5c	14216.1d	6764c	36.2b
Chemical fertilizer(CF)	0.902a	35.2b	256.4b	20613.2b	8764b	36.3b
Interactive effects - Drought stress × Fertilizer treatments						
C×NF	0.767c	26.7d	NS[1]	16640ed	4140d	27.4 d
C×IF	0.921a	38.2a	NS	23994.4a	10840.6a	44.2 a
C×VS	0.821b	32.4b	NS	17610.4c	7112.8bc	38.9 b
C×NB	0.831b	33.1b	NS	14221.3c	5765.7c	38.1 b
C×PB	0.801b	33.1b	NS	14216.3d	5765.7c	38.2 b
C×CF	0.902a	35.2b	NS	20613.3b	8112.8b	36.6 c
M×NF	0.601d	20.6e	NS	15973.5e	3031.5e	24.2 e
M×IF	0.871b	35.6ab	NS	21144.5b	8131.5b	40.7 b
M×VS	0.731c	31.4bc	NS	16988.5c	4131.5d	32. 4d
M×NB	0.767c	29.7c	NS	12231.5d	4131.5d	31.1 d
M×PB	0.715c	28.1c	NS	12566.6d	3920.6d	29.2 d
M×CF	0.861b	31.2bc	NS	19288.7c	5951.7c	32.1 d
S×NF	0.545e	14.3f	NS	6236.6 g	2486.6f	24.3 e
S×IF	0.773c	21.8e	NS	10499.6e	5911.6c	28.1d
S×VS	0.602d	14.2f	NS	9328.5f	3062.5e	28.1d
S×NB	0.616d	14.9f	NS	9247.6f	2712.6e	28. 4d
S×PB	0.621d	14.1f	NS	9500.5f	2631.5e	27.1d
S×CF	0.711c	14.4f	NS	10328.7e	3920.7d	23.3 e

[1]Not significant.

Source: authors (2019)

Table 5. Effect of location on grain yield, biological yield, and number of seeds per row.

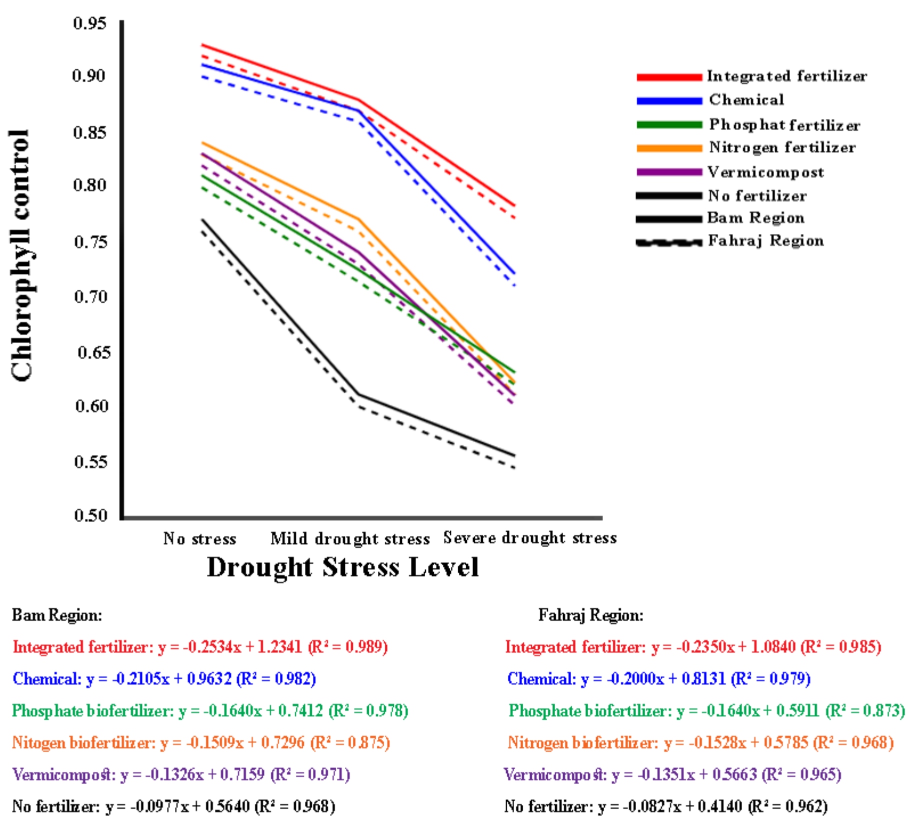
Location	Grain Yield ($kg\ ha^{-1}$)	Biological Yield ($kg\ ha^{-1}$)	Seeds per Row (number)
Bam	9687.4a	26994.1a	31.2a
Fahraj	8576.3b	26180.0b	26.3b

Source: authors (2019)

Chlorophyll a

Interaction effect of drought stress levels and fertilizer treatments on chlorophyll a content was statistically significant at 1 % probability level in both Bam and Fahraj regions (Tables 3 and 4). In the Bam region, the highest chlorophyll a content (0.931 mg g^{-1} leaf fresh weight) was obtained from Integrated fertilizer management treatment under optimal irrigation (Figure 2), described by the regression equation $y = -0.2534x + 1.2341$ with a high coefficient of determination ($R^2 = 0.989$). Conversely, the lowest content (0.556 mg g^{-1} leaf fresh weight) was observed in severe drought stress treatment with no fertilizer application. In the Fahraj region, a similar trend was observed. The highest chlorophyll a content (0.921 mg g^{-1} leaf fresh weight) was recorded in Integrated fertilizer management treatment with the equation $y = -0.2350x + 1.0840$ and ($R^2 = 0.985$). The lowest value (0.545 mg g^{-1} leaf fresh weight) was found in severe drought stress treatment without fertilization (Figure 2).

Figure 2. Regression plot of interaction effect between drought stress levels and fertilizer treatments on plant chlorophyll *a*.



Source: authors (2019)

Terzi and Kadioglu (2006) and Khayatnezhad and Gholamin (2012) confirmed the decrease in chlorophyll content with increased drought stress intensity. Sanchez *et al.* (1983) noted that nitrogen deficiency caused by drought stress could lead to reduced leaf chlorophyll levels. Maghsudi *et al.* (2014) showed that combined application of biological and chemical fertilizers increased leaf chlorophyll content in corn hybrids. Khazaie *et al.* (2007) reported that drought stress not only directly impacts chlorophyll degradation but also reduces root activity and nitrogen absorption.

Results suggest that using Integrated fertilizer managements can be an effective strategy for mitigating drought stress effects on chlorophyll content. Further studies are recommended to investigate the physiological mechanisms underlying these interactions.

Grain yield

The interaction effect of drought stress levels and fertilizer treatments on grain yield was significant at the 1 % probability level. In the Bam region, the Integrated fertilizer management treatment under no stress conditions reached the highest grain yield (12341.2 kg ha^{-1}), described by the regression equation $y = -2534x + 12341$ with a high determination coefficient ($R^2 = 0.989$) (Figure 3). In contrast, the No stress treatment had the lowest yield (5640.6 kg ha^{-1}) with the equation $y = -977x + 5640$ and ($R^2 = 0.968$).

Khaksar *et al.* (2014) showed that these results are similar to studies examining simultaneous effects of irrigation stress and fertilization on physiological characteristics related to corn yield. In the Fahraj region, Integrated fertilizer management treatment also showed significant superiority with a yield of 10840.6 kg ha^{-1} under no stress conditions, described by the equation $y = -2350x + 10840$ and ($R^2 = 0.985$). Duncan's mean comparison test ($p \leq 0.05$) showed that the No stress treatment with a yield of 4140 kg ha^{-1} was placed in the lowest statistical group.

Amyanpoori *et al.* (2015) in studying vermicompost and phosphate fertilizer application demonstrated that Integrated fertilizer managements can have a significant impact on crop yield improvement. Dadrasan *et al.* (2015) emphasized the importance of biological fertilizers in improving water-plant relationships in their study. Bashan *et al.* (2004) reported that this improvement results from the synergistic effects of biological and chemical fertilizers in increasing nutrient absorption and plant growth hormone production.

Andrade *et al.* (2002) showed that under drought stress conditions, proper plant nutrition plays a critical role in photosynthetic matter allocation to grains and maintaining harvest index. Ghasemi *et al.* (2011) also reported similar results regarding the positive effect of biological fertilizers in reducing drought stress effects.

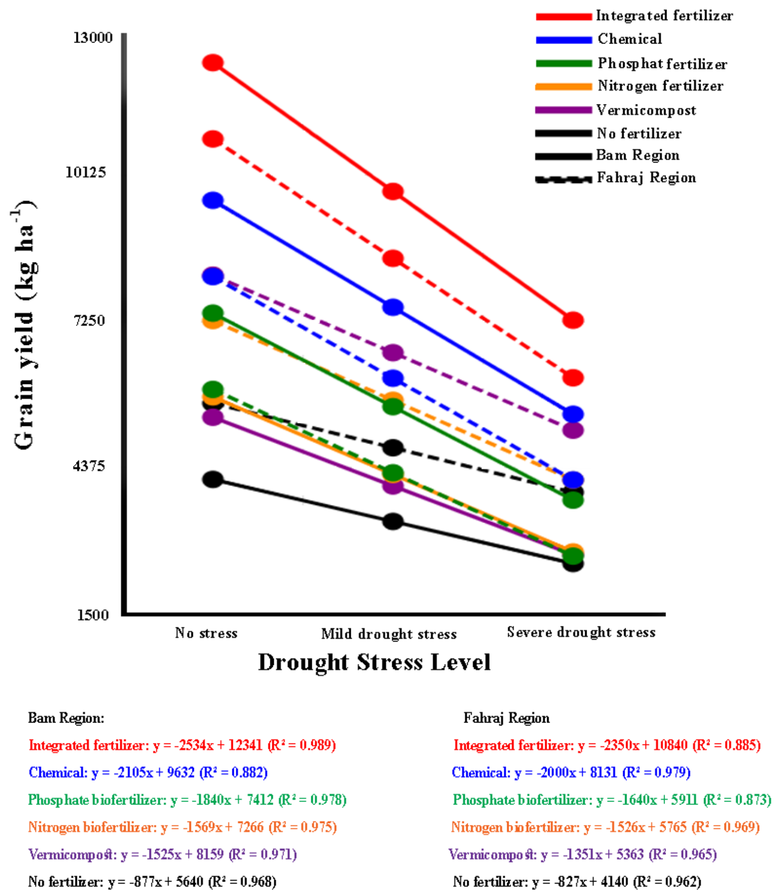
In both regions, severe drought stress significantly reduced grain yield; however, this reduction was less noticeable in Integrated fertilizer management treatments (Figure 3).

Caferri and Bassi (2022) emphasized the extensive effects of ecophysiological changes on water-plant relationships in his studies. The results of this research suggest that using Integrated fertilizer managements can be recommended as an effective strategy for increasing yield and drought stress tolerance in both regions, although regional differences in treatment responses should be considered.

Harvest index

The interaction effect of drought stress levels and fertilizer treatments on harvest index was significant at 1 % probability level. Mean comparison across treatments revealed that in both Bam and Fahraj regions, Integrated

Figure 3. Regression plot of interaction effect between drought stress levels and fertilizer treatments on plant grain yield.



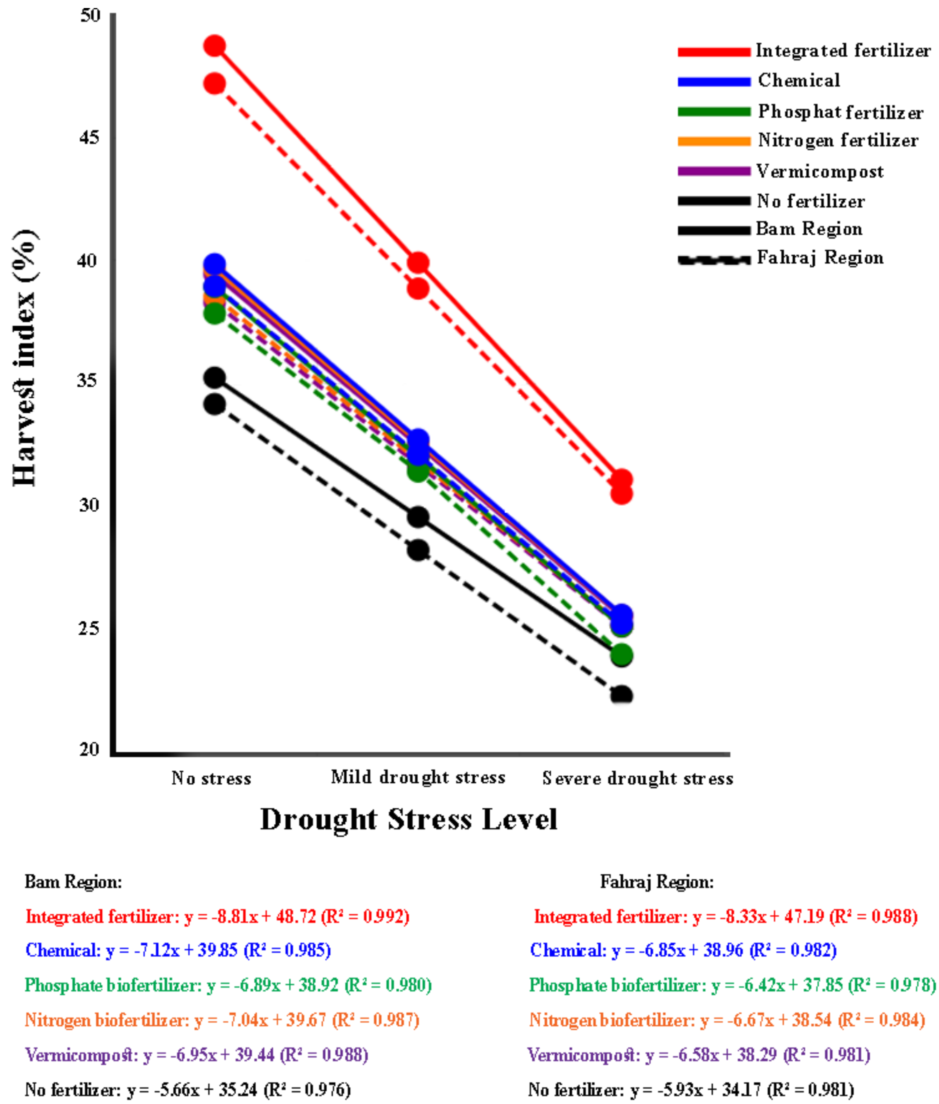
Source: authors (2019)

fertilizer management treatment under no stress conditions achieved the highest harvest index (Figure 4), which can be described by regression equations $y = -8.81x + 48.72$ ($R^2 = 0.992$) and $y = -8.33x + 47.19$ ($R^2 = 0.988$), respectively. In contrast, the No stress treatment in both regions showed the lowest harvest index values with equations $y = -5.66x + 35.24$ ($R^2 = 0.976$) and $y = -5.93x + 34.17$ ($R^2 = 0.981$).

The reduction in harvest index with increasing drought stress intensity can be attributed to a greater decrease in grain yield compared to total dry weight. Pandey *et al.* (2000) reported that the higher sensitivity of reproductive growth compared to vegetative growth under drought stress conditions is one of the main factors reducing maize harvest index. In both regions, severe drought stress caused a significant decrease in harvest index, such that in Bam region it declined from 45.94 % under no stress conditions to 27.61 % under severe drought stress for Integrated fertilizer management treatment (Table 3). A similar trend was observed in Fahraj region, albeit with less intensity.

Drought stress affects plant biochemical and physiological processes, leading to reduced photosynthetic efficiency and material translocation to grains. Saeidi *et al.* (2010) demonstrated in their study on wheat that drought stress alters source-sink relationships, which can result in reduced translocation of photosynthetic materials to grains. Patade *et al.*

Figure 4. Regression plot of interaction effect between drought stress levels and fertilizer treatments on plant harvest index.



Source: authors (2019)

(2011) also reported that drought stress affects plant growth and yield by influencing osmolyte accumulation and antioxidant defense systems.

The combined application of biological and chemical fertilizers was able to partially mitigate the negative effects of drought stress. Nguyen *et al.* (2012) showed that the use of organic fertilizers can improve plant water availability under drought stress conditions. Tartoura (2010) also confirmed that organic fertilizer application can reduce drought-induced oxidative stress. The higher harvest index in the combined biological and chemical fertilizer treatment can be attributed to a greater increase in grain yield relative to biological yield compared to other fertilizer treatments (Figure 4), indicating better efficiency of this fertilizer treatment in translocating photosynthetic materials to the grains.

Rafiee *et al.* (2010) also confirmed that drought stress, while reducing dry matter production, disrupts the allocation of carbohydrates to the reproductive part. Under severe stress conditions, no significant difference was observed between different fertilizer levels, indicating that the effect of drought stress on reducing the harvest index was dominant in these conditions (Tables 3 and 4). Masjedi *et al.* (2009) reported similar results, although in some conditions, they observed an increase in harvest index with increasing stress intensity due to a greater reduction in biological yield compared to grain yield.

Overall, the results suggest that the use of combined chemical and biological fertilizers, along with proper irrigation management, can improve harvest index and consequently increase maize production efficiency under water-limited conditions. This study demonstrated significant effects of drought stress levels and fertilizer applications on maize performance in Bam and Fahraj regions. Results revealed that increasing drought stress intensity led to substantial reductions in crop growth parameters, including crop growth rate, chlorophyll content, kernel number per row, and grain yield. The combined chemical and biological fertilizer treatment showed the best performance, significantly mitigating drought stress negative impacts. This outcome likely results from synergistic interactions between chemical and biological fertilizers, enhancing nutrient uptake, photosynthetic activity, root system development, and plant growth hormone production.

Comparing the two regions, Bam exhibited better performance than Fahraj, potentially due to climatic differences. In both regions, the most severe reductions in growth parameters occurred under severe drought stress conditions.

Conclusions

This study provides evidence that combining chemical and biological fertilizers can enhance crop resilience and productivity, offering a promising approach for sustainable agricultural practices in drought-prone areas.

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