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ORIGINAL PAPER

Precision drip Irrigation System and Foliar Application of Biostimulant and Fertilizers Containing Micronutrients Optimize Photochemical Efficiency and Grain Yield of Maize (*Zea mays* L)

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Abstract

Asymmetric drought propagation and depletion of soil nutrients threaten cereal crop productivity worldwide, calling for the application of validated agronomic practices to curtail their effect on crop production. This study evaluated the effect of precision drip irrigation, biostimulant, and micronutrients application on photochemical efficiency and yield of maize. An experiment laid in a randomized complete block design with irrigation and water stress was established in 2022 and 2023 growing seasons at the experimental area of the University of Debrecen. Other treatments included T1 (non-microbial biostimulant from plant origin), T2 (zinc based chemical fertilizer), T3 (boron and molybdenum based chemical fertilizer), and T4 (control). Data was collected on steady-state fluorescence (F'), maximal fluorescence (Fᴍ'), quantum photosynthetic yield or efficiency of photosystem II (ΦPSII or Y(II)), electron transport rate (ETR), and grain yield and yield components. Precision drip irrigation significantly optimized ΦPSII, ETR, cob weight, number of seeds per cob, weight of 1000 seeds and grain yield. The biostimulant and micronutrients optimized Fᴍ', ΦPSII, and ETR at VT and R2 growth stages. Regardless of the water management regime, T1, T2 and T3 seasonally optimized grain yield. Between water management regimes, biostimulant had the highest yield optimization effect under precision drip irrigation in the season with elevated water stress.Optimum photochemical efficiency and grain yield is achievable through precision drip irrigation, biostimulant, and micronutrient application. However, further research involving 2–3 application times at critical stages of maize under precision drip irrigation and/or combined application of these treatments at season specific precision drip irrigation is required.

Keywords Biostimulant · Micronutrients · Precision drip irrigation · Photochemistry · Water stress · Yield

1 Introduction

Maize (*Zea mays* L) is among the most important cereal crops, after rice (*Oryza sativa* L) and wheat (*Triticum aestivum* L) worldwide due to its economic and nutritional benefits (Prasanna et al. 2021; Ssemugenze et al. 2024). However, abiotic stresses such as water stress (extreme drought) and heat stress (Simkó et al. 2020) negatively impact its production and productivity. Moreover, these climate extremes are expected to increase globally (Zampieri et al. 2019; Simkó et al. 2020). A simulation by Zampieri et al. (2019) revealed that temperature rise by 2 °C in the late 2030s will affect maize production in both minor and major production areas like never experienced before. There exists a negative nexus between morphological, physiological, and biochemical changes in maize with drought and/or heat stress (Trivedi et al. 2018; Rehaman et al. 2023). In particular, drought stress significantly affects the nutritional status of maize (Ge et al. 2010; Klofac et al. 2023); hence, balanced supply of adequate mineral nutrients is pivotal (Kovács et al. 2009; Waraich et al. 2011; Klofac et al. 2023). Research has shown that although maize as a C_4 plant

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efficiently utilizes moisture under limited supply, its productivity is still reduced by drought, depending on the crop stage it onsets (Killi et al. 2017; Hussain et al. 2020). Kumar et al. (2024) noted that supply of moisture at stress-sensitive growth stage of crops enhances productivity. This calls for the application of precision water delivery technologies (Chen et al. 2023). Conversely, different fertilizer formulations are produced and applied in crop production to alleviate nutrient stress and increase productivity (Bojtor et al. 2021; Ocwa et al. 2023), though often micronutrients are neglected. For example, zinc is a major essential micronutrient, which in low supply limits crop growth (Ghani et al. 2022), and yield (Ma et al. 2017).

Supplementation of maize with nutrients such as zinc improves yield (Zhang et al. 2020), and zinc deficiency causes over 40% crop yield reduction (Noulas et al. 2018; Idrees et al. 2024). Besides, zinc plays a fundamental role in crop resistance against drought stress by regulating various physiological processes (Klofac et al. 2023). Though abundant in most soils, its uptake by plants is limited by several physicochemical soil conditions (Alloway, 2009) making it the most deficient element especially in certain soil types (Sadeghzadeh, 2013). On the other hand, despite the fact that boron requirement by maize is relatively low, it is one of the yield limiting factors in some geographic regions (Hayat et al. 2023). Conversely, besides chemical fertilizers, biostimulants are used to boost crop productivity (Abbott et al. 2018; Sible et al. 2021; Ocwa et al. 2024). Despite the use of these inputs, earlier, it was underscored that photosynthesis interference by drought and/or heat (Bresson et al. 2015; Dogru, 2021; Nematpour and Eshghizadeh, 2023), and nutrient stress (Rácz et al. 2021; Ocwa et al. 2024) decreases yield (Bresson et al. 2015). This necessitates undertaking critical assessments during the crop growth cycle to unravel the effects of applied agronomic interventions.

Chlorophyll fluorescence measurements are pivotal in monitoring the response of plants to stress (Sinsawat et al. 2004; Dogru, 2021) and amelioration capacity of agronomic interventions such as fertilization and irrigation. Among the vital parameters include minimal fluorescence (Fo), maximum fluorescence (Fm), variable fluorescence (Fv), and photochemical efficiency of photosystem II. According to Chen et al. (2019), chlorophyll florescence, photochemical reactions and other pathways utilize light energy in the photosystem II (PSII). As such, fluorescence yield indicates the fraction of absorbed light energy re-emitted as fluorescence while the photochemical yield of PSII is an indication of photochemical light use efficiency since it’s the fraction of absorbed photons used for photochemical reactions (Chen et al. 2019). According to Janušauskaite and Feiziene (2011), the efficiency of cereal crop photosystems depends on weather conditions. Rehaman et al. (2023) revealed that maximum quantum efficiency of PSII, ETR and intrinsic PSII activity significantly reduced due to drought stress by 11.3, 14.5, and 10.8%, respectively. Likewise, a report by Cendrero-Mateo et al. (2016) revealed a significant decrease in photochemical yield and steady-state fluorescence due to drought. Similarly, Arikan et al. (2022) reported a decrease in Fv/Fo (activity of the water-splitting complex on the donor site of the PSII and Fv/Fm by 48.6 and 14.1%, respectively under water stress compared to the control. Killi et al. (2020) noted that maize varieties tolerant to drought retained PSII function at the temperatures of 25 and 35°C treatments at limited water supply. Besides drought stress, fluorescence parameters can vary depending on plant nutrition (Tubuxin et al. 2015; Chen et al. 2016). In fact, nutrients supplied exogenously by biostimulants and/or chemical fertilizers affect chlorophyll fluorescence parameters differently, depending on several factors. Li et al. (2012) noted that the electron donor and acceptor performance in the reaction center of PSII was significantly increased by nitrogen application. Toth et al. (2022) indicated that the application of zinc and amino acids had no significant effect on Fo, reduced Fm while zinc alone reduced Fo. Some reports revealed higher Fm, Fv and Fv/Fm value in zinc application except Fo that was not affected (Wang and Jin, 2005; Guo and Tan 2015). Besides, Klofac et al. (2023) reported that quantum yield significantly increased after foliar application of zinc oxide micro (ZnO). Moreover, there exist a nexus between photochemical parameters and grain yield. Earlier, a comprehensive review by Guo and Tan (2015) revealed that although chlorophyll fluorescence has successfully been applied in plant research, inconsistencies in some results are still reported. Among the causes, include the type of equipment, light conditions and other abiotic stresses. Specifically, plant leaves exposed to high actinic light levels for several hours resist closure of PSII reaction centers even though high saturation light pulse is applied, hence affecting reliability of ΦPSII and ETR measurements (Loriaux et al. 2013). It is proposed that the solution is to apply the method called Fᴍ’ correction that uses multiple phased saturation flash available in Opti-Sciences such as Y(II) meter, OS1p, OS5p and OS5p+ (Loriaux et al. 2013); hence this study utilized OS5p+equipment. With this in mind, currently in Hungary, agro-technical innovations have been developed to ameliorate drought, heat and nutrient stresses in attempt to optimize maize production amidst unprecedented climate change. Hence, this study evaluated the effect of precision drip irrigation, biostimulant and chemical fertilizers containing micronutrients on chlorophyll fluorescence, photochemical efficiency and grain yield of maize.

2 Materials and Methods

2.1 Experimental Site

The experiments were carried out at the University of Debrecen, Böszörményi street experimental area (47°83, 030”N, 21°82, 060”E, 111 m asl). The season 2022 had elevated temperature and low precipitation between May to August, which were the active months of maize growth. In fact, the temperature was elevated by close to 1^{o}C in May, July, and August and, 2.4^{o}C in June while precipitation reduced by close to -1 mm in May and July, and -2 mm in June and August in 2022 compared to 2023 season. Generally, the precipitation in each of the months May to August was <0.8 mm in 2022 season and >1 mm in 2023 season (Fig. 1). The soil analysis and nutrient adequacy and/or deficiency interpretation was based on the Hungarian New Fertilization Guidelines (Antal et al. 1987). The soil type was leached chernozem. The soil in the experimental site had 5.3 mg kg^{-1} available nitrogen, 320.9 mg kg^{-1} available phosphorus and 256.2 mg kg^{-1} available potassium. The concentration

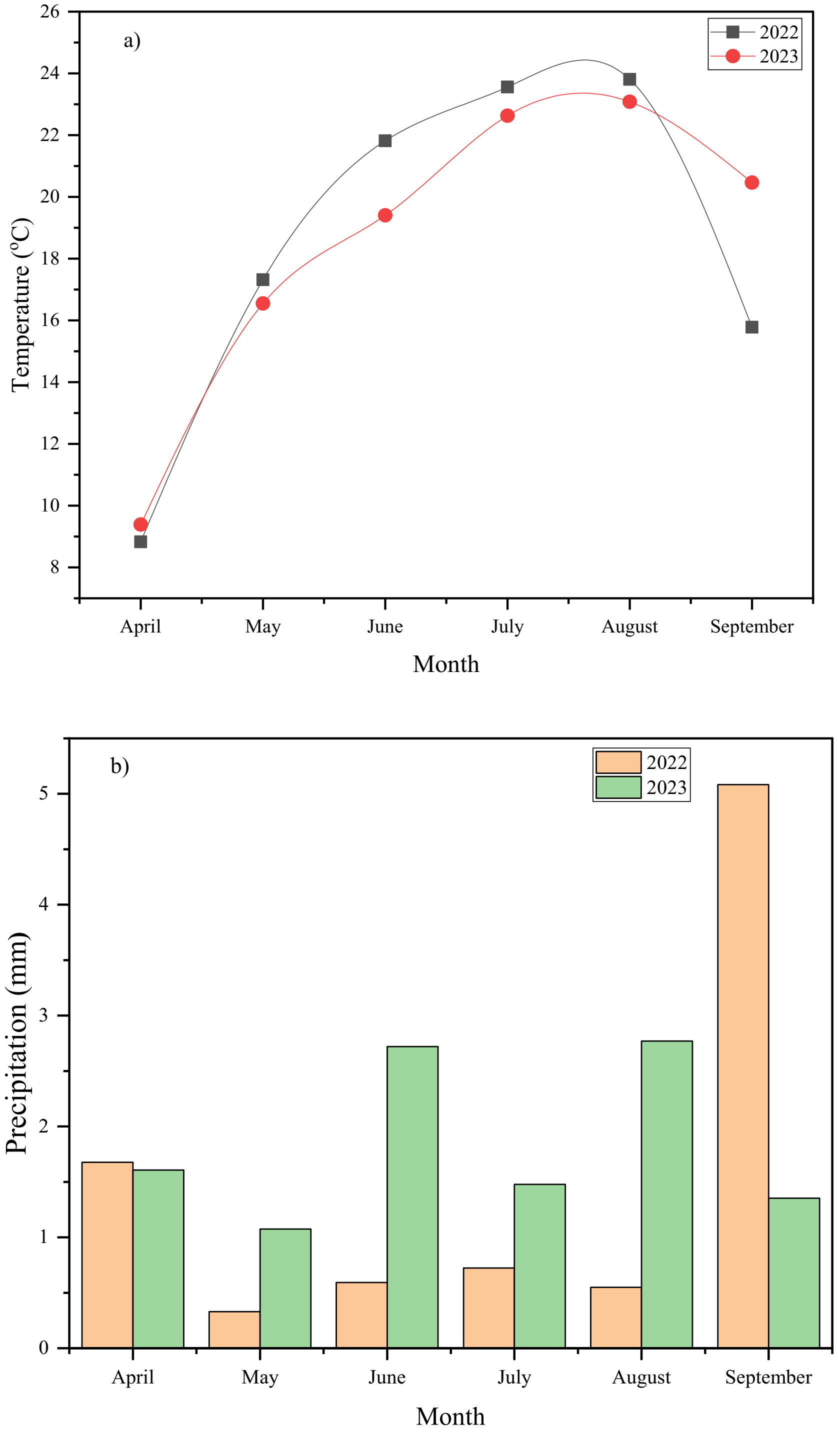


Fig. 1 Temperature (**a**) and the amount of precipitation received (**b**) during experimental period

Table 1 Chemical properties of chernozem soil at the University of Debrecen, Böszörményi street experimental area

Property	Value	Interpretation reference comment
pH (KCl 1:2.5)	7.6	Slightly alkaline
Arany plasticity index	45.5	Clay loam
$CaCO_3$ (m/m%)	16.3	Adequate
Humus (m/m%)	2.1	Weak (poor category)
Nitrogen (mg kg^{-1})	5.3	Weak
Phosphorus (mg kg^{-1})	321	Good
Potassium (mg kg^{-1})	256	Medium
Magnesium (mg kg^{-1})	452	Very good
Sulfur (mg kg^{-1})	8.8	Deficient
Manganese (mg kg^{-1})	60.1	Adequate
Zinc (mg kg^{-1})	2.7	Adequate
Copper (mg kg^{-1})	2.0	Adequate

of other essential elements and the pH of the soil are presented in Table 1.

2.2 Experimental Design and Treatments

The experiment was laid in a randomized complete block design (RCBD) with four replications. Experimental plots measured 10 m^2 each (32 plots in total), and water treatment had two levels: irrigated (IR) and water stress (WS). Precision drip irrigation system was installed on 27th May 2022 and 12th June 2023 prior to onset of drought and removed when maize attained physiological maturity. Based on the meteorological data, the installation was delayed by 15 days in 2023 because of adequate moisture in the soil. All irrigated plots were supplied with the same amount of water while water stress plots were not irrigated even when maize plants were at wilting point during drought (summer). Each row of maize had one drip irrigation line/strip. Soil moisture content was measured using a Campbell wet sensor at different depths (-0.1 m and -0.3 m). Irrigation was started at the minimum value of the maximum field water capacity value. The intensity of the irrigation was 3 l/m^2/ hour. If the probability of rain reached 80%, no irrigation was started. Irrigation was done between 9pm to 5am to reduce evapotranspiration. Total amount of water applied during the whole experimental period was 413.6 mm and 358 mm in 2022 and 2023 growing seasons, respectively. The drip irrigation system was precision-managed by remote control via a mobile phone application (Hydrawise application (Hunter)), where the amount of water applied, and intensity was continuously monitored. Biostimulant and chemical fertilizer treatments were designated as T1, T2, T3, and T4 (control). Detailed composition of the treatments and their application rates as recommended by the manufacturer are provided in Table 2. Treatments were applied once using a motorized pump at V8 stage when maize plants had attained large leaf surface area to absorb nutrients.

2.3 Seedbed Preparation, Sowing, and General Agronomic Practices

The seedbed was prepared using a KongsklideVibro Master SGC/SQ25 mounted seedbed cultivator (Kongskilde Agriculture, Albertslund, Denmark). Prior to planting, fertilizer was applied in the soil at the rate of 101.3 kgha^{-1} N, 26.3 kgha^{-1} CaO, 18.8 kgha^{-1} MgO on 11th April 2022 (2022 season) and 90.0 kgha^{-1} N, 23.0 kg ha^{-1} CaO, and 16.0 kg ha^{-1} MgO on 31st March 2023 (2023 season). The seeds of maize hybrid FAO 420 were sown on 2nd

Table 2 Composition of treatments used in the study

Treatment and ingredients	Value	Application rate
T1 (Biostimulant)		4 l ha^{-1}
Organic matter content (m/m%)	60.0	
Amino acid content (m/m%)	21.7	
Asparagine (%)	1.2	
Glutamine (%)	16.2	
Arginine (%)	<0.1	
Alanine (%)	2.6	
Leucine (%)	0.1	
Glycine (%)	0.3	
Histidine (%)	0.1	
Proline (%)	1.0	
Methionine (%)	<0.1	
Isoleucine (%)	<0.1	
Phenylalanine (%)	<0.1	
Lysine (%)	<0.1	
Cystine (%)	<0.1	
Saccharide content (m/m%)	6.2	
Fructose (%)	0.3	
Glucose (%)	0.7	
Raffinose (%)	0.5	
Sucrose (%)	0.3	
Trehalose (%)	3.5	
Cellulose (%)	1.0	
Fulvic acid content (m/m%)	23.1	
Nitrogen (m/m%)	8.0	
Phosphorus (m/m%)	0.5	
Potassium (m/m%)	0.2	
T2 (Zinc, water soluble %)	10.2	1.5 l ha^{-1}
T3		
P_2O_5(%)	16.8	1.4 kg ha^{-1}
K_2O (%)	11.0	
Boron (%)	8.4	
Molybdenum (%)	11.0	

May 2022 and 28th April 2023 using a Gaspardo MTR4 pneumatic precision seed drill (Maschio Gaspardo S.p.A., Campodarsego, Italy) with a spacing of 76.2 × 18.2 cm at a seed rate of one seed per hole, giving total plant population of 72,100 per hectare. FAO 420 hybrid was used because it is widely cultivated on a large scale in Hungary. In both seasons weed management was done as recommended.

2.4 Chlorophyll Fluorescence Measurements

Data was collected on chlorophyll fluorescence parameters such as F’, Fm’, ΦPSII and ETR. Chlorophyll fluorescence parameters were measured using Pulse Modulated Chlorophyll Fluorometer (PerkinElmer Inc., Waltham, MA, USA) at the V12 (twelve-leaf stage) VT (tasseling stage) and R2 (kernel blister stage) growth stages. In each plot, four plants were randomly selected (Yin et al. 2011), and measurements taken in the new fully expanded leaf of each plant at vegetative stage and leaf opposite the ear at the reproductive stage, respectively (Simkó et al. 2020). For saturation pulse intensity, prior to measurement, the selected leaves from each plant were dark adapted for 30 minutes (Hu et al. 2023). Measurements were taken for: F’ which is the steady-state fluorescence signal under actinic light prior to saturation pulse, Fm’ which is maximal fluorescence under actinic light at steady state photosynthesis when all the reaction centers are closed. The fluorescence difference between Fm’ and F’ (Fm’- F’) constituted Fq’ (Baker, 2008; Janka et al. 2015). The ΦPSII which is the quantum photosynthetic yield (efficiency) of PSII was calculated as (Fm′- F′)/Fm′ (Baker, 2008; Janka et al. 2015; Hazrati et al. 2016). The ETR, which is an estimate of the number of electrons transported through photosystem II under steady-state photosynthetic conditions, was calculated using the formula indicated in the manufacturer’s protocol as well as in published literature (Flexas et al. 2002; Hu et al. 2023). The equation used was:

$$\mathrm{ETR} = \text{Quantum photosynthetic yield} \times 0.84 \times 0.5 \times \mathrm{PAR} \tag{1}$$

Where 0.84 is average leaf absorptance value of PSII, and 0.5 means two photons used to excite one electron (Flexas et al. 2002), and PAR is photosynthetically active radiation. All measurements were taken at the temperature of 25°C (Yin et al. 2011) between 10 a.m. and 1 p.m.

2.5 Yield and Yield Components

Harvesting was done after the appearance of the black layer in the grains. Ten ears were randomly collected from 10 plants from each replication and processed using HALDRUP LT-35 laboratory thresher (HALDRUP GmbH, Ilshofen, Germany). Cob weight (g) was determined using electronic weighing balance. The number of seeds and 1000-seed weight (g) were determined using VSC-201 Vibrating Seed Counter (PLC Tuning Ltd - Hungary) and grain yield (GY) in t ha^{-1} calculated at moisture content of 14.5%.

2.6 Statistical Data Analyses

The normality and homogeneity of variance of data was tested using Shapiro Wilk and Levene’s tests, respectively. Data was analyzed using OriginPro Graphing and Analysis Software (version 2024) and R software (version 4.3.2). The two-way ANOVA was implemented and the differences between treatment means were compared using Tukey test at 5% probability level. The performance of the water management regimes was compared using the t-test. The Pearson correlation was used to assess the nexus between chlorophyll fluorescence, photochemical and grain yield. Figures were prepared using OriginPro Graphing and Analysis Software and R software.

3 Results

3.1 Response of Chlorophyll Fluorescence and Photochemical Yield of Maize to Water Management, and Foliar Biostimulant and Micronutrients Application

The chlorophyll fluorescence and photosynthetic efficiency significantly ($p < 0.05$) differed between precision drip irrigation and water stress treatments in both seasons. At the V12 growth stage in 2022 growing season, significantly lower Fm’, Fq’, ΦPSII, and ETR were recorded under precision drip irrigation compared to water stress. Contrary, at VT growth stage, precision drip irrigation optimized Fm’, Fq’, ΦPSII, and ETR by 23.4, 33.5, 10.4, and 10.4%, respectively. At R2 stage, ΦPSII and ETR were significantly improved by precision drip irrigation by 6.7 and 6.9%, respectively. In 2023 growing season, precision drip irrigation significantly improved chlorophyll fluorescence and photochemical yield at VT and R2 growth stages, respectively. At VT growth stage, Fm’, Fq’, ΦPSII and ETR were improved by 11.5, 15.2, 2.9 and 3.8%, respectively. At R2 growth stage, precision drip irrigation significantly improved both ΦPSII and ETR by 3.9%. Progressively, F’ reduced at the VT stage under precision drip irrigation and water stress in both seasons. Meanwhile, as water stress reduced Fm’, Fq’, ΦPSII, and ETR during the VT growth stage, precision drip irrigation optimized these parameters. The progress of chlorophyll and photochemical parameters is shown in Fig. 2.

Significant changes in chlorophyll fluorescence parameters (F’, Fᴍ’ and Fq’) in response to biostimulant and micronutrients application depended on the growth stage. In both seasons, F’ did not significantly ($p > 0.05$) differ including the interactive effects. As such, in both seasons, the F’ value of the treatments ranged from 335–435 and 320–410, respectively, under both precision drip irrigation and water stress in all the stages. Conversely, biostimulant and micronutrients application significantly ($p < 0.05$) affected Fᴍ’ at the R2 growth stage under water stress in 2022 season, and at VT and R2 under both water management regimes in 2023 season. At the R2 growth

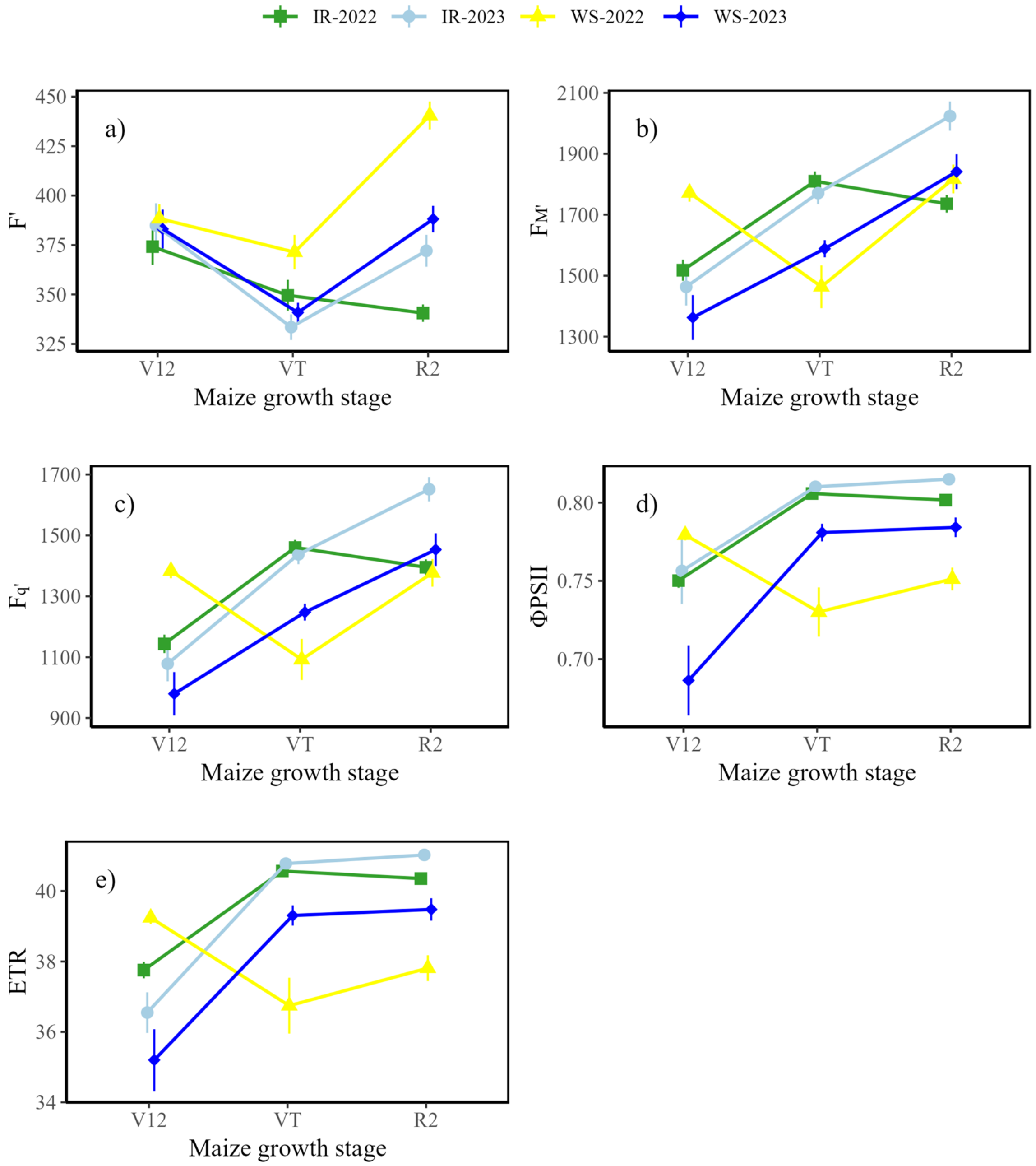


Fig. 2 Dynamics of chlorophyll fluorescence and photochemical yield under precision irrigation and water stress at different maize growth stages in 2022 and 2023 growing seasons. **a**) F’ (steady-state fluorescence signal under actinic light prior to saturation pulse), **b**) FM’ (maximal fluorescence under actinic light at steady state photosynthesis when all the reaction centers are closed), **c**) Fq’ (fluorescence difference between FM’ and F’), **d**) ΦPSII (quantum photosynthetic yield (efficiency) of photosystem II, **e**) ETR (electron transport rate). Vertical bars indicate the standard error

stage in 2022 season under precision drip irrigation, all the treatments had Fᴍ’ values ranging from 1659–1733 while under water stress, only T1 and T2 had significantly higher values of 1870, 1833 compared to 1795 and 1773 in T3 and the control, respectively. In 2023 season at the VT growth stage, the Fᴍ’ was 1887, 1730 and 1831 in T1, T2 and T3, respectively compared to 1636 in the control under precision drip irrigation while under the water stress, only T1 had significantly higher Fᴍ’ value of 1670 compared to 1512, 1569 and 1603 in T2, T3 and the control, respectively. The same trend was followed in R2 growth stage. In terms of the Fq’, only T1 had a significant ($p < 0.05$) effect at R2 growth stage in 2022 season. The Fq’ was 1413 in T1 compared to 1397, 1343 and 1355 in T2, T3 and the control, respectively under water stress while under precision drip irrigation, all treatments had similar performance. In the 2023 season, T1 had significantly better performance at VT and R2 stages. At the VT growth stage, the Fq’ was 1544, 1403, and 1491 in T1, T2, and T3 compared to 1313 in the control, respectively, under precision drip irrigation while under water stress, Fq’ was 1327, 1177 and 1230 in T1, T2 and T3 compared to 1257 in the control, respectively. Similarly, at the R2 growth stage, T1 still had higher Fq’ of 1721 compared to 1539, 1681 and 1665 in T2, T3 and the control under precision drip irrigation while under water stress, T1 maintained higher Fq’ of 1530 compared to 1269, 1581 and 1434 in T2, T3 and the control.

Although the individual effects of the biostimulant and micronutrients within each water regime were not significant, the interactive effects between biostimulant and micronutrients × water management on ΦPSII and ETR were significant at VT and R2 growth stages in both seasons. At the VT growth stage in 2022 season, T1 under drip precision irrigation had significantly higher (0.88) ΦPSII as compared to 0.75 and 0.72 in T2 and T3 under water stress, respectively. Similarly, T3 under precision irrigation had higher (0.85) ΦPSII compared to 0.72 in T3 under water stress. At the R2 growth stage, all the treatments still had higher ΦPSII under precision irrigation compared to their performance under water stress. Equally, in 2023 season, T1, T2 and T3 had higher ΦPSII under precision drip irrigation compared to their efficacy under water stress. However, more peculiar was that T2 under water stress had higher reduction of ΦPSII compared to all other treatments under precision drip irrigation both at the VT and R2 growth stages (Fig. 3). On the other hand, like the ΦPSII, the significant interactive effects revealed higher ETR of treatments T1, T1 and T3 under precision drip irrigation compared to water stress. In fact, at the VT and R2 growth stages in both seasons, only T1 maintained a higher ETR. It is also worthwhile to note that in both seasons, no significant effects on ETR were recorded at the V12 growth stage (Fig. 4).

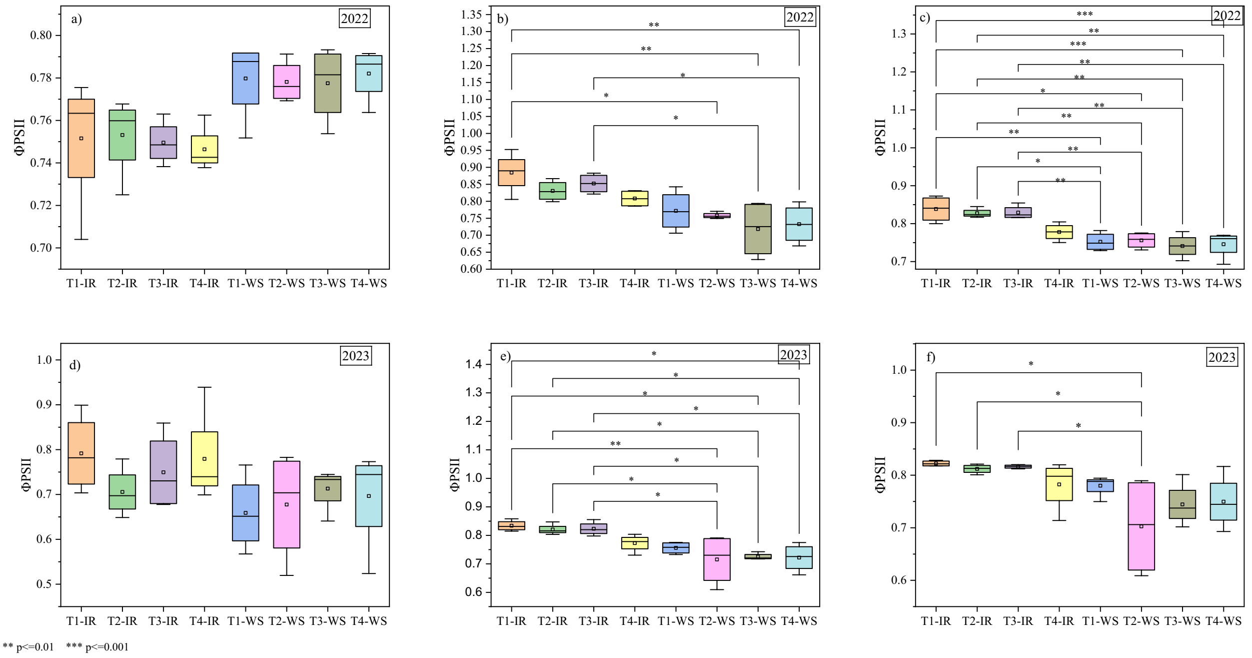


Fig. 3 Quantum photosynthetic yield (efficiency) of photosystem II (ΦPSII), under biostimulant and micronutrient treatments for precision drip irrigation and water stress conditions at different stages of maize growth. (**a**) V12 growth stage in 2022 season, (**b**) VT growth stage in 2022 season, (**c**) R2 growth stage in 2022 season, (**d**) V12 growth stage in 2023 season, (**e**) VT growth stage in 2023 season, (**f**) R2 growth stage in 2023 season. IR – Precision drip irrigation, WS – Water stress, T1 – biostimulant, T2 and T3 – chemical fertilizers containing micronutrients (details in the methodology), T4 – control. *, **, and *** means significant differences by Tukey test at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively (treatments not compared were not significantly different)

3.2 Effect of Water Management, Foliar Biostimulant and Micronutrients Application on Yield and Yield Components of Maize

3.2.1 Number of Seeds per Cob, Weight of 1000 Seeds and Cob Weight

In both seasons, water management significantly ($p<0.05$) improved the number of seeds per cob, with precision drip irrigation having 538 and 506 seeds per cob compared to 164 and 468 seeds per cob under water stress in 2022 and 2023 seasons, respectively. The individual effects of treatments T1, T2 and T3 under each water regime and their interactions with water management did not significantly differ in the two seasons. In 2022 season under precision drip irrigation, the seed number per cob was 573, 529 and 571 in T1, T2 and T3 compared to 478 in the control. Similarly, under water stress conditions, the seed number per cob was 142, 194 and 177 in T1, T2 and T3 compared to 144 in the control. This similar trend was recorded in the 2023 season. In terms of weight of 1000 seeds, precision drip irrigation significantly improved 1000 seed weight both in 2022 and 2023 seasons. Precisely, the weight of 1000 seeds under precision drip irrigation was 363.3 and 534.7 g compared to 268.3 and 505.2 g under water stress. Meanwhile, the treatment and interaction effects were only significant for 2023 season. In 2022 season, all treatments (not significant) had 1000 seed weight between 312.5 and 318.6 g while in 2023, treatments T1, T2 and T3 had 1000 seed weight of 537.3, 531.6 and 525.2 g compared to 485.4 g in the control. Interactively, T2 had the highest (569.9 g) 1000 seed weight under precision drip irrigation (Fig. 5). Looking at cob weight, in both 2022 and 2023 seasons, precision drip irrigation significantly improved cob weight with weight of 222.19 and 304.6 g compared to 57.3 and 261.9 g under water stress. On the other hand, although the individual effects of the biostimulant and micronutrients within each water regime did not significantly differ, specific comparison of their performance between the two water management regimes revealed a higher cob weight under precision drip irrigation in both seasons. The respective cob weight in the 2022 season was 237.8, 226.0, and 230.0 g in T1, T2 and T3 under precision drip irrigation compared to 49.8, 68.4 and 63.2 g under water stress. Correspondingly, in 2023 season, T1, T2 and T3 under precision drip had cob weights of 316.4, 310.8, and 300.8 g compared to 260.7, 266.2 and 274.9 g under water stress.

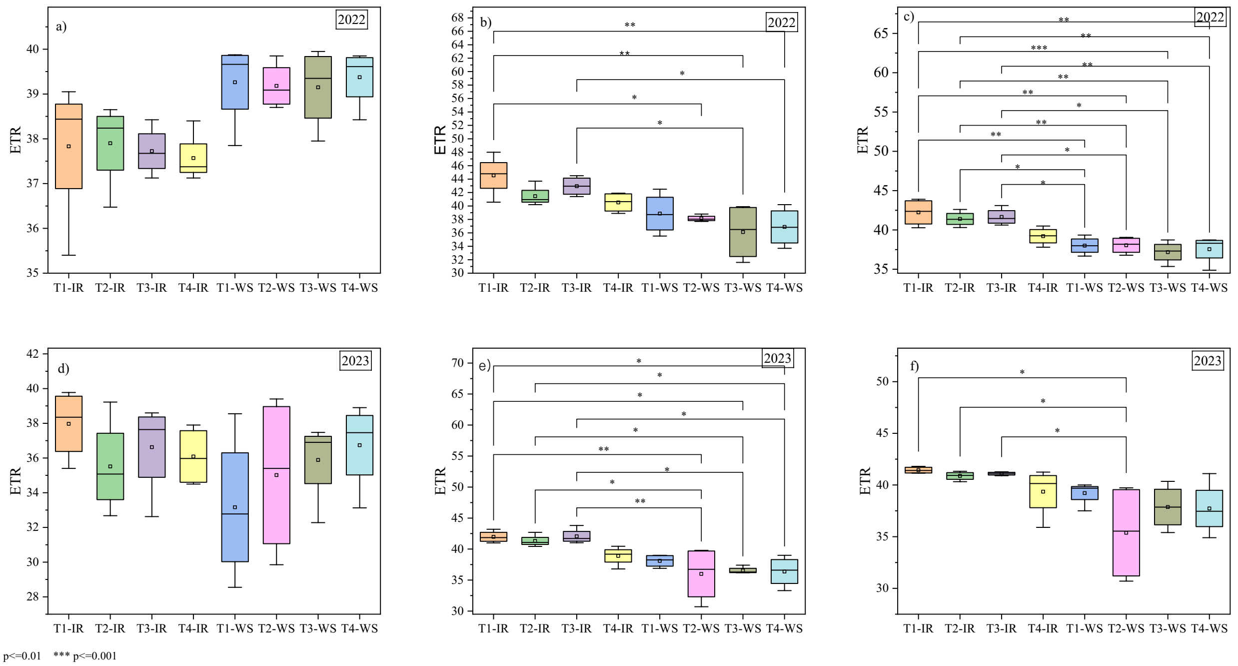


Fig. 4 Electron transport rate (ETR) under biostimulant and micronutrient treatments for precision drip irrigation and water stress conditions at different stages of maize growth. (**a**) V12 growth stage in 2022 season, (**b**) VT growth stage in 2022 season, (**c**) R2 growth stage in 2022 season, (**d**) V12 growth stage in 2023 season, (**e**) VT growth stage in 2023 season, (**f**) R2 growth stage in 2023 season. IR – Precision drip irrigation, WS – Water stress, T1 – biostimulant, T2 and T3 – chemical fertilizers containing micronutrients (details in the methodology), T4 – control. *, **, and *** means significant differences by Tukey test at $p<0.05$, $p<0.01$, and $p<0.001$, respectively (treatments not compared were not significantly different)

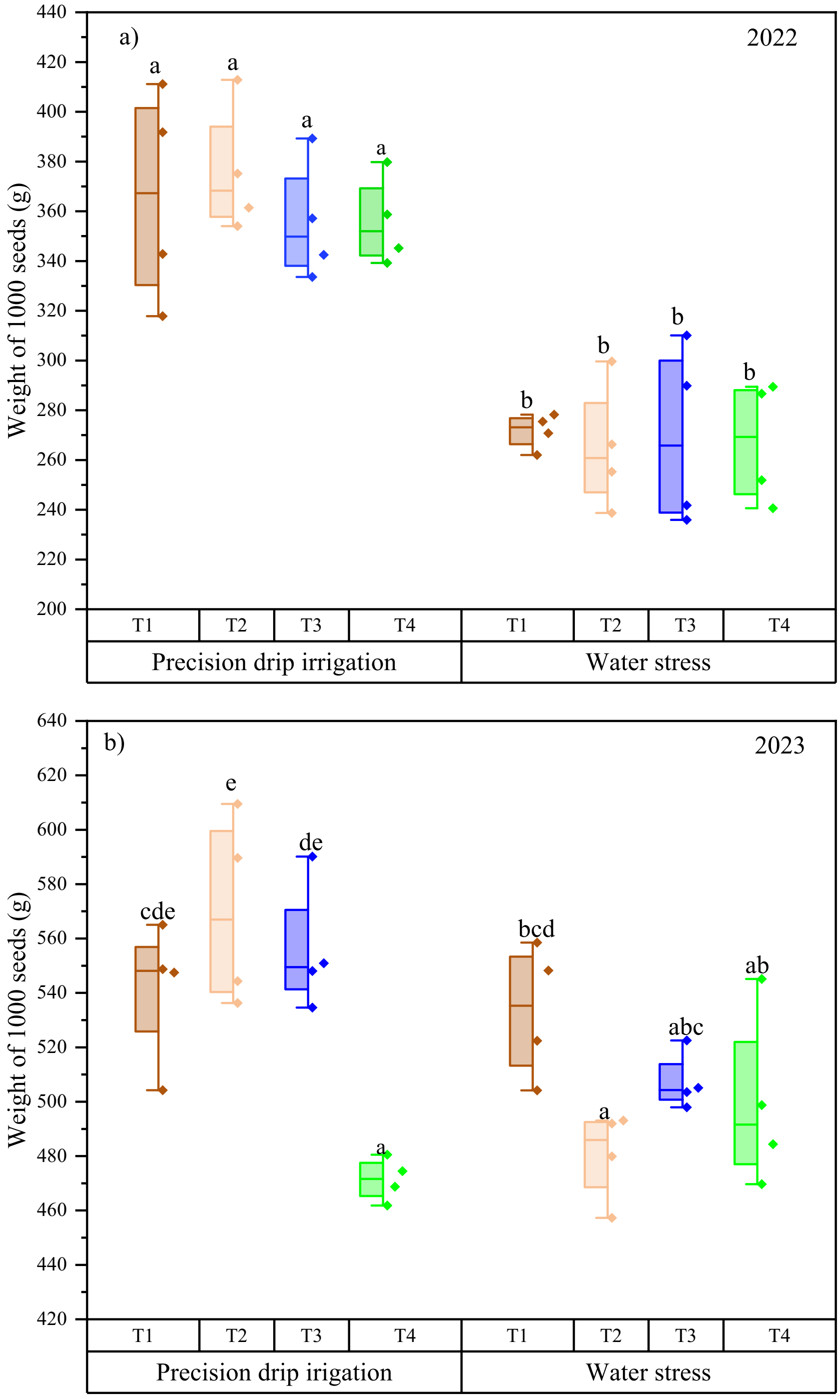


Fig. 5 Interactive effects of water management and biostimulant, and micronutrients on the weight of 1000 seeds in 2022 (**a**) and 2023 (**b**) growing seasons. T1 – biostimulant, T2 and T3 – chemical fertilizers containing micronutrients (details in the methodology), T4 – control. Different letters show significant difference between treatments by Tukey test at $p < 0.05$

3.2.2 Overall Grain Yield (t ha^{-1})

Water management, foliar biostimulant and micronutrients application optimized grain yield. In fact, water management significantly ($p < 0.05$) improved grain yield in both seasons. Grain yield under precision drip irrigation was 13.3 and 19.4 t ha^{-1} compared to 3.8 and 17.3 t ha^{-1} under water stress in 2022 and 2023 growing seasons, respectively. In this case, precision drip irrigation optimized grain yield by 9.5 and 2.1 t ha^{-1}, respectively. Contrastingly, regardless of the water management regime, biostimulant and micronutrients application significantly ($p < 0.05$) optimized grain yield only in 2023 growing season. In 2022 growing season, treatments T1, T2, and T3 had yield between 8.4 and 8.6 t ha^{-1} compared to 7.1 t ha^{-1} in the control. In 2023 growing season, grain yields of 18.7, 18.7 and 18.6 t ha^{-1} were obtained from T1, T2 and T3, respectively compared to 17.5 t ha^{-1} in the control. Although, the yield of T1, T2 and T3 did not significantly differ from each other, each of these treatments improved yield by 1.0 t ha^{-1} compared to the control in 2022 season. In 2023 season, grain yield was significantly optimized by 6.9% (1.2 t ha^{-1}) under T1 and T2, and 6.3% (1.1 t ha^{-1}) under T3 treatments, respectively (Fig. 6). The comparative analysis of the efficacy of treatments T1, T2 and T3 between precision drip irrigation and water stress indicated a considerably higher yield under precision drip irrigation compared to water stress. T1 under precision drip irrigation had yield of 14.2 and 20.8 t ha^{-1} compared to 2.5 and 17.4 t ha^{-1} under water stress in 2022 and 2023 growing seasons, respectively. Accordingly, T2 under precision drip irrigation had yield of 13.6 and 19.8 t ha^{-1} compared to 3.7 and 17.6 t ha^{-1} under water stress in 2022 and 2023 growing seasons, respectively. Figure 7 provides the detailed comparison of grain yield of maize under biostimulant and micronutrient treatments between precision drip irrigation and water stress conditions.

3.2.3 Relationship Between F′, FM′, Fq′, ΦPSII, ETR and Grain Yield

Figure 8 shows the correlation between chlorophyll fluorescence parameters, photochemical yield and grain yield

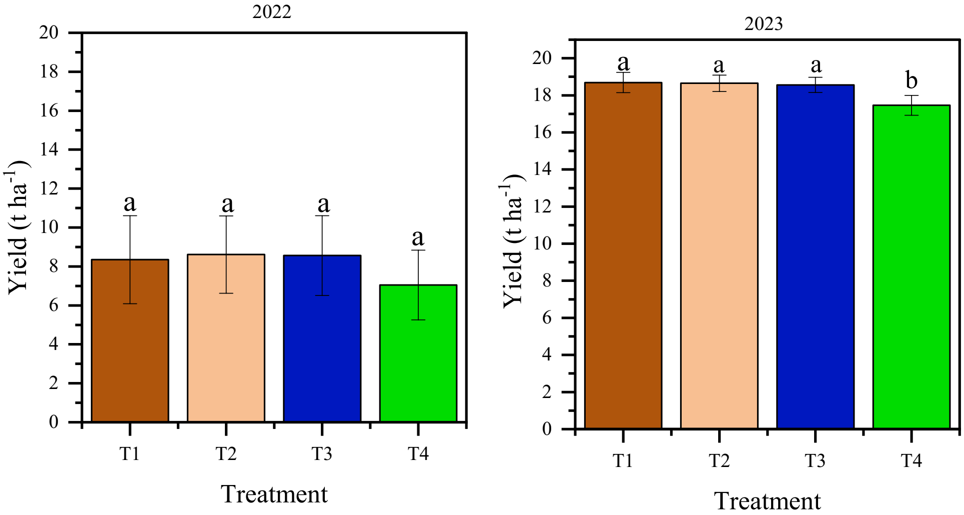


Fig. 6 Overall yield response to foliar biostimulant and micronutrient application in 2022 and 2023 seasons. T1 – biostimulant, T2 and T3 – chemical fertilizers containing micronutrients (details in the methodology), T4 – control. Error bar is the standard error. Different letters on the bars in each season show significant difference between treatments by Tukey test at $p<0.05$

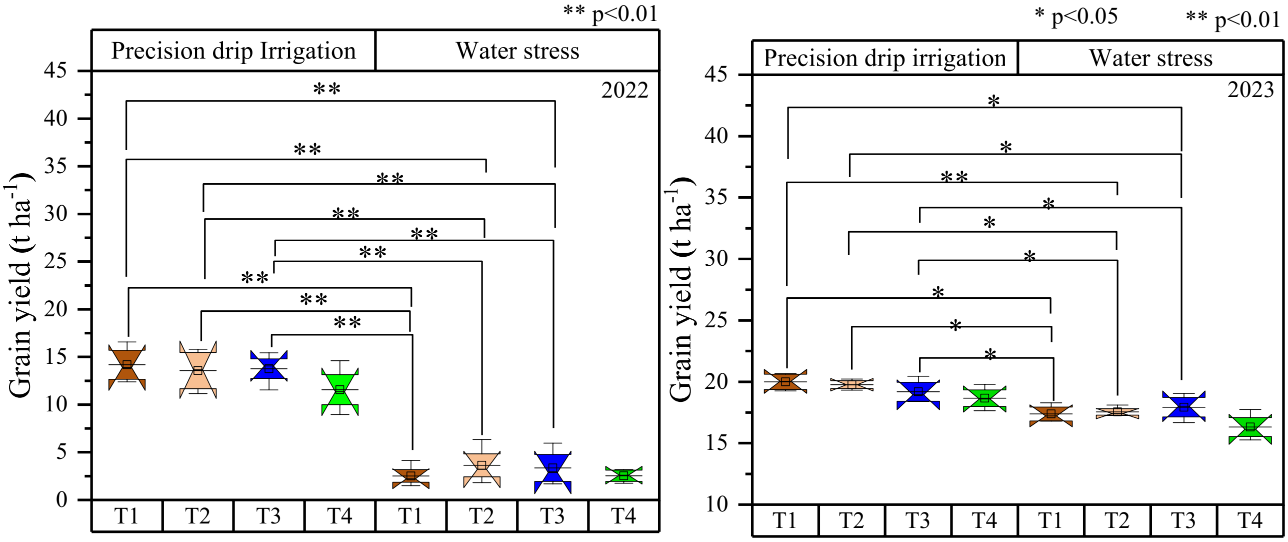
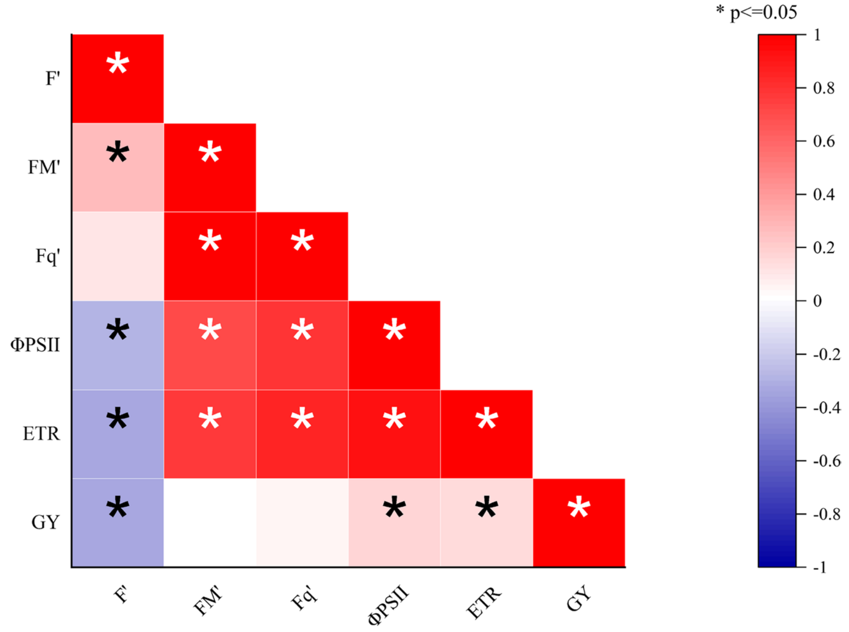


Fig. 7 Grain yield of maize under foliar biostimulant and micronutrient treatments with precision drip irrigation and water stress conditions in 2022 and 2023 growing seasons. IR – Precision drip irrigation. WS – Water stress, T1 – biostimulant, T2 and T3 – chemical fertilizers containing micronutrients (details in the methodology), T4 – control. * and ** means significant differences by Tukey test at $p<0.05$ and $p<0.01$, respectively. Comparisons were only made where significant differences existed between T1, T2 and T3 between water management regimes

Fig. 8 Correlation between chlorophyll fluorescence, quantum efficiency of photosystem II, and grain yield of maize. F' (minimal fluorescence), Fᴍ' *(*maximal fluorescence), Fq' (fluorescence difference between Fᴍ' and F', ΦPSII (quantum photosynthetic yield or efficiency of photosystem II), ETR (electron transport rate), GY (Grain yield)



of maize. From the results, Fᴍ', Fq', ΦPSII and ETR were positively correlated, while F' negatively correlated with ΦPSII, ETR and grain yield. Further, there was a significant positive correlation between ΦPSII, ETR, and grain yield.

4 Discussion

The photochemical efficiency and yield of maize was optimized by precision drip irrigation in both seasons while the biostimulant and micronutrient significant effects were seasonal. In both seasons, it is only F' that uniformly decreased at VT stage though higher under water stress, and generally increased at R2 stage. According to dos Reis et al. (2019), increase in the minimum fluorescence relates to the deleterious effects on photosynthesis, hence reduced excitation energy transfer to the reaction centers from the PSII antenna complex. However, parameters Fᴍ', Fq', ΦPSII, and ETR depicted opposite patterns in 2022, and similar progressive patterns in 2023 growing season. Although the discrepancy of Fᴍ', Fq', ΦPSII and ETR was evidenced between the two water regimes, precision drip irrigation maintained optimal effects in both growing seasons. Abiotic stresses including water stress negatively affect chlorophyll biosynthesis, efficiency of photosystems, and ETR, causing reduction in overall photosynthetic efficiency (Sharma et al. 2020). Similarly, other reports show diminished photochemical activity and ETR as well as undesirable effects of extreme accumulation of excitation energy on photosynthesis due to water/drought stress (Zivcak et al. 2013; Hu et al. 2023). In this study, the effects of water stress were significantly evident at the VT and R2 stages because of distinct reduction in the ΦPSII and ETR, which precision drip irrigation ameliorated. In terms of grain yield, precision drip irrigation significantly increased yield in both seasons. However, maize grain yield was generally lower in 2022 compared to 2023, attributed to high heat stress and low precipitation (validated by climate data) between June to August, which were the active months of maize growth. Gombos and Nagy (2023) conducted an independent study to examine maize growth meteorological conditions at Debrecen in 2022 (similar location as this study) and revealed that the area experienced severe drought exacerbated by high temperatures than before, especially during summer months, making average maize yield to be lower than before. Overall, extreme soil water gradient (high or low) decreases photosynthetic efficiency (Zhao et al. 2019) and, in particular, drought stress damages the PSII reaction centers, hence compromising productivity. Generally, in this study, precision drip irrigation ameliorated drought effects on chlorophyll fluorescence, photochemical efficiency, and yield of maize.

Optimization of photochemical yield by the biostimulant and micronutrients was higher under precision drip irrigation compared to water stress. Abidi et al. (2023) utilized biostimulants from moringa extracts and recorded lower ETR as an indication of decreased response of PSII opening centers to drought, but generally fluorescence parameters were improved under irrigation. Similarly, dos Reis et al. (2019) revealed that chitosan derivatives positively enhanced photosynthetic activity and electron transport yield in PSII. In this study, biostimulant was rich in nitrogen, organic matter, amino acids and fulvic acid, which improved photosynthetic activity. Studies show that nitrogen increases chlorophyll content and enzymatic activity that promotes efficient functioning of the photosynthetic systems (Nasar et al. 2022; Nematpour and Eshghizadeh, 2023). Niu et al. (2023) noted that amino acid glycine betaine regulates growth and development processes in plants. According to Cheng et al. (2024), optimal application of amino acid containing biostimulants improve productivity and exhibit prospective widespread application to sustain agricultural production. Generally, our results show that the efficacy of the biostimulant and micronutrients improves with supply of adequate moisture through precision drip irrigation. This implies that in the advent of rapidly propagating drought, maximum agronomic efficiency of exogenously applied nutrients is attainable only if adequate moisture is supplied at critical stages of maize growth.

The yield and yield components (cob weight and 1000 seed weight) under treatments were seasonally optimized. Moreover, comparative analysis of yield performance by treatments under precision drip irrigation and water stress indicated a considerably higher yield under precision drip irrigation compared to water stress. Specifically, T1 had higher grain yield in both seasons under precision drip irrigation, suggesting its application efficacy under this water regime. Generally, in both seasons, T1, T2 and T3 reversed the deleterious effects of water stress on grain yield. Reduction in yield due to water stress is attributed to stomatal closure as a responsive mechanism that causes carbon starvation due to lowered CO_2 absorption and transportation (Sharma et al. 2020). The results of this study suggest that efficacy of T1, T2 and T3 to enhance maize grain yield and overall productivity is practical under precision irrigation depending on season. However, regardless of the water application regime, the fact that the individual yield of T1, T2 and T3 did not differ from each other (under each water regime), but differed compared to the control, suggests the need to test the effect of combined foliar application of these treatments to ascertain the existence of synergistic effects. Based on soil analysis results, nitrogen soil content was inadequate. This implies single application of T1 did not meet maize nitrogen demand for optimum productivity. This suggests two options: first, to maintain single T1 application but boost nitrogen supply to maize through increased soil application. However, this may not be sustainable because of potential effects of nitrogen pollution. Secondly, to have multiple applications of T1 at different phenophases. These necessitate further investigation to ascertain exact times of application versus precision drip irrigation regimes. In other words, the productivity potential of the biostimulant was not attained. Crop response to biostimulants depends on biostimulant formulation and utilization approach, climate conditions (Długosz et al. 2020), plant factors (Berta et al. 2014), among other factors. Similarly, the fact that zinc was adequate in the soil suggests the need to test the efficacy of T2 in zinc deficient soils (locations) under varying drip irrigation regimes. Hussain et al. (2020) reported similar yield of maize in potassium and zinc fertilized plots with well-irrigated plots without potassium and zinc fertilization, and the authors emphasized the need for evaluation of irrigation scheduling. However, Idrees et al. (2024) noted that zinc supplementation enhanced yield components compared to non-zinc treatment both under watered and water stress conditions. Similarly, Elshamly et al. (2024) revealed that with 75% irrigation, zinc application enhanced optimum dry matter accumulation and economic yield. Zinc is a critical micronutrient that regulates metabolic processes and enhances photosynthetic carbon assimilation by maize under severe abiotic stress (Sun et al. 2021; Ghani et al. 2022; Idrees et al. 2024).

The correlation analysis revealed a significant positive nexus between ETR, ΦPSII and grain yield. This is an indication that ΦPSII and ETR are better indicators of the potential effect of water management, foliar biostimulant and micronutrient application on maize productivity. Jin et al. (2023) reported a positive correlation between chlorophyll fluorescence and photosynthesis, with a substantial increase in water stress. However, variation in the results of chlorophyll and photochemical parameters at different stages of maize growth indicates the possibility of using these parameters to detect and ameliorate deleterious water stress effects on maize yield at early stages. In other words, this will make utilization of agronomic interventions sustainable since early remediation measures enhance attainment of planned yield.

5 Conclusion

Fertilization and precision water supply remain the principal impetuses to the achievement of sustainable maize productivity. In this study, precision drip irrigation, foliar application of the biostimulant and micronutrients optimized maximal fluorescence, photosynthetic efficiency and electron transport rate. Although precision drip irrigation significantly optimized yield and yield components in both seasons, biostimulant and micronutrient effects were seasonally conspicuous regardless of irrigation. Comparative performance of the biostimulant and micronutrients under water management regimes indicated higher yield under precision irrigation compared to water stress. However, since the soils in the experimental site were deficient in nitrogen and adequate in zinc, it suggests several research gaps: (i) a study tailored to 2–3 application times at critical stages of maize under season specific precision irrigation, (ii) need to test the effect of combined foliar application of T1 (non-microbial biostimulant from plant origin), T2 (zinc based chemical fertilizer), and T3 (boron and molybdenum based chemical fertilizer) to ascertain the existence of synergistic effects, and (iii) need to test the efficacy of T2 in soil types (locations) deficient in zinc under precision drip irrigation.

Overall, precision drip irrigation, foliar application of biostimulant and micronutrients demonstrated their capacity to optimize photosynthetic efficiency, yield and yield components of maize.

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Data Availability All the data are presented in the article.

Declarations

Conflict of interest The authors declare no conflict of interest.

References

Abbott LK, Macdonald LM, Wong MTF, Webb MJ, Jenkins SN, Farrell M (2018) Potential roles of biological amendments for profitable grain production – A review. Agric Ecosyst Environ 256:34–50. https://doi.org/10.1016/j.agee.2017.12.021

Abidi W, Akrimi R, Gouiaa M (2023) Mitigating drought stress by plant-derived biostimulant in Arbequina olive (*Oleaeuropeae* L.) cultivar conducted in super high density. Acta Physiol Plant 45:132. https://doi.org/10.1007/s11738-023-03613-9

Alloway BJ (2009) Soil factors associated with zinc deficiency in crops and humans. Environ Geochem Health 31:537–548. https://doi.org/10.1007/s10653-009-9255-4

Antal J, Buzás I, Debreczeni B, Fekete A, Nagy M, Patócs I (1987) New fertilization guidelines MÉM NAK. Budapest, pp 1–65

Arikan B, Ozfidan-Konakci C, Alp FN, Zengin G, Yildiztugay E (2022) Rosmarinic acid and hesperidin regulate gas exchange, chlorophyll fluorescence, antioxidant system and the fatty acid biosynthesis-related gene expression in *Arabidopsis thaliana* under heat stress. Phytochem 198:113157. https://doi.org/10.1016/j.phytochem.2022.113157

Baker NR (2008) Chlorophyll fluorescence: a probe of photosynthesis in vivo. Annu Rev Plant Biol 59:89–113. https://doi.org/10.1146/annurev.arplant.59.032607.092759

Berta G, Copetta A, Gamalero E, Bona E, Cesaro P, Scarafoni A, D'Agostino G (2014) Maize development and grain quality are differentially affected by mycorrhizal fungi and a growth-promoting pseudomonad in the field. Mycorrhiza 24:161–170. https://doi.org/10.1007/s00572-013-0523-x

Bojtor C, Illés Á, Mousavi SMN, Széles A, Tóth B, Nagy J, Marton CL (2021) Evaluation of the nutrient composition of maize in different NPK fertilizer levels based on multivariate method analysis. Inter J Agron 2021:5537549. https://doi.org/10.1155/2021/5537549

Bresson J, Vasseur F, Dauzat M, Koch G, Vile D (2015) Quantifying spatial heterogeneity of chlorophyll fluorescence during plant growth and in response to water stress. Plant Methods 11:23. https://doi.org/10.1186/s13007-015-0067-5

Cendrero-Mateo MP, Moran MS, Papuga SA, Thorp KR, Alonso L, Moreno J, Ponce-Campos G, Rascher U, Wang G (2016) Plant chlorophyll fluorescence: active and passive measurements at canopy and leaf scales with different nitrogen treatments. J Exp Bot 67:275–286. https://doi.org/10.1093/jxb/erv456

Chen Y, Liu L, Guo Q, Zhu Z, Zhang L (2016) Effects of different water management options and fertilizer supply on photosynthesis, fluorescence parameters and water use efficiency of *Prunella vulgaris* seedlings. Biol Res 49:12. https://doi.org/10.1186/s40659-016-0069-4

Chen X, Mo X, Hu S, Liu S (2019) Relationship between fluorescence yield and photochemical yield under water stress and intermediate light conditions. J Exp Bot 70:301–313. https://doi.org/10.1093/jxb/ery341

Chen C, Lin K, Chang Y, Chang Y (2023) Application of water-saving irrigation and biostimulants on the agronomic performance of maize (*Zea mays*). Process Saf Environ Prot 77:1377–1386. https://doi.org/10.1016/j.psep.2023.08.008

Cheng J, Cheng J, Sun R, Cao S, Wang X, Yang H (2024) Foliar application of amino acid biostimulants increased growth and antioxidant activity of *Epipremnum aureum*. Cogent Food Agric 10:1–10. https://doi.org/10.1080/23311932.2024.2321680

Długosz J, Piotrowska-Długosz A, Kotwica K, Przybyszewska E (2020) Application of multi-component conditioner with clinoptilolite and *Ascophyllum nodosum* extract for improving soil properties and *Zea mays* L. growth and yield. Agron 10:2005. https://doi.org/10.3390/agronomy10122005

Dogru A (2021) Effects of heat stress on photosystem II activity and antioxidant enzymes in two maize cultivars. Planta 253:85. https://doi.org/10.1007/s00425-021-03611-6

dos Reis CO, Magalhães PC, Avila RG, Almeida GL, Rabelo MV, Carvalho TD, Cabral FD, Karam D, Souza CT (2019) Action of *N*-Succinyl and *N,O*-Dicarboxymethyl chitosan derivatives on chlorophyll photosynthesis and fluorescence in drought-sensitive maize. J Plant Growth Regul 38:619–630. https://doi.org/10.1007/s00344-018-9877-9

Elshamly AMS, Iqbal R, Ali B, Ahmed I, Akram MI, Ali S, Ditta A, Elshikh ÇIGF, Mustafa MS, Hamed AEMA HM (2024) Zinc and amino acids improve the growth, physiological, and biochemical attributes of corn under different irrigation levels. Rhizosphere 29:100820. https://doi.org/10.1016/j.rhisph.2023.100820

Flexas J, Escalona JM, Medrano H (2002) Water stress induces different levels of photosynthesis and electron transport rate regulation in grapevines. Plant Cell Environ 22:39–48. https://doi.org/10.1046/j.1365-3040.1999.00371.x

Ge TD, Sui GF, Nie S, Sun NB, Xiao H, Tong LC (2010) Differential responses of yield and selected nutritional compositions to drought stress in summer maize grains. J Plant Nutr 33:1811–1818. https://doi.org/10.1080/01904167.2010.503829

Ghani MI, Saleem S, Rather SA, Rehmani MS, Alamri S, Rajput VD, Kalaji HM, Sial TA, Liu M (2022) Foliar application of zinc oxide nanoparticles: an effective strategy to mitigate drought stress in cucumber seedling by modulating antioxidant defense system and osmolytes accumulation. Chemosphere 289:133202. https://doi.org/10.1016/j.chemosphere.2021.133202

Gombos B, Nagy G (2023) Meteorological conditions of maize growing experiments on agricultural campus of the University of Debrecen in the growing season 2022. Crop Prod 72:5–19

Guo Y, Tan J (2015) Recent advances in the application of Chlorophyll *a* fluorescence from Photosystem II. Photochem Photobio 91:1–14. https://doi.org/10.1111/php.12362

Hayat SH, Rehman A, Farooq A, Naveed M, Ali HM, Hussain M (2023) Boron seed coating combined with seed inoculation with boron tolerant bacteria (*Bacillus* sp. MN-54) and maize stalk biochar improved growth and productivity of maize (*Zea mays* L.) on saline soil. Heliyon 9:e22075. https://doi.org/10.1016/j.heliyon.2023.e22075

Hazrati S, Tahmasebi-Sarvestani Z, Modarres-Sanavy SAM, Mokhtassi-Bidgoli A, Nicola S (2016) Effects of water stress and light intensity on chlorophyll fluorescence parameters and pigments of Aloe vera L. Plant Physiol Biochem 106:141–148. https://doi.org/10.1016/j.plaphy.2016.04.046

Hu F, Zhang Y, Guo J (2023) Effects of drought stress on photosynthetic physiological characteristics, leaf microstructure, and related gene expression of yellow horn. Plant Signal Behav 18(1):2215025. https://doi.org/10.1080/15592324.2023.2215025

Hussain S, Maqsood M, Ijaz M, Ul-Allah S, Sattar A, Sher A, Nawaz A (2020) Combined application of potassium and zinc improves water relations, stay green, irrigation water use efficiency, and grain quality of maize under drought stress. J Plant Nutri 43:2214–2225. https://doi.org/10.1080/01904167.2020.1765181

Idrees K, Aziz A, Naeem M, Azhar FM, Farooq S, Hussain M (2024) Combined application of zinc and silicon improved growth, gas exchange traits, and productivity of maize (*Zea mays* L.) under water stress. Silicon 16:831–841. https://doi.org/10.1007/s12633-023-02732-9

Janka E, Korner O, Rosenqvist E, Ottosen C (2015) Using the quantum yields of photosystem II and the rate of net photosynthesis to monitor high irradiance and temperature stress in chrysanthemum (*Dendranthema Grandiflora)*. Plant Physiol Biochem 90:14e22. https://doi.org/10.1016/j.plaphy.2015.02.019

Janušauskaite D, Feiziene D (2011) Chlorophyll fluorescence characteristics throughout spring triticale development stages as affected by fertilization. Acta Agric Scand B 62:7–15. https://doi.org/10.1080/09064710.2011.560122

Jin EJ, Yoon JH, Lee H, Bae EJ, Yong SH, Choi MS (2023) Evaluation of drought stress level in Sargent's cherry (*Prunus Sargentii* Rehder) using photosynthesis and chlorophyll fluorescence parameters and proline content analysis. Peer J 11:e15954. https://doi.org/10.7717/peerj.15954

Killi D, Bussotti F, Raschi A, Haworth M (2017) Adaptation to high temperature mitigates the impact of water deficit during combined heat and drought stress in C3 sunflower and C4 maize varieties with contrasting drought tolerance. Physiol Plant 159:130–147. https://doi.org/10.1111/ppl.12490

Killi D, Raschi A, Bussotti F (2020) Lipid peroxidation and chlorophyll fluorescence of photosystem II performance during drought and heat stress is associated with the antioxidant capacities of C3 sunflower and c4 maize varieties. Int J Mol Sci 21:4846. https://doi.org/10.3390/ijms21144846

Klofac D, Antosovsky J, Skarpa P (2023) Effect of zinc foliar fertilization alone and combined with trehalose on maize (*Zea may* s L.) growth under the drought. Plants 12:2539. https://doi.org/10.3390/plants12132539

Kovács AB, Kincses I, Vágó I, Loch J, Filep T (2009) Effect of application of nitrogen and different nitrogen-sulfur ratios on the quality and quantity of mustard seed. Commun Soil Sci Anal 40:453–461. https://doi.org/10.1080/00103620802694399

Kumar S, Narjary B, Paudayal K, Yadav RK, Kamra SK (2024) Assessing zero-till direct seeding at variable water stress levels compared to traditional puddled transplanting of rice under groundwater-fed irrigation systems in north-west India. Irrig Drain 73:928–943. https://doi.org/10.1002/ird.2930

Li G, Zhang ZS, Gao HY, Liu P, Dong ST, Zhang JW, Zhao B (2012) Effects of nitrogen on photosynthetic characteristics of leaves from two different stay-green corn (*Zea mays* L.) varieties at the grain-filling stage. Can J Plant Sci 92:671–680. https://doi.org/10.4141/cjps2012-039

Loriaux SD, Avenson TJ, Welles JM, McDermitt DK, Eckles RD, Riensche B, Genty BSD (2013) Closing in on maximum yield of chlorophyll fluorescence using a single multiphase flash of subsaturating intensity. Plant Cell Environ 36:1755–1770. https://doi.org/10.1111/pce.12115

Ma D, Sun D, Wang C, Ding H, Qin H, Hou J, Huang X, Xie Y, Guo T (2017) Physiological responses and yield of wheat plants in zinc-mediated alleviation of drought stress. Front Plant Sci 8:860. https://doi.org/10.3389/fpls.2017.00860

Nasar J, Wang G–Y, Ahmad S, Muhammad I, Zeeshan M, Gitari H, Adnan M, Fahad S, Khalid MHB, Zhou X–B, Abdelsalam NR, Ahmed GA, Hasan ME (2022) Nitrogen fertilization coupled with iron foliar application improves the photosynthetic characteristics, photosynthetic nitrogen use efficiency, and the related enzymes of maize crops under different planting patterns. Front Plant Sci 13:988055. https://doi.org/10.3389/fpls.2022.988055

Nematpour A, Eshghizadeh HR (2023) Biochemical responses of sorghum and maize to the impacts of different levels of water deficit and nitrogen supply. Cereal Res Commun. https://doi.org/10.1007/s42976-023-00411-4

Niu T, Zhang J, Li J, Gao X, Ma H, Gao Y, Chang Y, Xie J (2023) Effects of exogenous glycine betaine and cycloleucine on photosynthetic capacity, amino acid composition, and hormone metabolism in *Solanum melongena* L. Sci Rep 13:7626. https://doi.org/10.1038/s41598-023-34509-w

Noulas C, Tziouvalekas M, Karyotis T (2018) Zinc in soils, water and food crops. J Trace Elem Med Biol 49:252–260. https://doi.org/10.1016/j.jtemb.2018.02.009

Ocwa A, Harsanyi E, Széles A, Holb IJ, Szabó S, Rátonyi T, Mohammed S (2023) A bibliographic review of climate change and fertilization as the main drivers of maize yield: implications for food security. Agric Food Secur 12:14. https://doi.org/10.1186/s40066-023-00419-3

Ocwa A, Mohammed S, Mousavi SMN, Illés Á, Bojtor C, Ragán P, Rátonyi T, Harsányi H (2024) Maize grain yield and quality improvement through biostimulant application: a systematic review. J Soil Sci Plant Nutr 24:1609–1649. https://doi.org/10.1007/s42729-024-01687-z

Prasanna R, Hossain F, Saxena G, Singh B, Kanchan A, Simranjit K, Ramakrishnan B, Ranjan K, Muthusamy V, Shivay YS (2021) Analyses of genetic variability and genotype x cyanobacteria interactions in biofortified maize (*Zea mays* L.) for their responses to plant growth and physiological attributes. Eur J Agron 130:126343. https://doi.org/10.1016/j.eja.2021.126343

Rácz D, Szőke L, Tóth B, Kovács B, Horváth É, Zagyi P, Duzs L, Széles A (2021) Examination of the productivity and physiological responses of maize (*Zea mays* L.) to Nitrapyrin and foliar fertilizer treatments. Plants 10:2426. https://doi.org/10.3390/plants10112426

Rehaman A, Fatma M, Jan AT, Shah AA, Asgher M, Khan NA (2023) Co-application of nitric oxide and vermicompost improves photosynthetic functions, antioxidants, and nitrogen metabolism in maize (*Zea mays* L.) grown under drought stress. J Plant Growth Regul 42:3888–3907. https://doi.org/10.1007/s00344-022-10854-4

Sadeghzadeh B (2013) A review of zinc nutrition and plant breeding. J Soil Sci Plant Nutr 13:6907–6927. https://doi.org/10.4067/S0718-95162013005000072

Sharma A, Kumar V, Shahzad B, Ramakrishnan M, Sidhu SPG, Bali SA, Handa N et al (2020) Photosynthetic response of plants under different abiotic stresses: a review. J Plant Growth Regul 39:509–531. https://doi.org/10.1007/s00344-019-10018-x

Sible CN, Seebauer JR, Below FE (2021) Plant biostimulants: a categorical review, their implications for row crop production, and relation to soil health indicators. Agron 11:1297. https://doi.org/10.3390/agronomy11071297

Simkó A, Gáspár SG, Kiss L, Makleit P, Veres S (2020) Evaluation of nitrogen nutrition in diminishing water deficiency at different growth stages of maize by chlorophyll fluorescence parameters. Plants 9:676. https://doi.org/10.3390/plants9060676

Sinsawat V, Leipner J, Stamp P, Fracheboud Y (2004) Effect of heat stress on the photosynthetic apparatus in maize (*Zea mays* L.) grown at control or high temperature. J Exp Bot 52:123–129. https://doi.org/10.1016/j.envexpbot.2004.01.010

Ssemugenze B, Ocwa A, Bojtor C, Illés Á, Esimu J, Nagy J (2024) Impact of research on maize production challenges in Hungary. Heliyon 10:e26099. https://doi.org/10.1016/j.heliyon.2024.e26099

Sun L, Song F, Zhu X, Liu S, Liu F, Wang Y, Li X (2021) Nano-ZnO alleviates drought stress via modulating the plant water use and carbohydrate metabolism in maize. Arch Agron Soil Sci 67:245–259. https://doi.org/10.1080/03650340.2020.1723003

Toth B, Moloi MJ, Mousavi SMN, Illés Á, Bojtor C, Szoke L, Nagy J (2022) The evaluation of the effects of Zn, and amino acid-containing foliar fertilizers on the physiological and biochemical responses of a Hungarian fodder corn hybrid. Agron 12:1523. https://doi.org/10.3390/agronomy12071523

Trivedi K, Vijay Anand KG, Kubavat D, Patidar R, Ghosh A (2018) Drought alleviatory potential of *Kappaphycus* seaweed extract and the role of the quaternary ammonium compounds as its constituents towards imparting drought tolerance in *Zea mays* L. J Appl Phycol 30:2001–2015. https://doi.org/10.1007/s10811-017-1375-0

Tubuxin B, Rahimzadeh-Bajgiran P, Ginnan Y, Hosoi F, Omasa K (2015) Estimating chlorophyll content and photochemical yield of photosystem II (ΦPSII) using solar-induced chlorophyll fluorescence measurements at different growing stages of attached leaves. J Exp Bot 66:5595–5603. https://doi.org/10.1093/jxb/erv272

Wang H, Jin Y (2005) Photosynthetic rate, chlorophyll fluorescence parameters, and lipid peroxidation of maize leaves as affected by zinc deficiency. Photosynthetica 43:591–596. https://doi.org/10.1007/s11099-005-0092-0

Waraich EA, Ahmad R, Saifullah, Ashraf MY, Ehsanullah (2011) Role of mineral nutrition in alleviation of drought stress in plants. Aust J Crop Sci 5:764–777

Yin X, Sun Z, Struik PC, Van Der PuttenPEL,VanIeperen W, Harbinson J (2011) Using a biochemical C4 photosynthesis model and combined gas exchange and chlorophyll fluorescence measurements to estimate bundle-sheath conductance of maize leaves differing in age and nitrogen content. Plant Cell Environ 34:2183–2199. https://doi.org/10.1111/j.1365-3040.2011.02414.x

Zampieri M, Ceglar A, Dentener F, Dosio A, Naumann G, van den Berg M, Toreti A (2019) When will current climate extremes affecting maize production become the norm? Earth's Futur 7:113–122. https://doi.org/10.1029/2018EF000995

Zhang L, Yan M, Li H, Ren Y, Siddique HMK, Chen Y, Zhang S (2020) Effects of zinc fertilizer on maize yield and water-use efficiency under different soil water conditions. Field Crops Res 248:107718. https://doi.org/10.1016/j.fcr.2020.107718

Zhao J, Lang Y, Zhang S, Zhao Q, Zhang C, Xia J (2019) Photosynthetic characteristics and chlorophyll a fluorescence transient in *Lonicera japonica* under drought stress. Acta Physiol Plant 41:124. https://doi.org/10.1007/s11738-019-2912-z

Zivcak M, Brestic M, Balatova Z, Drevenakova P, Olsovska K, Kalaji HM, Yang X, Allakhverdiev SI (2013) Photosynthetic electron transport and specific photoprotective responses in wheat leaves under drought stress. Photosynth Res 117:529–546. https://doi.org/10.1007/s11120-013-9885-3