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**OPTIMIZATION OF MAIZE PRODUCTIVITY THROUGH PRECISION DRIP
IRRIGATION AND FOLIAR BIOSTIMULANT COMPLEX AND
MICRONUTRIENTS APPLICATION**

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**Debrecen
2025**

**OPTIMIZATION OF MAIZE PRODUCTIVITY THROUGH PRECISION DRIP
IRRIGATION AND FOLIAR APPLICATION OF BIOSTIMULANT COMPLEX AND
MICRONUTRIENTS**

Dissertation submitted in partial fulfilment of the requirements for the doctoral (Ph.D.)
degree in agricultural sciences

Written by Akasairi Ocwa certified Master of Science in Crop Science

Prepared in the framework of the Kálmán Kerpely doctoral school of the University of
Debrecen
(Crop production and Horticulture programme)

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1. INTRODUCTION

Global population increase raises food insecurity concerns (Wu *et al.*, 2019; Lai *et al.*, 2023; Du *et al.*, 2024) with over 1 billion people lacking adequate dietary energy and suffering from micronutrient deficiencies (Barrett, 2010). This calls for the increase in production and biofortification of major food crops including maize (*Zea mays* L.) (Tejada *et al.*, 2016). Because of its global economic and nutritional relevance (Ocwa *et al.*, 2024a; Ray *et al.*, 2024; Ssemugenze *et al.*, 2024), there is remarkable expansion in maize cultivation area (Tian *et al.*, 2024) with annual production exceeding 1 billion tons (Erenstein *et al.*, 2022; Galindo *et al.*, 2024). According to the recent FAO data, Europe contributed 8.8% of the global maize production by 2022. In Hungary, the harvested area of maize decreased with a remarkable increase in yield (Figure 1). Meeting the rising food demand necessitates circa 40% maize yield improvement in the next four decades (Sui *et al.*, 2018). This makes maize a significant contributor to evolving landscape of agri-food systems (Erenstein *et al.*, 2022). The agroecosystem's ability to produce adequate food (Ocwa *et al.*, 2023; Viana *et al.*, 2022) to satisfy the rising global population is affected by declining soil fertility (Wu *et al.*, 2019; Ssemugenze *et al.*, 2024; Tolisano *et al.*, 2024) and climate change (Chen *et al.*, 2015; Juhász *et al.*, 2020; Harsányi *et al.*, 2021; Balaout *et al.*, 2022; Melash *et al.*, 2023; Xiang *et al.*, 2024). Climate change is projected to add pressure on water resources due to increased drought. Yet, alleviating the impact of water/drought stress caused by climate change on maize production is challenging due to its co-occurrence with high temperature/heat stress (Qu *et al.*, 2024). Moreover, heat stress reduces electron transport rate, photosynthesis, and grain filling (Ferguson *et al.*, 2021) which have a direct effect on overall maize productivity.

Irrigation is a common practice used to deliver water to support crop production (Mohammed *et al.*, 2022; Ma *et al.*, 2024) to alleviate the deleterious effects of drought/water and heat stress (Horváth *et al.*, 2020; El-Sanatawy *et al.*, 2021). Use of irrigation technologies or systems that are efficient is vital for sustainability since they determine the amount of water saved and the sustainability of future water resources (Pool *et al.*, 2021). According to Qu *et al.* (2024), issues related to water use efficiency of the irrigation system, availability of the technology, and the need to deliver water at critical stages of crop growth remain the principal considerations. In addition to crop response to irrigation, soil types in given agro-ecosystems affect efficiency of

irrigation (Hondebrink *et al.*, 2017; Qu *et al.*, 2024). Conventional flood irrigation system is commonly used because it is simple to operate at a low cost; though it is no longer sustainable with the advent of climate change because of water shortages, and its requirement for much water input results in low water productivity and leaching of nutrients (Liang *et al.*, 2019; Ning *et al.*, 2024). This makes utilization of precision irrigation techniques inevitable.

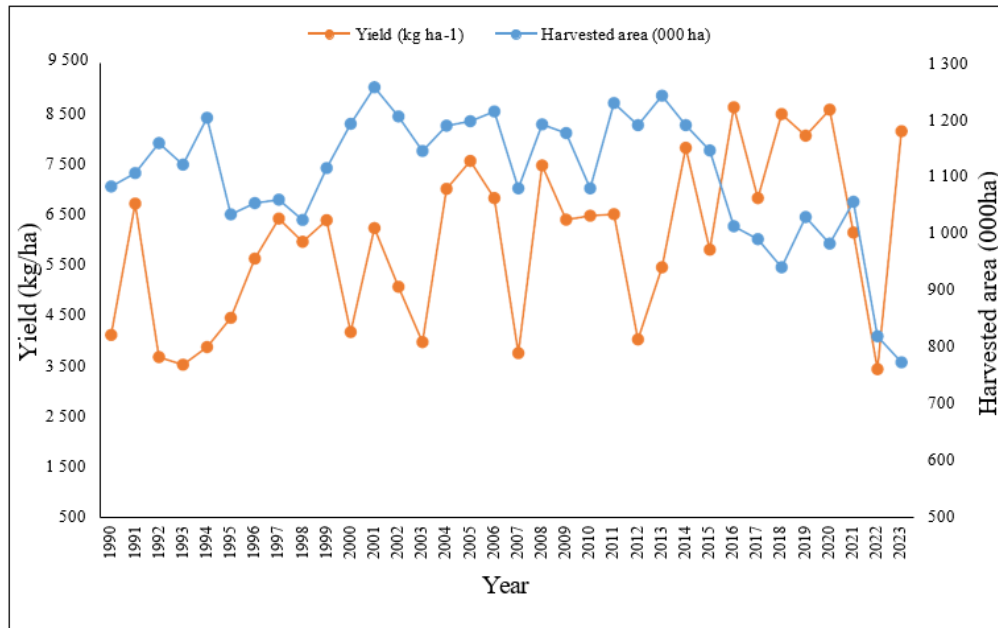


Figure 1 Harvested and maize yield in Hungary from 1990-2023.
Source: Data extracted from Hungarian Central Statistical Office.

Producing more food with less water (Toumi *et al.*, 2016) requires development of new scientific strategies to increase crop water use efficiency (Cantero-Navarro *et al.*, 2016; Wasonga *et al.*, 2020; Allakonon and Akponikpe, 2022) to sustainably increase crop production while maintaining water quality (Ferin and Kucharik, 2024). According to Zhang *et al.* (2021), utilizing water efficient irrigation methods is inevitable since water allocation for irrigation is affected by other economic sectors. Additionally, Ünlü *et al.* (2011) noted the scarcity of irrigation water is due to factors such as climate change, high urban and industrial consumption, and environmental pollution. Therefore, since productivity of crops is limited by water scarcity, judicious management and supply of water through irrigation become pivotal to sustain high crop yield and overall farm profits (Zhao *et al.*, 2022). This is because crop yield is a useful indicator of farmland productivity under varying

conditions (Meng *et al.*, 2012; Wu *et al.*, 2024). Since conventional flood irrigation is no longer sustainable because of increasing current water scarcity, utilization of water saving methods such as drip irrigation is inevitable (Li *et al.*, 2018; Xuan *et al.*, 2021; Patra *et al.*, 2022). For example, Brar *et al.* (2022) noted that subsurface drip irrigation saved irrigation water by up to 30% through reduction of drainage losses, while Ning *et al.* (2024) reported considerably higher grain yield and water productivity under deficit irrigation. Drip irrigation improves irrigation water productivity of maize (Qu *et al.*, 2024). On the other hand, regulated deficit irrigation with 75 % field capacity had significantly higher maize dry weight, cob fresh and dry weight, and plant height compared to 100% full irrigation - field capacity (control) while economic yield was higher under partial root-zone drying irrigation with 50 % field capacity compared to regulated deficit irrigation (Chen *et al.*, 2023). In this perspective, it is eminent that there are differential crop growth and yield responses to irrigation systems in the advent of climate change.

Besides affecting the sustainability of water resources and the functionality of irrigation systems in relation to crop production (Pool *et al.*, 2021), climate change has both direct and indirect effects on soil fertility (Biswa, 2022). Therefore, as an amelioration technique, fertilization is an essential practice to enhance soil fertility, crop growth (Qu *et al.*, 2024) and overall crop productivity (Zhang *et al.*, 2019; Mousavi and Nagy, 2021; Tian *et al.*, 2024). In crop production, maize and wheat account for circa 30% of the global chemical nitrogen fertilizer consumption (Ladha *et al.*, 2016; Galindo *et al.*, 2024). The excessive use of chemical fertilizers in an attempt to sustain soil fertility and crop production causes water pollution due to leaching and deposition of nutrients into water bodies (Al-Kaisi and Yin, 2003; Ju *et al.*, 2006; Li *et al.*, 2016); necessitating improvement in water application, and nutrient supply techniques (Sun *et al.*, 2023). Besides, Ram *et al.* (2017) noted that the efficacy of nutrients applied to the soil is lower for both micro and macro nutrients with 5% for micronutrients, and 50%, 40% and <15% for nitrogen, potassium, and phosphorus, respectively, due to limited synchrony between nutrient release by fertilizers versus crop demand at critical growth stages. Yet, foliar nutrient supply methods are considered a supplementary approach (Rajasekar *et al.*, 2017; Patil *et al.*, 2018). The nutrients can be supplied through foliar chemical fertilizer and biostimulant application and their integration with moisture supply

significantly boosts maize production.

Specifically, the water and nutrient requirement of maize depends on the growth stage (Wang *et al.*, 2021; Guo *et al.*, 2022; Illés *et al.*, 2022); hence, supply of moisture and nutrients at critical stages is of paramount importance. Therefore, the use of precision technologies that can detect water and nutrient deficiencies becomes handy. Currently, in Hungary, diverse biostimulant formulations, and chemicals fertilizers have been developed with limited robust field efficacy tests, which are necessary for farmer recommendation and/or re-constitution if field efficacy is null. Besides, conventional agronomic traits and yield assessments, this study included chlorophyll fluorescence and photochemical measurements, which are useful indicators of physiological water stress during the active vegetative and reproductive stages of maize plant growth. In fact, chlorophyll efficiency relates to crop assimilation ability (Ali *et al.*, 2018a) shown by fluorescence parameters (Guo *et al.*, 2022). Besides, photochemical efficiency of PSII (F_v/F_m) is recommended for studies involving drought stress (Faraloni *et al.*, 2011) and nutrition stress (Simkó *et al.*, 2020). With this in mind, this study hypothesized that utilizing precision drip irrigation and biostimulant, and micronutrients foliar application does not affect the phenological, chlorophyll fluorescence and photochemical parameters, and grain yield and quality of maize. To test this hypothesis, this study conducted with following objectives:

- a) Assess the effect of precision drip irrigation and biostimulant, and micronutrients foliar application on growth characteristics of maize.
- b) Determine the response of chlorophyll fluorescence and photochemical yield of maize to precision drip irrigation and biostimulant, and micronutrients foliar application.
- c) Evaluate the response of yield and yield components of maize to precision drip irrigation and biostimulant, and micronutrients foliar application.
- d) Evaluate the effect of precision drip irrigation and biostimulant, and micronutrients foliar application on grain quality maize.

2. LITERATURE REVIEW

2.1 Climate change and drought (water shortage) versus crop production and resource allocation

Climate change precipitates uncertainty of water supply by water resources (*Li et al.*, 2017). Water scarcity for agriculture in recent decades has significantly increased (*Li et al.*, 2021; *Ukwu et al.*, 2024), raising concerns because of increasing population growth and climate change (*Li et al.*, 2021; *Yang et al.*, 2023). In fact, climate change determines optimal allocation of agricultural water due to increased demand and yet fluctuating supply. Matching demand-supply versus meeting optimum water use efficiency is a great challenge to water resource allocation (*Cao et al.*, 2023). According to *Li et al.* (2022), the variance between increasing demand for water and its limited supply is bottleneck to synergetic management of agricultural water and overall land resources. Moreover, *Li et al.* (2021) explained that agricultural irrigation water affects cropland use, hence necessitating synchronised allocation of agricultural irrigation water and cropland to constructively alleviate water scarcity and associated impacts. For example, in the southwestern states of the US, there was an 11–21% decline in crop yields of total irrigated land since 1978 due to shortage of surface water (*Elias et al.*, 2016). Therefore, the interaction between agricultural water and land resources has a strong relationship with food security (*Amnuaylojaroe et al.*, 2024). This reflects need to pay attention to all climate indices and other resources affected by climate change that have a pronounced effect on crop production. *Farkas et al.* (2021) emphasized that adapting crop production to the detrimental impacts of climate change has become key.

In the context of Hungary, there have been increasing cases of drought affecting crop production. Spatial heterogeneous increase in drought hazard during the 21st century in Hungary is linked to climate change (*Blanka et al.*, 2013), hence calling for early mitigation efforts (*Buzási*, 2021). Earlier, *Bartholy et al.* (2013) projected significant increase in drying periods in summer. Analysis by *Mohammed et al.* (2022) also showed severe drought for the period 1961–2010 which adversely affected crop yield in southern and western Hungary; hence varying crop drought resilience factor (Figure 2). In the past 90 years, 17-39% of crop yield was

accounted for by climate, with the proportion increasing to 67% for the period 1981-2010 (Pinke and Lövei, 2017).

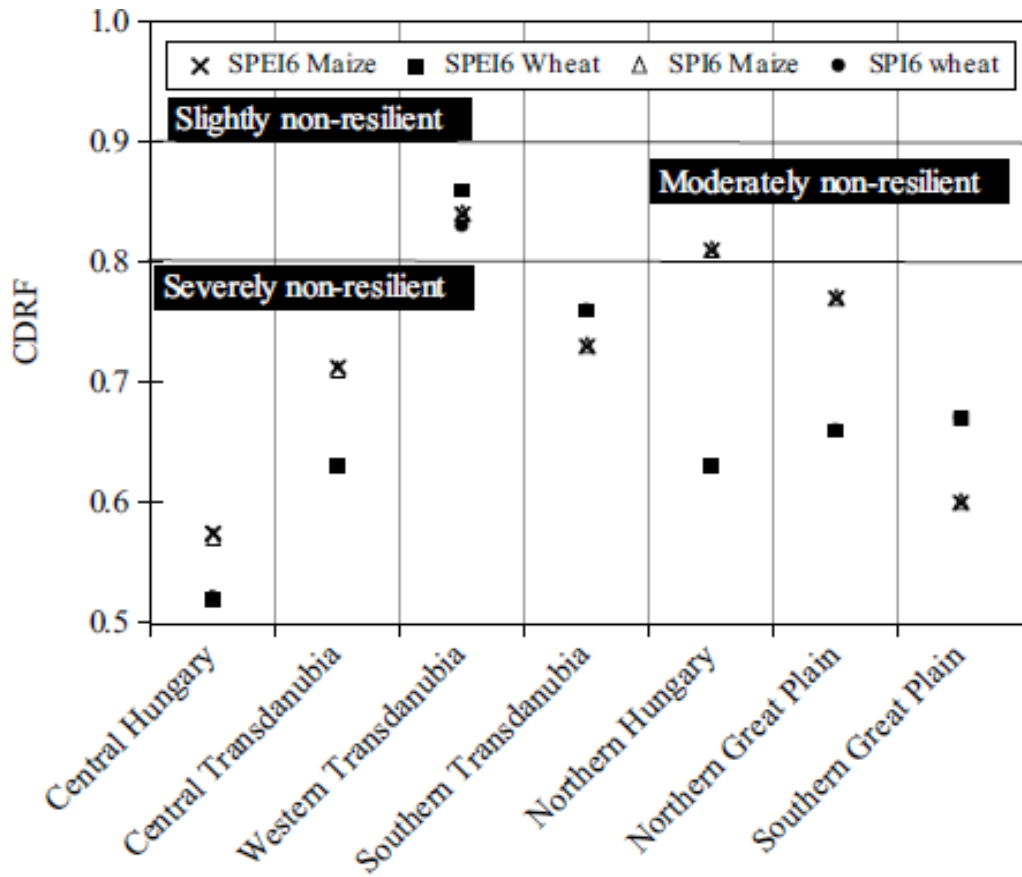


Figure 2 Crop drought resilience factor (CDRF) for maize and wheat in Hungary (six months' time scale) for the period 2000 and 2010. Standardized Precipitation Evapotranspiration Index 6 (SPEI6). Standardized Precipitation Index 6 (SPI6). Source: Mohammed *et al.* (2022)

2.2 Chlorophyll fluorescence and photochemical yield (efficiency) dynamics of maize under irrigation and water stress

Chlorophyll fluorescence is a sensitive rapid nonintrusive method for detection and monitoring of photosynthetic and plant physiological status and evidencing abiotic stress (Kocheva *et al.*, 2004; Mehta *et al.*, 2010; Chengli *et al.*, 2017). This allows varying decisions to be taken to alleviate the impact of abiotic stress on maize productivity. To achieve this, minimum fluorescence (F_o), maximum fluorescence (F_m), maximal quantum efficiency (F_v/F_m) (Herzog and Chai-Arree 2012; Wang *et al.*, 2023a) and electron transport rate (Chen *et al.*, 2023) are assessed at varying water sensitive phenophases. The F_v/F_m also called the maximum quantum

efficiency of the PSII provides evidence of photosynthate rate. Several studies have shown varying results related to the response of fluorescence and photochemical yield of maize to water management/soil moisture conditions. *Rehaman et al.* (2023) recorded reduction by 10.8% and 14.5% of *intrinsic* PSII activity and PSII, respectively, due to drought. A study by *Gholamin and Khayatnezhad* (2011) showed that under water stress, F_v/F_m and chlorophyll content reduced with a marked increase in minimal fluorescence. Similarly, a reduction of 14.1 % and 48.6% of PSII and F_v/F_o under water stress compared to the control was reported by *Arikan et al.* (2022).

In addition to the above, another study showed that photochemical yield and non-photochemical quenching decreased while fluorescence yield increased under low and intermediate light conditions in response to water stress (*Chen et al.*, 2019). A study by showed that high-temperature + elevated water content of the soil treatments significantly enhanced variable fluorescence, maximal quantum efficiency, actual photosynthetic rate, and net photosynthetic rate, and reduced canopy temperature by 1-3 °C. The report emphasized that elevating soil moisture content during the grain filling stage enhances photosynthesis and general adaptation to the warming influence of climate change in maize production (*Wang et al.*, 2023a). Water stress predominantly affects photosynthetic performance of crops through stomatal limitation (*Li et al.*, 2024a). *Li et al.* (2019) reported reduction in PSII photochemistry due to severe drought and leaf aging while rewatering did not improve photoprotection.

Generally, the effect of water stress on fluorescence and photochemical parameters can be alleviated through irrigation, which also yields varying results depending on the irrigation type, water quality, crop type/growth stage, agronomic practices, and other environmental factors. According to *Ibrahim et al.* (2022), irrigation positively impacted chlorophyll fluorescence with a 7% noticeable increase. Meanwhile, compared to rain-fed conditions, irrigation significantly improved F_v/F_m and photochemical quenching by 56.57% and 9.14 % while non-photochemical quenching reduced by 22.8%. Figure 3 summarises the overall literature undertaken on abiotic stresses including water stress vs photochemistry.

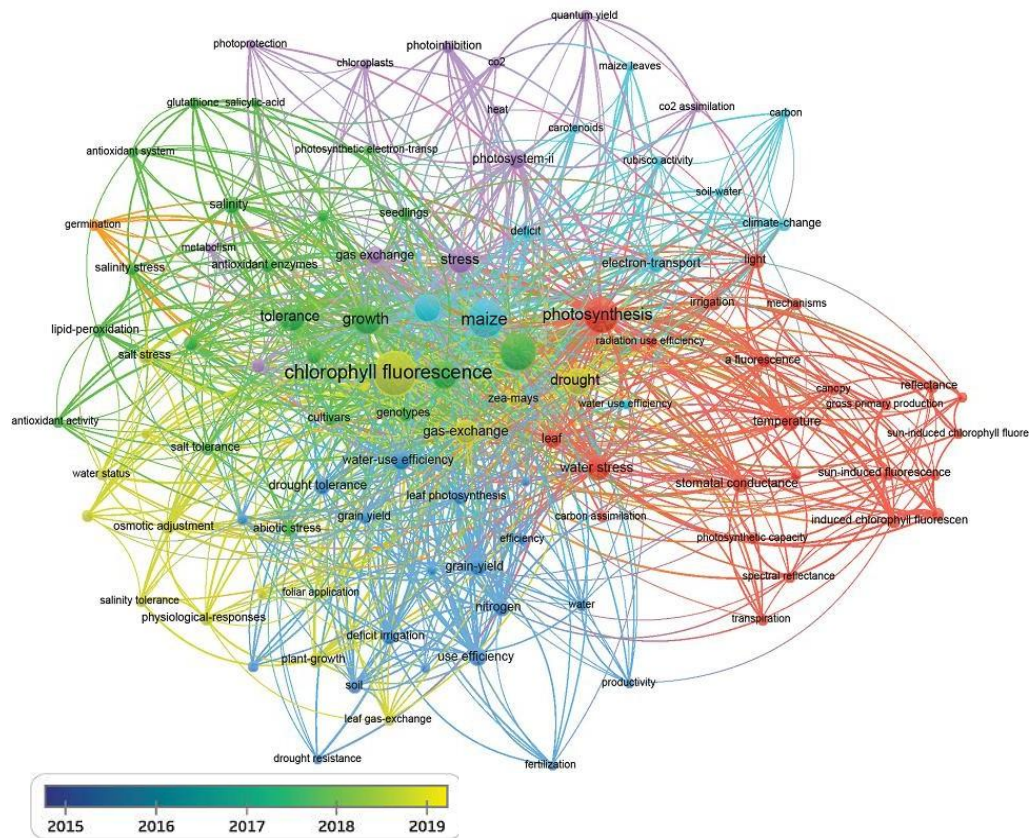


Figure 3 Undertaken research on abiotic stress and maize photochemical response. Latest areas of research are designated by yellow and green colours.
Source: Author (based on Vosviewer analysis of published literature extracted from Web of Science database).

In addition, the interactive effect of nitrogen fertilization and water management had a significant positive effect on F_v/F_m (Gao *et al.*, 2022). Accordingly, drip irrigation under mulching optimized photosynthetic capacity by 18.6% compared to the control (rain-fed practice). Qu *et al.* (2024) reported similar results where net photosynthetic rate under drip irrigation was higher than flood irrigation treatments. In terms of irrigation quota, 400 quota drip irrigation (buried drip irrigation -400 mm) optimized leaf nitrogen metabolism, chlorophyll fluorescence and photosynthetic characteristics of maize (Xu *et al.*, 2023b). Xu *et al.* (2019) also indicated that higher irrigation quotas significantly improved the actual and maximum photosynthetic efficiency of PSII compared to the control. With deficit water supply, a study by Chen *et al.* (2023), revealed that deficit irrigation at 75 % field capacity had higher photochemical quenching, effective quantum yield (Φ_{PSII}), and electron transfer rate compared to 50 % field capacity and the control, while 50 % field capacity had higher maximal quantum efficiency (F_v/F_m) than 75 % field capacity. A report by Niknam *et al.* (2023) revealed that F_o increased due

to 30% water requirement reduction, while pre- and after sowing irrigation improved F_v/F_m . However, in terms of water quality, irrigation with salty water (high NaCl level) significantly reduced maximum quantum yield and photochemical quenching of maize (Chengli *et al.*, 2017). The nexus between chlorophyll fluorescence parameters under varying abiotic stresses dictate the direction of other physiological processes, which determine assimilate partitioning and final yield. According to Wang *et al.* (2020), there was a positive nexus between photosynthetic capacity and maximum carboxylation rate. Therefore, understanding the relationship between different parameters is vital in monitoring maize growth.

2.3 Maize growth and yield response to irrigation

Maize susceptibility to water stress especially at anthesis and silking growth stages (Das *et al.*, 2024) compromises its productivity. Water stress (20% of optimal irrigation) at vegetative and reproductive stages causes yield loss of 0.5-17.5% and 46%, respectively while 20 - 40% water stress at both growth stages reduces yield by 44% (Allakonon and Akponikpe, 2022). Water stress remediation requires accurate detection of crop water deficit (Qin *et al.*, 2021) to ensure stable production. Once water stress is detected, water is supplied using appropriate system. Wu *et al.* (2024) noted that crop production and productivity are negatively affected by conventional inefficient irrigation systems. Moreover, the available irrigation systems have varying efficacies and consequently varying water use efficiency, and crop productivity effects. Wang *et al.* (2021) revealed that optimum irrigation quotas of 720, 540, and 180 mm for arid areas, semi-arid, and semi-humid areas utilised 11–60% less water, enhanced water use efficiency by 11–65% and produced a yield of $>15 \text{ t ha}^{-1}$ compared to traditional irrigation.

According to Dhayal *et al.* (2023), the productivity of wheat-moongbean-maize cropping system under subsurface drip irrigation improved by 4.5%, total water and irrigation water productivity improved by 45% and 118% compared to flood irrigation. Specifically, crop evapotranspiration (ET_C) at 0.8 optimized system productivity by 10% compared to 0.6 ET_C . Contrary, Xu *et al.* (2023a) revealed that the yield of maize varieties tolerant to drought reduced with a decrease in drip irrigation quota. Similarly, Liu *et al.* (2023) revealed a negative correlation between

irrigation quota and yield with irrigation quota of 540 mm (optimized quota) having higher efficacy in optimizing maize water use efficiency, growth and yield under drip irrigation. Interestingly, another report showed that although water application was reduced by 31% under 360 mm furrow irrigation, it had an equivalent yield to the control. Meanwhile, at -30 kPa, drip irrigation decreased water application by 57%, and increased yield and net profit by 15 and 23%, respectively (Zhang *et al.* 2021). A study by Sujatha *et al.* (2023) showed considerably higher water productivity under drip irrigation than furrow irrigation. Likewise, drip irrigation enhanced water use efficiency by 33% compared to furrow or sprinkler irrigation (Kuang *et al.*, 2021). Compared to border irrigation, drip irrigation saved 227 mm of irrigation water during dry season compared to conventional border irrigation hence yield variability of 12.1% less than border irrigation (Guo *et al.*, 2021). Additionally, drip irrigation saved 30% of water input and improved overall growth and yield of maize compared to surface irrigation system (Ibrahim *et al.*, 2022). According to Rasool *et al.* (2020), drip irrigation saved circa 60% of water and significantly improved grain yield attaining up to 9.9 t ha⁻¹ compared to the furrow irrigation method. A global meta-analysis by Zhu *et al.* (2023) revealed higher yield of 2.8-3.2 t ha⁻¹ under drip irrigation. Earlier, O'Neill *et al.* (2008) revealed that surface drip irrigation saved 30% irrigation, soil and rainwater (total water consumption) required to produce an equivalent quantity of grain under furrow irrigation whereas only 8% was saved by sprinkler irrigation. In fact, irrigation water productivity and overall water productivity were 1.7, 1.4, and 1.3 t/ML and 2.3, 1.7 and 1.9 t/ML under drip, sprinkler, and furrow irrigation, giving the yield of 11.8, 10.5, and 10.1 t ha⁻¹, respectively. In addition, drip irrigation with good quality water attained higher grain yield of 8.5 t ha⁻¹, yield reduction of by 5 and 12% under drip irrigation with marginal quality and drip irrigation with poor quality water was observed. Meanwhile, rain-fed maize production buttressed with drip irrigation had higher photosynthetic efficiency, resulting in a 53% yield increment (Bai and Gao, 2020). Also, subsurface drip irrigation (installed at the depth of 0.15 m) recorded the highest water productivity of 2.07 and 2.08 kg/cm³, and optimum grain yield of 8.8 and 8.9 t ha⁻¹ in 2019 and 2020 seasons of the experiment, respectively (Muneer *et al.*, 2022). However, a study by Monistrol *et al.* (2024) revealed that positive effects of subsurface drip irrigation on maize phenology and yield were evident in the second year of the experiment.

A study by *Liu et al.* (2023) revealed a significantly higher leaf area index, plant height, water use efficiency under drip irrigation as compared to conventional border irrigation. Translocation of dry matter, efficiency of dry matter transfer, and partitioning and translocation of dry matter to grain yield significantly increased by 27.4, 13.9 and 7.9% under drip irrigation compared to conventional border irrigation. *Al-aridhee et al.* (2022) showed that surface drip irrigation saved irrigation water since it reduced maize water consumption. *Liu et al.* (2022) analysed irrigation levels optimal to improve maize productivity, and water use efficiency under drip irrigation. Results showed that 540 mm drip irrigation quota produced the highest water use efficiency, dry matter accumulation, growth index and yield compared to 420, 480 and 600 mm quotas. In addition, 540 mm drip irrigation quota significantly increased efficiency of dry matter transfer, dry matter translocation contribution to the grain compared to 420 mm quota. *Qin et al.* (2016) noted that under drip irrigation, the frequency of irrigation was higher with lower irrigation amount, wetting depth and deep percolation. Meanwhile, maize growth was accelerated and growth stages shortened and overall maize evapotranspiration lowered by 10%. According to *Irfan et al.* (2014), not only drip irrigation but also the quality of irrigation water affected germination rate, plant height, water use efficiency and overall production of maize. *Li et al.* (2024a) showed that drip irrigation has the potential to produce higher harvest index and yield compared to flood irrigation. *Nawaz et al.* (2024) in glasshouse experiment investigated the effect of varying irrigation levels including the 100% or full irrigation full irrigation (no stress), and deficit irrigation that is 75%, 50%, 25% of required water quantity to reach pot capacity) on maize. Results showed that showed that 100% irrigation had better performance with 125 cm plant height, 92.8 cm root length, 180.4 and 73.4 g fresh and dry above-ground biomass weight, 91.7 and 28.7 g fresh and dry root weight, 18.0 mm stem diameter, and 350 cm² leaf area, followed by 75% deficit irrigation treatment. Conversely, irrigation with high level of salty water reduced fresh and dry shoot weight at jointing and tasseling stage by 9.1 and 4.9%, respectively, compared to the control because of presence of sodium chloride (*Chengli et al.*, 2017). A study by *Wang et al.* (2023a) showed that both regulated deficit irrigation and deficit irrigation had lower daily crop evapotranspiration, ineffective crop evapotranspiration and phase water-consumption coefficient by 12.6-35.1%, 6.7-16.6% and 3.4-9.9%, respectively, with optimum leaf area index in

the 6 leaf stage, higher water productivity of 10.3-33.4% resulting into higher grain yield of $> 15 \text{ t ha}^{-1}$. Contrary, full irrigation strategy (100% of maize water requirement) produced the highest yield while water deficit (20-30%) strategy reduced yield by 4-8%, albeit the maximum water use efficiency (*Liu et al.*, 2017). *Wu et al.* (2024) noted that combining different precision micro-sprinkler irrigation methods considerably decreases water consumption, enhances water use efficiency, and attainment of significant yield improvement, hence enhancing sustainable agricultural production. On the other hand, *Guo et al.* (2021), notes that compared to border irrigation, drip irrigation increased phosphorus and nitrogen accumulation in the root zone, and lowered yield variability. Meanwhile, *Wang et al.* (2022) showed a higher yield of 8.9% and 4.7% under transparent plastic film mulching combined with low, and high drip irrigation amount. Accordingly, change in irrigation regime from normal to severe resulted into 27 and 46% reduction in fresh and dry forage yield of maize (*Hajibabae et al.*, 2012). From this literature, it is evident that application of irrigation systems in maize production requires both technical and economic validation. For example, *Valentín et al.* (2020) noted that although, irrigation systems such as subsurface irrigation are water saving techniques (reducing water consumption) and improve water use efficiency in maize production, their application depends on the cost and availability.

In context of Hungary, several studies have been conducted on utilisation of irrigation on maize production. Although several literature exist on sprinkler irrigation or centre pivot irrigation, its specific application in the context of maize was limited. The available literature underscored key considerations in the application of sprinkler or variable rate systems. For example, *Angura et al.* (2024) noted that the effectiveness of sprinkler irrigation system depends on factors including variability of inherent field conditions especially soil properties. Relatedly, according to *Szabó et al.* (2022), planning and effective traffic control of variable rate irrigations (VRI) systems, as well as determination of optimal quantity of irrigation water requires consideration of *VRI maps*, terrain characteristics, plant characteristics, and soil properties. *Magyar et al.* (2023), revealed that irrigation effects at two different stages of maize growth improved crop water productivity in 2021 and 2022 by 6% and 4%, respectively. *Siphiwe et al.* (2024) used Hydrus 2D to model soil moisture for effective irrigation planning in maize using crop

evapotranspiration and physical soil properties as inputs, and results revealed that 32.2 and 17.51 V/V% as optimal irrigation schedules to maintain soil moisture. *Bencze et al. (2022)* compared sprinkler irrigation (rain-like watering with console) and drip irrigation (solenoid valve-controlled tape drip irrigation) effect on maize production. The results showed a better growth and yield performance under drip irrigation due to high water use efficiency. However, the authors urged that the aspect of economic viability under convention filed conditions needs to be factored in as well as the choice of arable crops to apply drip irrigation. Generally, *Széles et al. (2024)* emphasized the importance of irrigation and other precision technologies in ensuring sustainable maize production.

2.4 Maize growth, photochemical, phenological, grain yield and quality parameters response to biostimulants and fertilizers

2.4.1 Growth parameters response to biostimulants and fertilizers

The application of fertilizers affect growth parameters. *Tariq et al. (2014)* showed that foliar application of zinc significantly optimized physiological parameters such as crop growth rate except stem diameter, number of leaves, days to 50% tasselling, and plant height. However, *Nik-Khah et al. (2024)* reported significantly higher plant height from single foliar application of FeSO₄, ZnSO₄, MnSO₄ compared to the control. Similarly, *Khalafi et al. (2021)* recorded higher plant height of 280.0 cm from application of micronutrients zinc and iron compared to control treatments that had values ranging from 196.8 - 221.5cm. Meanwhile the interactive effect of nitrogen fertilization and water management had a significant positive effect on SPAD (*Guo et al., 2021*). On the other hand, both microbial and non-microbial biostimulants elicit effect divergent effects depending on factors such as their formulation, climate and soil factors (*Długosz et al., 2020; Ocwa et al., 2024a*). Microbial biostimulants predominantly constituted from bacterial and fungus. The phenological impacts they elicit depends on microorganism species in question (*Cardarelli et al., 2022; Ocwa et al., 2024b*). According to *Rudolph et al. (2015)* plant growth promoting bacteria promotes early growth vigour in seeds of low vigour. As such, plants treated with *Bacillus* exhibited significant increase in root length (79.20 cm), and leaf area (214.20 cm⁻²) compared to the untreated control (*Nawaz et al., 2024*). Similarly seed treatment with *Bacillus subtilis* optimised stem

diameter (Moreno *et al.*, 2021) while *Bacillus firmus* I-1582 affected plant height and root surface area (Vagedes and Lindsey, 2020). According to Nawaz *et al.* (2024), 100% irrigation combined with *Bacillus simplex* enhances maximum water use efficiency. Additionally, the positive impact emanates from the *Bacillus* bacteria ability to improve availability and uptake of phosphorous (Pereira *et al.*, 2020) and nitrogen (Mandić *et al.*, 2018). According to Zeffa *et al.* (2019), *Azospirillum brasilense* seed inoculation enhanced nitrogen use efficiency and plant growth hence a promising environmentally sustainable and economic viable approach to maize production. Relatedly, a study by Ferrarezi *et al.* (2022) showed that the combination of *Bacillus thuringiensis* + *Azospirillum brasilense* consortia significantly improved stalk diameter and plant height compared to the control (non-inoculated) and the other treatments. However, the same report emphasized the challenge of achieving similar results under field conditions. Alao *et al.* (2024) analysed maize response to arbuscular mycorrhizal fungi (*Glomeraceae*), and results showed that combination of 50% NPK_Urea + biostimulant positively affected growth traits though similar to the effect induced by 100% NPK_Urea. On non-microbial biostimulants, Martini *et al.* (2021) showed that a utilization of biostimulant derived from algae species *Chlorella sorokiniana* enhanced maize root development in deficiency of nitrogen. Dineshkumar *et al.* (2019) evaluated microalgae as a potential biofertilizer and revealed optimized seed germination, and early stage effects on growth parameters. Priolo *et al.* (2024) reported the biostimulant derived from an extract of duckweed to improve maize root development and biomass production. Also, Cheng *et al.* (2024) noted that foliar application of biostimulants containing amino acids enhances nutrient absorption and overall productivity. This is because amino acids regulate photosynthesis and reduce susceptibility of plants to environmental stress (Al-Karaki and Othman, 2023; Cheng *et al.*, 2024). On the same note, Canellas *et al.* (2024) revealed the biostimulating potential of proteins hydrolysates in conjunction with humic substances in promoting maize growth due to significant increase in uptake of amino acid. In the same way, the optimizing efficacy of hydrolysate from sheep wool on maize leaf area and plant height depended on the concentration. The hydrolysate increased nitrogen use efficiency hence optimizing shoot fresh and dry biomass by 32.5 and 34.4%, respectively (Metomo, *et al.*, 2024). Meanwhile, dos Reis *et al.* (2019) showed that spraying of biostimulant synthesized from chitosan derivatives

prompted tolerance to water deficit, besides enhancing photosynthetic traits. In addition, the biostimulating effect of foliar application of an extract of *Elusine indica* on drought stress significantly enhanced plant fresh and dry weight, height, and leaf chlorophyll content. The report suggested subsequent utilization of *Elusine indica* extracts as an environmentally and cost friendly strategy to boost drought tolerance in maize (Han et al., 2024). Correspondingly, the biostimulating effect of 1.5% concentration of an extract from *Sargassum boveanum* applied to on maize plants alleviated the deleterious effect of water stress (Alasvandyari et al., 2024). Relatedly, humic acid enhanced chlorophyll content, growth characteristics, and photosynthetic assimilation rate (29.2%), and root, stem and leaf biomass accumulation (Abu-Ria et al., 2024). According to Chen et al. (2022), the effect of humic acids relates to phytohormones regulation. Besides, Bulgari et al. (2019) noted that humic acids promote uptake of nutrients and water by enhancing cell membrane permeability, hence enhancing growth and tolerance to drought.

2.4.2 Photochemical parameters response to biostimulants and fertilizers

Application of different fertilizers either chemical or biostimulants affect maize phenological, photochemical and grain attributes differently. The fertilizer formulations contain varied composition of both macro and micro essential plant nutrients and/or substances that influence productivity of maize. Their effects manifest in isolation or in combination with other agronomic practices such as irrigation, and tillage methods, among others. The effect on photochemical parameters such as F_o , F_m , F_v/F_m , PSII and ETR have been reported with contrasting results by different authors. For example, reduction by 25% of optimal nitrogen fertilizer rate + dicyandiamide had maximum PSII energy conversion potential, maximum quantum efficiency of PSII, electron transfer rate, and net photosynthesis at the jointing, flowering, and grain-filling stages (Han et al., 2023). Wu et al. (2013) recommended that nitrogen delayed under water logging conditions enhance photosynthetic efficiency and reduces photodamage of maize seedlings. According to Abd El-Mageed et al. (2021), foliar application of silicon improved stomatal conductance and photosynthetic efficiency signifying silicon ability to enhance drought tolerance by maize. On the same note, foliar Zn-lysine application mitigated water stress effect on photosynthetic efficiency, water relations and yield

of maize cultivars (*Shehzad et al.*, 2022). *Wang et al.* (2009) noted that although zinc application did not improve drought stress adaptation by maize, it improved photosynthetic rate under irrigated conditions due to increased stomatal conductance and consequently intercellular CO₂ concentration. In terms of biostimulants, *Chen et al.* (2023) revealed that sole application of soil-treated chitin had higher photochemical quenching and F_v/F_m compared to other chemical treatments. The chlorophyll content, net photosynthesis, transpiration rate, water use efficiency biomass under partial root-zone drying irrigation at 50 % field capacity + foliar glycine application were higher compared to other chemical treatments, including without chemical application.

2.4.3 Yield and grain quality response to biostimulants and fertilizers

Ameliorating the impact of nutrient stress on crop productivity involves the utilization of different nutrient inputs. Fertilizers and biostimulants (microbial or non- microbial nature) elicit effects on maize grain yield and quality when applied solely or integrated with other agro-technical inputs and/or practices such as irrigation. A meta- analysis by *Cui et al.* (2024) revealed a higher yield of 9.4 t ha⁻¹ under irrigation + fertilization compared to 8.7 t ha⁻¹ in the control. According to *Tadesse et al.* (2024), yield positively responded to increasing levels of nitrogen application and irrigation. Specifically, under full and deficit irrigation, 92 kg N ha⁻¹ significantly optimized agronomic yield. Another study showed that fertilization and drip irrigation contributed to mean yield increase circa 25%, and 80% during dry season (*Zarski and Kusmierek-Tomaszewska*, 2023). The combination of urea nitrogen fertilizer types with slow-release nitrogen fertilizer reduced reduction of yield by water stress. Accordingly, although, the yield of slow-release nitrogen fertilizer under 100% crop evapotranspiration had the highest grain yield among all the assessed treatments, it was not significantly different from urea fertilizer under 100% crop evapotranspiration (*Guo et al.*, 2022). On the other hand, *Khalafi et al.* (2021) noted variation in the weight of 1000 seeds by micronutrients. The highest weights of 385.0 and 383.5 g were recorded under iron and zinc foliar application compared to 278.0 g under zinc soil application, while in terms of cob weight, zinc had a pronounced effect. A report by *Nik-Khah et al.* (2024) showed that a combination of zinc and iron had the highest effect on cob weight, seeds per cob and cob length. However, for grain quality, zinc fertigation

according to *Khalafi et al.* (2021) had the highest protein content. According to *Capo et al.* (2024), zinc application did not significantly improve yield of maize grain except kernel weight. *Tariq et al.* (2014) showed that foliar application of zinc significantly optimized yield. Generally, although nitrogen application and irrigation are the critical factors that influence maize growth and yield (*Ning et al.*, 2024), limited supply of essential micronutrients can be a limiting factor. The most important micronutrients include zinc, boron, and iron among others (*Ahmad et al.*, 2012; *Safdar et al.*, 2023). Apart from overall metabolic roles, zinc enhances maize growth and development under different soil conditions (*Capo et al.*, 2024). According to *Akhtar et al.* (2024), bioactive zincated urea improved, nitrogen use efficiency, reduced nitrogen application by 80% without negatively affecting yield and quality of maize and rice grain. Conversely, boron plays an important role in proteins and carbohydrates metabolism which affects the reproductive processes including development of seeds (*Oosterhuis and Zhao*, 2001; *Safdar et al.*, 2023). According to *Khalafi et al.* (2021), though soil application considerably improved plant Fe and Zn uptake by maize plants, the foliar application significantly boosted maize growth and yield.

The use of biostimulants has been reported to ameliorate abiotic stress in plants and consequently improve productivity (*Santi et al.*, 2017; *Cholakova-Bimbalova et al.*, 2019; *Panfili et al.*, 2019; *Mannan et al.*, 2023; *Benito et al.*, 2023; *Gul et al.*, 2024). Several types of biostimulants have been manufactured and tested under both laboratory and field conditions with promising results. Accordingly, the combined use of biostimulant with foliar fertilizers has been reported to increase nutrient use efficiency and consequently crop yield. *Kostadinova and Hristoskov* (2014) revealed that joint nitrogen application with foliar application of *Amalgerol* increased maize grain yield by 31%, compared to unfertilized plots. In fact, foliar products and fertilisation at increased rate of $N_{300}P_{150}K_{150}$ had comparable effects. A global systematic review of maize response to an array of biostimulants by *Ocwa et al.* (2024a) revealed a distinct impact on grain yield but limited on grain quality. The review further showed that although the impact was generally positive, some microbial and non-microbial biostimulants reduced yield depending on water stress level. Yet, biostimulants are aimed principally to optimize crop quality and productivity while minimizing chemical fertilizer dependency (*Nivetha et al.*, 2024; *Yogendra et al.*, 2024). Overall, biostimulants are promising innovative

agents with the capacity to bridge the contemporary requirements of sustainable agriculture (Garcia- Gonzalez and Sommerfeld, 2016; Mattarozzi et al., 2020; Gupta et al., 2021; Mutlu- Durak and YildizKutman, 2021 Ocwa et al., 2024c). Gandhi et al. (2023) indicated that seaweed extracts application proved highly effective and significantly improved maize grain yield. In particular, the yield improved by 19, 20 and 21% in *Kappaphycus alvarezii*, and *Sargassum cinctum* and *Gracilaria debilis* treatments, respectively. According to Layek et al. (2015), compared to the control (recommended dose of fertilizers), saps from seaweed significantly optimized grain yield by 10.5 - 13.1%. Similarly, *Kappaphycus* seaweed extract improved grain yield by 36.4% and 13.5% under water stress and well irrigated conditions, respectively (Trivedi et al., 2018). The application of seaweed (*Kappaphycus alvarezii*) extracts enhances the uptake of nitrogen and potassium resulting in increased amino-nitrogen (van Tol de Castro et al., 2024). Conversely, a study by Fontana et al. (2024) indicated a zeolite-based biostimulant to promote higher nitrogen use efficiency and as such at 50 and 80 kg N ha⁻¹ fertilisation rates, zeolite-based biostimulant foliar application improved grain number per m² by 7.9% and 9.3%, respectively, while at the lowest rates of nitrogen fertilisation, overall maize grain yield improved by 7.2%. Relatedly, chicken feather biostimulant was reported to enhance maize yield (Tejada et al., 2018). Likewise, microalgae as biofertilizer was reported to enhance grain yield (Dineshkumar et al., 2019). A study by Ali et al. (2018b) revealed that the combination of humic acid and varying irrigation levels reduced injurious effect of water stress on maize yield. In fact, humic acid (20 kg ha⁻¹) combined with 350 and 175 mm irrigation had grain yield of 4.88 and 4.76 t ha⁻¹ compared to 3.29 t ha⁻¹ in the control (mean), hence producing an improvement of 48.3 and 44.6%. Application of humic urea 216 kg N hm⁻² produced yield enhancement of 57.4% (3.1 t ha⁻¹), ascribed to nutrient (phosphorous and nitrates) balance in the soil (Kong et al., 2022). Additionally, Niaz et al. (2016) explained that humic acid yield improvement is linked to hormonal processes that control plant physiological activities. However, on the contrary, under severe and moderate water stress, 2 and 4 l ha⁻¹ of humic acid reduced grain yield (Charkhab et al., 2022). Therefore, confirming the positive effects of biostimulant on different crops under pedoclimate conditions to fully unravel mechanisms of plant response as well as highlight the economic viability of their use (Fontana et al., 2024) is necessary. According to

Kálmán et al. (2023), the efficacy of biostimulants (microbial) needs assessment under field conditions since competition with soil microflora affects their survival hence the ability to elicit desired effects on the host plant. *Eswaran and Sundaram* (2024) noted that although, microbial biostimulants from plant growth promoting rhizobacteria stimulates plant growth and overall productivity, their instability and low viability limit commercial utilization in the field. However, studies have still shown positive impact of microbial biostimulants on grain yield. For example, microbial soil inoculation with *Pseudomonas putida*, *Bacillus megaterium*, *Saccharomyces cerevisiae*, *Pseudomonas fluorescens*, *Bacillus pumilus* and others improved grain yield by 75% (*Kálmán et al.*, 2023). On the other hand, according to *Alao et al.* (2024), 50% NPK_Urea + biostimulant elicited 21.1 - 27.8% improvement in the uptake of phosphorus while the overall grain yield under mycorrhizal biostimulant was 8.4% higher than 100% NPK_Urea. Another study revealed that a combination of arbuscular mycorrhiza with 50% NPK % enhanced grain yield by 3.8 and 3.6 t ha⁻¹ in two different locations (*Fall et al.*, 2023). Also, as compared to the control, *Azospirillum brasilense* seed inoculation produced grain yield improvement of 1.1 t ha⁻¹ (*Silva et al.*, 2022). Likewise, *Pseudomonas tolaasii* seed inoculation had overall higher yield compared to the control (*Viruel et al.*, 2014).

Apart from the impact of biostimulants on grain yield above, several studies have revealed varying effect on grain quality parameters such as protein, starch and oil content of maize. A study by *Tejada et al.* (2018) showed that maize quality was optimized by foliar fertilisation with biostimulant synthesized from chicken feathers. Authors explained that effect was elicited because chicken feathers were rich in low molecular weight peptides and amino acids, and organic matter. Another study by *Kálmán et al.* (2023) showed that soil inoculation with biostimulants (microbial) affected kernel nutritive value. In fact, *Pseudomonas putida* had higher (8.6%) protein compared to the control (8.5%) while *Saccharomyces cerevisiae* (8.4%) and *Pseudomonas fluorescens* (8.3%) had protein content below the control. Meanwhile, *Dineshkumar et al.* (2019) revealed that microalgae as biofertilizer enhanced carbohydrate and protein content. According to *Layek et al.* (2015), compared to the control (recommended dose of fertilizers), saps from seaweed significantly optimized protein and carbohydrate content by 4.8% and 12.3- 17.4%, respectively. Equally, the protein content of 9.5 and 10.3% was registered under

1.5 and 3 kg ha⁻¹ humic acid compared to the 6.6% in the control (Azeem *et al.*, 2021). A study by Ördög *et al.* (2021) also revealed the protein content of 9.4% from the biostimulant constituted from *Nostoc piscinale* cyanobacteria compared to 8.2% in the control. Conversely, humic acid at varying application rates enhanced grain oil content of maize (Niaz *et al.*, 2016). Another study reported the oil content of 3.94, 3.56 and 3.30% in season one and 3.41, 3.43%, 3.40 in season two, under 50% mineral fertilizer + seaweed extract (5%), *Glomus mosseae* + *Pseudomonas fluorescens*, and recommended mineral fertilizers, respectively. A systematic review by Ocwa *et al.* (2024a) revealed that protein, oil and starch improvement by different categories of biostimulants ranged from 0.1-3.7, with most evaluated studies depicting limited significant differences. The same review underscored the trend of biostimulants effect on grain quality attributes to be predominantly positive, depicting their potential application. Appropriate combination of fertilizers with other agronomic practices such as proper tillage practices and irrigation enhance maize productivity (Saddique *et al.*, 2020). Besides, utilization synergy exists between the concentration of essential nutrients and occurrence of other nutrients (Capo *et al.*, 2024) and agronomic practices employed (Saddique *et al.*, 2020). Between the elements for example, mobility of zinc in the soil and consequently plant uptake is limited by high concentration of phosphorus (Akhtar *et al.*, 2019; Capo *et al.*, 2024), and promoted by nitrogen (Capo *et al.*, 2024). Conversely, several scholars have documented production effect synergy between nutrients supplied by fertilizers and irrigation. According to Dhayal *et al.* (2023), combining fertilization and irrigation allows visualization of synergistic effects of water and nutrients on crop productivity under irrigated cropping systems. For example, application of nitrogen above 180 kg ha⁻¹ did not significantly improve grain yield but its combination with irrigation at 40 mm produced optimum positive effect (Ning *et al.*, 2024). Correspondingly, the coupling of potassium fertilizer application and drip irrigation improved maize yield (Qu *et al.*, 2024). Earlier, Széles *et al.* (2012) noted that increase in nitrogen levels does not necessarily improve yield if water supply at a given stage is limited. Therefore, optimized water and fertilizer supply does not only reduce agricultural irrigation and fertilization requirements, but also guarantees higher crop yields (Ma *et al.*, 2024). On the other hand, research shows that fertilizer application methods, soil and climate conditions, the type of chemical fertiliser utilised determines the

response of plants to micronutrients (*Khalafi et al.*, 2021). Latest report by *Ahmad et al.* (2021) indicated that foliar application of nutrients reduced the undesirable drought effect by enhancing plant physio-biochemical attributes, growth and phosphorus use efficiency under water stress conditions. *Farooqi et al.* (2012) accentuated that although there were limited effects of potassium application at sowing on maize crop due to adequate potassium at the experimental site soil, foliar supplementation with 1% at reproductive stage significantly improved yield and quality. However, *Racz et al.* (2021) showed that maize leaves in plots with foliar fertilizer application alone had a low critical value of some elements such as nitrogen, potassium and sulphur due to the drought stress factor at V12 stage. Therefore, it is evident that understanding the effects of the nutrient application at different at different on growth, yield and yield components of maize is of paramount importance.

In conclusion, understanding the relationship between different categories of maize parameters allows targeted nutrient and water applications at growth stage(s) where effects of the nutrients and water on growth, yield and yield components are optimum. Besides each growth parameter has a direct or indirect effect on yield and yield component. For example, *Jin et al.* (2023) observed a positive relationship between photosynthesis and chlorophyll fluorescence with a considerable increase under water stress. A study by *Nik-Khah, et al.* (2024) revealed a significant positive correlation between number of leaves and stem diameter but a negative correlation with cob length, seed number per cob and grain yield. In addition, cob length, plant height, seed number per cob, and grain yield had a significant positive correlation. *Tariq et al.* (2014) noted that stem diameter is one of the traits that contributes to grain yield of maize since it significantly controls grain size, and number per cob. *Khatibi et al.* (2023) also reported a significant correlation between stem diameter, leaf area and plant dry weight. Grain starch content and moisture content were negatively correlated with grain yield. *Kálmán et al.* (2023) showed that grain moisture content negatively correlated with grain oil and protein content and dry matter. However, starch and oil content, as well as starch, oil and protein content of the grain were positively correlated.

3. MATERIALS AND METHODS

3.1 Experimental site

The experiments were conducted at the University of Debrecen, Institutes of Agricultural Researches and Educational Farm Bemutatókert experimental area (47°83, 030”N, 21°82, 060”E, 111 m asl). The preliminary experiment was conducted in 2021 while other confirmation experiments were conducted in 2022 and 2023 growing seasons. In 2021 season, the highest temperature (24.3°C) was recorded in July and lowest (8.9 °C) in April. Accordingly, 2022 season had lowest temperature of 8.8 °C in April and the highest temperatures in the months of July (23.6 °C) and August 23.8 °C). A similar trend was followed in the 2023 growing season. In terms of precipitation, generally, the growing season 2022 recorded the lowest precipitation of 22.4 mm and 17.0 mm in the months of July and August compared to 68.6 mm and 38.2 mm in the 2021 growing season, and 45.8 mm and 85.9 mm 2023 growing season, respectively (Figure 4).

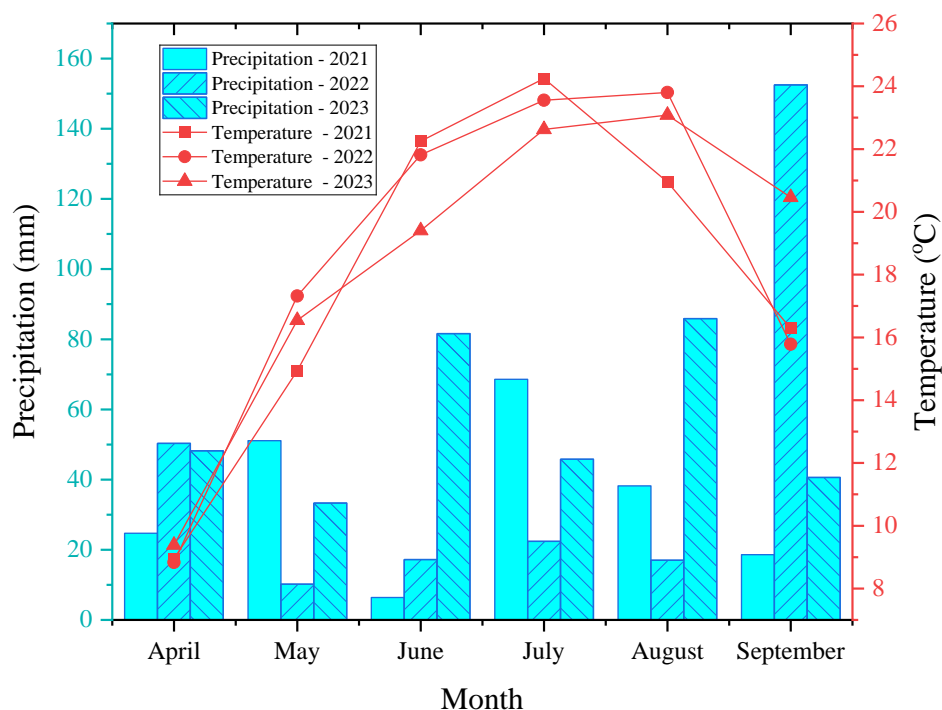


Figure 4 Average monthly temperature and total monthly precipitation in the growing seasons (Debrecen, 2021-2023).

Analysis of soil and subsequent interpretation was done according to the Hungarian New Fertilization Guidelines (Antal *et al.*, 1987). The soil type in the experimental site was leached chernozem with pH of 7.6. The concentration of plant nutrients in the soil was: nitrogen (5.3%), phosphorus (320.9 mg kg⁻¹), potassium (256.2 mg kg⁻¹), magnesium (451.6 mg kg⁻¹), sulphur (8.8 mg kg⁻¹), sodium (55.7 mg kg⁻¹), copper (2.0 mg kg⁻¹), manganese (60.1 mg kg⁻¹), and zinc (2.7 mg kg⁻¹) (Table 1).

Table 1 Chemical properties of chernozem soil at the experimental area (Debrecen, 2022)

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 ⁻¹)	16.3	Adequate
Organic matter (m m ⁻¹)	2.1	Weak
Nitrogen (mg kg ⁻¹)	5.3	Weak
Phosphorus (mg kg ⁻¹)	321.0	Good
Potassium (mg kg ⁻¹)	256.0	good
Magnesium (mg kg ⁻¹)	452.0	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

Interpretation: Based on the Hungarian New Fertilization Guidelines (Antal *et al.*, 1987).

3.2 Experimental design and treatments

The experiments were laid out in a randomized complete block design (RCBD) with two water management options i.e non-irrigated (NI) and precision drip irrigation (IR) except in the 2021 preliminary study that only had precision drip irrigation. Precision drip irrigation system was installed on 14th June 2021, 27th May 2022 and 12th June 2023 prior to the onset of drought and removed when maize plants attained physiological maturity. 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 liters/hour. If the probability of rain reached 80%, no irrigation was started. Irrigation was done between 9 pm to 5 am to reduce evapotranspiration. Total amount of irrigation water applied during the experimental period was 283.8 mm in the 2021 preliminary study, and 413.6 mm and 358.0 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 complex and chemical fertilizer treatments were designated as T1 (biostimulant from plant origin), T2 (zinc based foliar fertilizer) T3 (Molybdenum and boron based foliar fertilizer) and T4 (negative control). In terms of composition, T1 had organic matter (60 m/m%), amino acids; asparagine, arginine, glutamine, alanine, leucine, histidine, glycine, proline, methionine, isoleucine, phenylalanine, lysine, and cystine (21.67 m/m%), Saccharides; fructose, glucose, raffinose, sucrose, trehalose and cellulose (6.2 m/m%), fulvic acid (23.1 m/m%), nitrogen (8 m/m%), phosphorus (0.5 m/m%), potassium (0.2 m/m%), T2 had zinc, water soluble (10.2%), T3 had P₂O₅ (16.8%), K₂O (11%), boron (8.35%), and molybdenum (11%) and T4 (control). The treatments were applied once according to the manufacturer's recommended rates as shown in Table 2. A motorized pump was used to apply the treatments at V8 growth stage when leaves of maize plants attained large leaf surface area necessary for absorption of nutrients.

Table 2 Composition of treatments used in the study

Treatment	Application rate
T1	4 l ha ⁻¹
T2	1.5 l ha ⁻¹
T3	1.4 kg ha ⁻¹

3.3 General agronomic practices in the experiments

Preparation of the seedbed was done using the KongskildeVibro Master SGC/SQ 25 mounted seedbed cultivator (Kongskilde Agriculture, Albertslund, Denmark). Before sowing, on 27th April 2021 (for the preliminary study), soil was fertilized with 90 kg ha⁻¹ N, 23.0 kg ha⁻¹ CaO and 16.0 kg ha⁻¹ MgO. For 2022 season, on 11th

April 2022, soil was fertilized with 101.25 kg ha⁻¹ N, 26.25 kg ha⁻¹ CaO and 18.75 kg ha⁻¹ MgO. Similarly in on 31st March 2023 (2023 season), soil fertilizer application at the rate of 90 kg ha⁻¹ N, 23 kg ha⁻¹ CaO, and 16 kg ha⁻¹ and MgO was done. Sowing of FAO 420 maize hybrid seeds was conducted on the 2nd May 2022 and 28th April 2023 using a Gaspardo MTR 4 pneumatic precision seed drill (Gaspardo S.p.A., Campodarsego, Italy). The sowing depth was 5 cm with a seed rate of one seed/hole at the spacing of 76.2 × 18.2 cm hence an overall plant population of 72.100 per hectare. The choice of FAO 420 hybrid was due to its wide and large-scale cultivation and exceptional agronomic performance in Hungary. Weeding was done when necessary and no irrigation was applied to water stress plots even at the wilting point of the maize plants.

3.4 Data collection

3.4.1 Growth characteristics

The agronomic characteristics measured were plant height, stem diameter, The Soil Plant Analysis Development (SPAD), Normalised Difference Vegetation Index (NDVI), and Leaf Area Index (LAI). The measurements were taken at 12 leaf stage (V12), tasseling stage (VT) and kernel blister stage (R2) on ten randomly selected maize plants. Plant height was measured using a meter rule calibrated in centimetres (cm) while stem diameter was determined using a digital Vanier calliper calibrated in millimetres (mm). Chlorophyll assessments as SPAD and NDVI were determined using the Greenseeker and chlorophyll meter, respectively on the third last expanded leaf at vegetative stage and a leaf opposite the ear at reproductive stage. For precision of NDVI measurements, the distance between the Greenseeker was always maintained at 60 cm as recommended by the manufacturer. Chlorophyll is an indicator of the amount of nitrogen in the plant; hence, NDVI shows the health status of maize plants. LAI was measured using a Sunscan. In each plot, ten measurements were taken and average was calculated.

3.4.2 Measurement of chlorophyll fluorescence and photochemical yield

The parameters measured included steady-state fluorescence (F'), maximal fluorescence (F_M'), quantum photosynthetic yield (efficiency) of PSII (Φ PSII or YII) and electron transport rate (ETR). These measurements were taken are V2, VT and

R2 growth stages using Pulse Modulated Chlorophyll Fluorometer (PerkinElmer Inc., Waltham, MA, USA). During measurement, four maize plants were selected randomly in each treatment per replication (Yin *et al.*, 2011). Measurements were done on fully expanded new leaves of each randomly selected maize plants at vegetative stage and leaves opposite the ear at the reproductive stage (Simkó *et al.*, 2020). Before measurement (application of a saturation pulse), the leaves were dark adapted for 30 minutes (Hu *et al.*, 2023) and after, measurements were taken for F' , F_M' , Φ PSII and ETR. F' was the steady-state fluorescence signal under actinic light prior to saturation pulse, F_M' was maximal fluorescence under actinic light at steady state photosynthesis when all the reaction centers are closed. The difference in fluorescence between F_M' and F' ($F_M' - F'$) was the F_q' (Baker, 2008; Janka *et al.*, 2015). The Φ PSII was the quantum photosynthetic yield (efficiency) of PSII calculated as $(F_M' - F')/F_M'$ (Baker, 2008; Janka *et al.*, 2015; Hazrati *et al.* 2016). The ETR was an estimate of the number of electrons transported through photosystem II under steady-state photosynthetic conditions, calculated using the formula indicated in the manufacturer's protocol as well as in published literature (Flexas *et al.* 2002; Hu *et al.*, 2023) as:

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

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 am. and 1 pm.

3.4.3 Yield and yield components assessment

Data was collected on parameters: cob length (cm), cob weight (g), cob diameter (mm), number of seeds/cob, weight of seeds per cob (total seed weight), 1000 seed weight and yield per hectare. Ten cobs per treatment in each replication were randomly collected and processed using HALDRUP LT-35 laboratory thresher (HALDRUP GmbH, Ilshofen, Germany). Cob length was measured using a ruler calibrated in cm. Cob diameter (mm) as determined using a digital Vanier calliper. Cob weight was determined using an electronic weighing balance. Seeds/cob, weight of seeds per cob (total seed weight), and 1000 seed weight were

determined using the VSC-201 Vibrating Seed Counter (PLC Tuning Ltd - Hungary) and grain yield (t ha^{-1}) was calculated at moisture content of 14.5%.

3.4.4 Analysis of grain quality

The quality of grain in terms of protein content, oil content, starch content and moisture content were determined using Perten DA7250 NIR infrared grain analyser. The Perten DA7250 NIR infrared grain analyzer has the capacity to obtain 30 spectra at 5 nm interval. The samples were analysed in the range of 570-1100 nm (*Szabó et al., 2022*).

3.5 Statistical data analyses

The data was analysed using two-way ANOVA except for 2021 (preliminary study) where one-way ANOVA was used. Biostimulant and micronutrients means were separated using Tukey test at 5% probability level. The water regimes was compared using the t-test. The relationship between growth traits, chlorophyll fluorescence parameters, photochemical efficiency/yield, and yield and yield components was established using Pearson correlation. These analyses were done using OriginPro Graphing and Analysis Software (version 2024) and R software (version 4.3.2).

4. RESULTS AND DISCUSSION

4.1 Preliminary results of grain yield and quality response to biostimulant and micronutrients application in 2021 experiment

There were no significant ($p>0.05$) differences in cob length, cob weight, cob diameter, weight of 1000 seeds, yield per hectare except for seed number pc cob⁻¹. The cob length was 18.9, 19.9, 21.0 cm and 20.1 cm in T1, T2, T3 and T4, respectively. The cob weight was 225.3, 238.9, 279.1 and 251.3 g in T1, T2, T3 and T4, respectively while the cob diameter was 47.8, 48.6, 50.1 and 49.8 mm in T1, T2, T3 and T4, respectively. However, T3 significantly had higher seed number pc cob⁻¹ of 598 (Figure 5). The weight of seeds pc cob⁻¹ was 195.5, 206.2, 237.8, and 214.1 g in T1, T2, T3 and T4, respectively while the weight of 1000 seeds was 388.4, 371.9, 396.7, and 407.5 g in T1, T2, T3 and T4, respectively. The overall grain yield was 13.7, 14.4 and 16.6 t ha⁻¹ in T1, T2, and T3 and compared to 14.9 t ha⁻¹ in the control. Similarly, no significant ($p>0.05$) differences were recorded on grain quality attributes. Despite limited significant differences, there was a positive direction of effect by T2 and T3, except T1 where slight reduction was recorded. Generally, the effect of biostimulant on yield contradicts earlier studies. For example, *Gandhi et al.* (2023) indicated that seaweed extracts application proved highly effective and significantly improved maize grain yield. In particular, the yield improved by 19, 20 and 21% in *Kappaphycus alvarezii*, and *Sargassum cinctum* and *Gracilaria debilis* treatments, respectively. According to *Layek et al.* (2015), compared to the control (recommended dose of fertilizers), saps from seaweed significantly optimized grain yield by 10.5 - 13.1%.

In terms of grain quality, preliminary results showed limited effects by all the three treatments as compared to the control. All treatments had an oil content of circa 3.5% and starch content of 64%. The moisture content was 16.6% in T1 and T2, 17.3% in T3 compared to 17.0% in T4 (control). The protein content in all treatments was circa 5.5% except T3 that had 6.2%. Arising from these results, there was need to confirm these results. Confirmation studies are necessary to ensure repeatability and/or replicability of results or allow for reconstitution or further field studies. *Fontana et al.* (2024) underscored the need to confirm the biostimulant effects under pedoclimate conditions on different crops and full understanding of mechanisms of plant response as well as highlight the economic viability of their use (*Fontana*

et al., 2024). This is because of inconsistencies and variability of efficacy of different biostimulant products under field conditions (*Kálmán et al.*, 2023; *Eswaran and Sundaram*, 2024). Based on this, and the results of this preliminary study, there was a need to deepen the investigations to include growth and photochemical parameters under both precision irrigation and water stress conditions since preliminary study assessed only yield and yield components under precision drip irrigation.

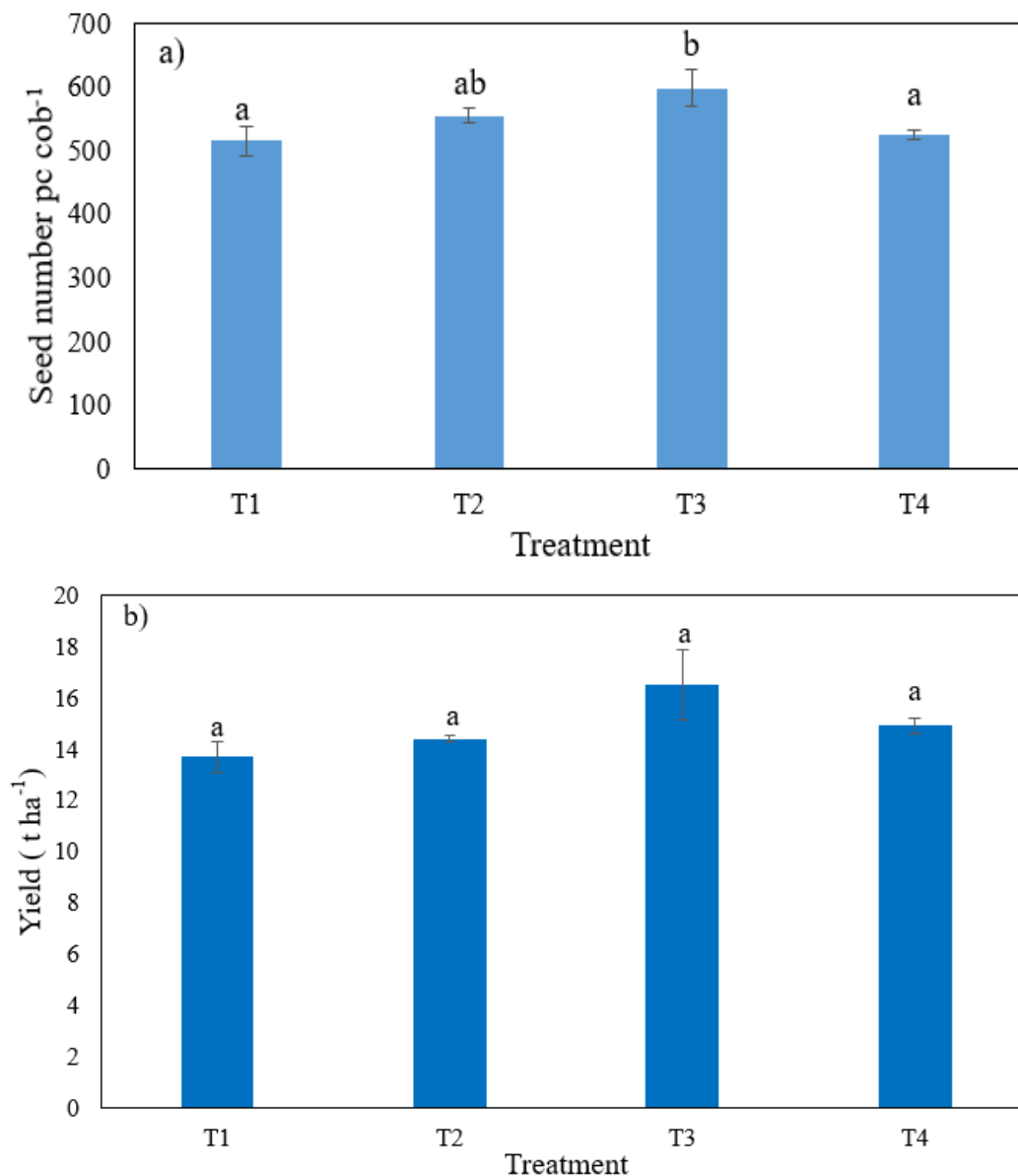


Figure 5 Number of seeds pc cob⁻¹ (a) and grain yield (b) of maize under biostimulant and micronutrient application. T1 – biostimulant, T2 and T3 – chemical fertilizers containing different micronutrients, T4 – control. Different lowercase letters indicate treatment significant differences by Tukey test at p<0.05. (Debrecen, 2021)

4.2 Results of 2022 and 2023 confirmation experiments

4.2.1 Differential response of agronomic parameters to precision drip irrigation and biostimulant and micronutrients foliar application

4.2.1.1 Plant height response to precision drip irrigation and biostimulant and micronutrients foliar application

Plant height was significantly ($p < 0.05$) higher under precision drip irrigation compared to non-irrigated conditions at V12, VT and R2 growth stages in both seasons (Table 3). In 2022 growing season, precision drip irrigation optimized plant height by 3.7%, 418.9%, and 75% at the V12, VT and R2 growth stages, respectively compared to non-irrigated conditions. Similarly, in 2023 growing season, precision drip irrigation optimized plant height by 10.6%, 4.5%, and 1.9% at the V12, VT and R2 growth stages, respectively compared to non-irrigated conditions. On average, plant height for both seasons was optimally higher under precision drip irrigation. This was attributed to supply of adequate moisture are the critical stages of maize growth. The results of this study corroborate with *Nawaz et al.* (2024) that full irrigation at 100% produced optimum plant height of 125 cm. Similarly, *Liu et al.* (2023) reported that significantly higher plant height under drip irrigation. Also, a medium irrigation quantity was reported to produce a 13.8% and 10.8% improvement in plant height at the filling stage, and 12.9% and 10.7% at the maturity stage (*Gu et al.*, 2021).

Table 3 Differential response of plant height to water management. (Debrecen, 2022-2023).

Water management	2022		
	V12	VT	R2
IR	102.8±1.34 ^a	153.6±3.99 ^a	266.9±9.61 ^a
NI	99.14±1.10 ^b	129.6±1.86 ^b	152.5±8.21 ^b
	2023		
IR	121.0±1.94 ^a	271.6±3.11 ^a	297.2±1.82 ^a
NI	109.4±2.02 ^b	259.9±1.55 ^b	291.6±1.15 ^b

The individual effects of biostimulant and micronutrients as well as the interactive effects between water management × biostimulant and micronutrients were not significantly ($p > 0.05$). In 2022 growing season, all treatments T1, T2 and T3 had plant height from 99.3 - 105.5 cm under precision drip irrigation and 97.3 - 100.1 cm under non-irrigated conditions at the V12 growth stage. At the VT growth stage,

T1, T2, T3, and the control had plant height of 156.6, 157.1, 158.1, and 142.8 cm under precision drip irrigation. Under non-irrigated conditions, T1, T2, T3, and the control had plant height of 135.0, 127.9, 126.6 and 129.0 cm, respectively. This shows improvement of height by 9.7, 10.0, and 10.7% by T1, T2 and T3 by precision drip irrigation. However, under non-irrigated conditions, only T1 improved plant height by 4.7% while T2 and T3 slightly reduced plant height by -0.9 and -1.9%, respectively. The trend of results of R2 growth stage in 2022 season, and all the three growth stages in 2023 growing season was the same. Generally, slightly low plant height was recorded in all treatments in 2022 growing season under water stress (Figure 6).

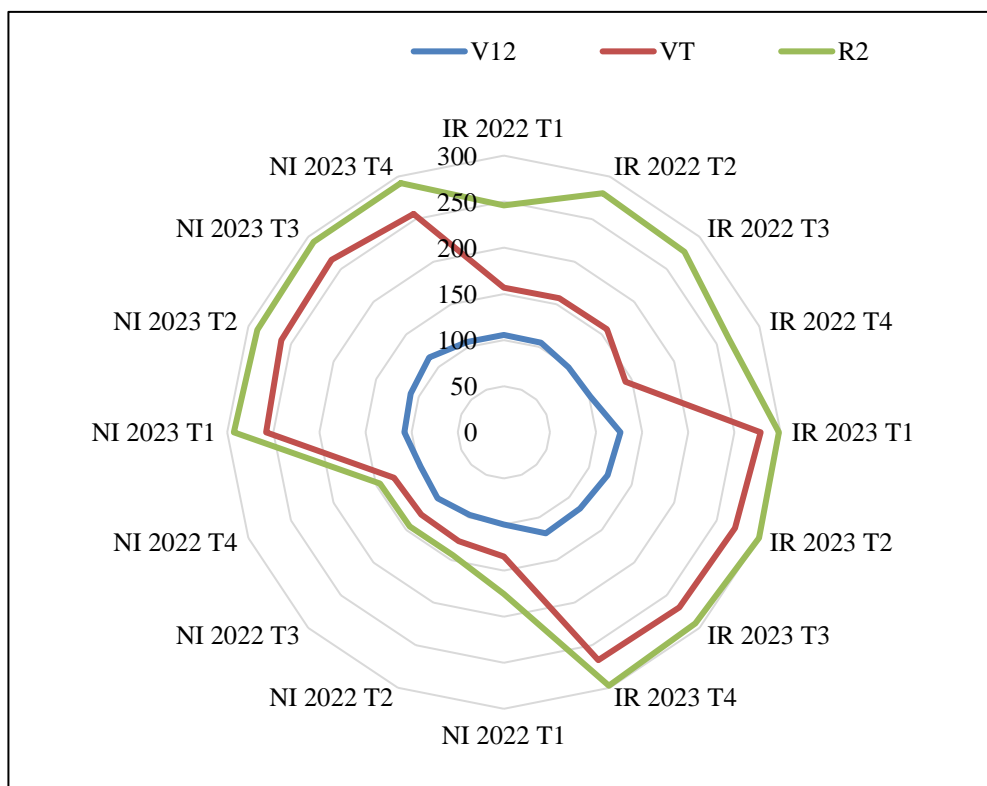


Figure 6 Radar chart of plant height for all treatments under precision drip irrigation (IR) and non-irrigated (NI) conditions in the three growth stages. (Debrecen, 2022-2023).

The t-test comparison of each treatment performance between the water management regimes showed that T1, T2 and T3 had better performance under precision drip irrigation. T1 significantly improved plant height by 5.4%, 16.0%, and 40.2% at V12, VT and R2 growth stages, respectively in the 2022 growing season and by 17.1%, 8.0%, and 3.5% in 2023 growing season. Similarly, T2 significantly optimized plant height by 8.2%, 22.8%, and 94.2% at V12, VT and R2 growth stages in the 2022 growing season, only at V12 and VT growth stages by 11.2 and 3.8% in

2023 growing season, respectively. The performance of T3 was optimal in all stages just like T1 except at the V12 stage in the 2023 growing season (Figure 7). A study *Nik-Khah et al. (2024)* reported significantly higher plant height from single foliar application of FeSO₄, ZnSO₄, MnSO₄ compared to the control. Similarly, *Khalafi et al. (2021)* recorded higher plant height of 280.0 cm from application of micronutrients zinc and iron compared to control treatments that had values ranging from 196.8 - 221.5 cm. In addition, the biostimulating effect of foliar application of an extract of *Elusine indica* on drought stress significantly enhanced plant height (*Han et al., 2024*). In addition, 1.5% concentration of *Sargassum boveanum* extract alleviated the deleterious effect of water stress on maize (*Alasvandyari et al., 2024*). Generally, the results of this study indicate the potential synergy between precision drip irrigation and T1, T2 and T3 in enhancing plant height of maize since their sole effects were suboptimal.

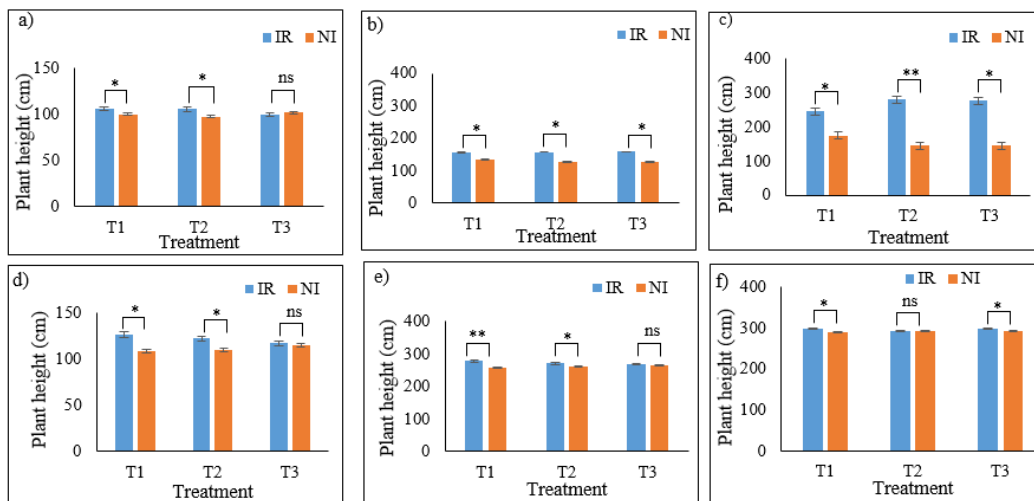


Figure 7 Comparative plant height performance of biostimulant and micronutrients treatments between precision drip irrigation (IR) and non-irrigated (NI) conditions at different stages of maize growth in the two seasons. a) V12 (season 2022), b) VT (season 2022) c) R2 (season 2022), d) V12 (season 2023), e) VT (season 2023), f) R2 (season 2023). T1 – biostimulant, T2 and T3 – chemical fertilizers containing different micronutrients, T4 – control. Significance levels: ns (not significant), * ($p < 0.05$), ** ($p < 0.01$). (Debrecen, 2022-2023).

4.2.1.2 Stem diameter response to precision drip irrigation and biostimulant and micronutrients foliar application

Stem diameter was significantly ($p < 0.05$) affected by water management in both seasons except at the V12 and VT growth stages in the 2022 growing season (Table 4). In 2022 growing season, precision drip irrigation significantly optimized stem

diameter by 9.4% at R2 growth stage, compared to non-irrigated conditions. In the 2023 growing season, precision drip irrigation optimized stem diameter by 8.2%, 6.6%, and 7.4% at the V12, VT and R2 growth stages, respectively compared to non-irrigated conditions. According to *Nawaz et al. (2024)*, irrigation improved stem diameter. Irrigation supply amount at high quantity was earlier reported to produce 8.5% improvement in stem diameter compared to lower irrigation at jointing stage (*Gu et al., 2021*).

Table 4. Response of stem diameter to water management (Debrecen, 2022-2023).

Water management	2022		
	V12	VT	R2
IR	21.3±0.26 ^a	23.8±0.44 ^a	23.6±0.52 ^a
NI	21.6±0.19 ^a	22.6±0.19 ^a	21.5±0.17 ^b
	2023		
	V12	VT	R2
IR	29.1±0.53 ^a	32.0±0.51 ^a	29.0±0.41 ^a
NI	26.9±0.37 ^b	30.0±0.53 ^b	27.0±0.34 ^b

The sole effect of the biostimulant was not significantly different. Progressively (Figure 8), positive effect of T1, T2 and T3 was evident in both seasons except under non-irrigated conditions in 2022 season where T1 and T3 had stem diameter reduction at the VT and R2 growth stages when compared to the control. Earlier, *Tariq et al. (2014)* showed that foliar application of zinc significantly optimized plant physiological parameters except for stem diameter, number of leaves, days to 50% tasselling, and plant height. Relatedly, higher stem diameter was recorded from the interactive effect of blended fertilizer (highest level) and 30% deficit irrigation (*Chinasho et al., 2023*). According to *Zou et al. (2024)*, declined in stem diameter resulted from reduction in fertilizer application level. Understanding the response of stem diameter to agronomic practices is of paramount importance. *Joy et al. (2023)* noted that stem diameter is a vital trait in maize production since it affects stem weight and plant height. In fact, larger stem diameter promotes higher plant height (*Joy et al., 2023; Yerli et al., 2023*). In this study, conspicuous effects were only evident under precision drip irrigation unlike the biostimulant and micronutrients.

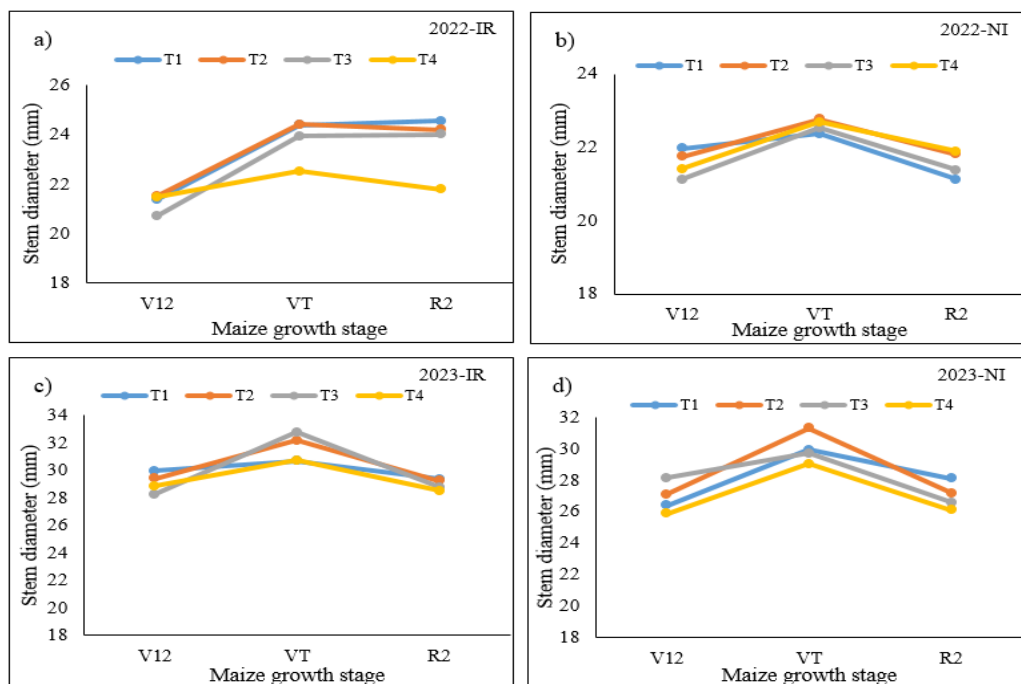


Figure 8 Progression of stem diameter of maize under precision drip irrigation and non-irrigated conditions at different maize growth stages. a) precision drip irrigation - season 2022, b) non-irrigated season 2022, c) precision drip irrigation - season 2023, d) non-irrigated season - 2023. T1 – biostimulant, T2 and T3 – chemical fertilizers containing different micronutrients. (Debrecen, 2022-2023).

4.2.1.3 Leaf area index (LAI) response to precision drip irrigation and biostimulant and micronutrients foliar application

Water management significantly affected LAI at the VT and V12 growth stages only in the 2022 growing season where precision irrigation significantly improved LAI (Table 5). In 2022 growing season, the LAI under precision drip irrigation was 4.5 and 4.3 compared to 1.9, and 2.0 under non-irrigated conditions at the VT and R2 growth stages of maize, respectively. This represents LAI optimization of 134.2% and 121.0 % by precision drip irrigation. Overall, on average, the LAI in the two seasons was high under precision drip irrigation.

Table 5 Differential response of Leaf area index to water management (Debrecen, 2022-2023).

Water management	2022		
	V12	VT	R2
IR	1.7±0.08 ^a	4.5±0.07 ^a	4.3±0.16 ^a
NI	1.6±0.04 ^a	1.9±0.07 ^b	2.0±0.08 ^b
	2023		
	V12	VT	R2
IR	2.8±0.10 ^a	4.9±0.05 ^a	5.0±0.12 ^a
NI	2.8±0.09 ^a	4.8±0.08 ^a	4.8±0.01 ^a

On the other hand, sole biostimulant complex and micronutrients application had no significant effect. However, in terms of overall average change in the direction of effects, it appeared that T1 had general positive effect under precision drip irrigation. On the other hand, T2 and T3 showed general reduction under non-irrigated conditions at the V12 growth stage (Figure 9). Earlier irrigation was reported to improve leaf area (Nawaz *et al.*, 2024). In fact, according to Liu *et al.* (2023), drip irrigation had higher LAI of 22.2% compared to conventional border irrigation. Gu *et al.* (2021) noted that medium irrigation improved LAI by was 22.6% and 16.7% compared to lower and high irrigation amounts.

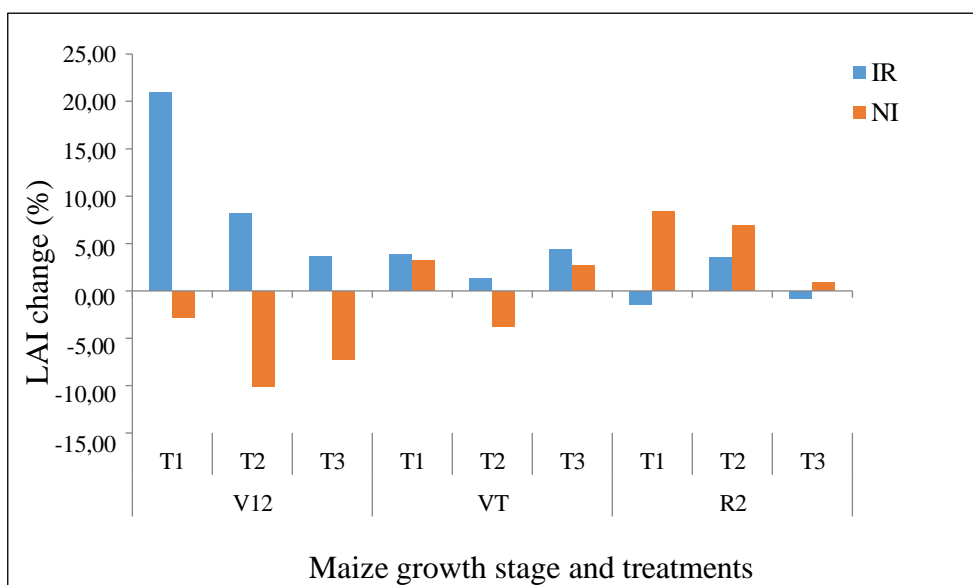


Figure 9 Average changes in LAI by biostimulant complex and micronutrients treatment under precision drip irrigation (IR) and non-irrigated (NI) conditions at different maize growth stages. a) V12 growth stage, b) VT growth stage, c) R2 growth stage. (Debrecen, 2022-2023).

The comparison of each treatment performance between the water management regimes by the t-test showed T1, T2 and T3 to have better performance under precision drip irrigation. In the 2022 growing season, T1 significantly enhanced LAI by 71.5%, 176.3%, and 106.9% at V12, VT and R2 growth stages, respectively. Similarly, T2 significantly improved LAI by 43.4%, 142.8%, and 118.7% in the three maize growth stages. Correspondingly, 63.3%, 127.6%, and 112.6% improvement was elicited by T3 at the three maize growth stages. However, in the 2023 growing season, only T2 and T3 at V12 and R2 stages significantly optimised LAI by 13.4% and 14.1%, respectively. The comparative LAI of each treatment at each growth stage between the two water regimes is shown in Figure 10. In this

study, relatively conspicuous effects were evident by T1, T2 and T3 under precision irrigation as opposed to their individual sole effects. Previously, it was reported that the combination of a blended fertilizer with full irrigation had higher LAI of 4.8 (Chinasho *et al.*, 2023). According to Yan *et al.* (2021), LAI was significantly affected by the amount of irrigation and fertilization levels. LAI can be used to identify the condition of crop growth and consequently to estimate crop water consumption and yield (Huang *et al.*, 2023). From the results of the t-test, it is clear that higher LAI under T1, T2 and T3 in 2022 season was attributed to high water use efficiency that enhanced rapid expansion of leaves.

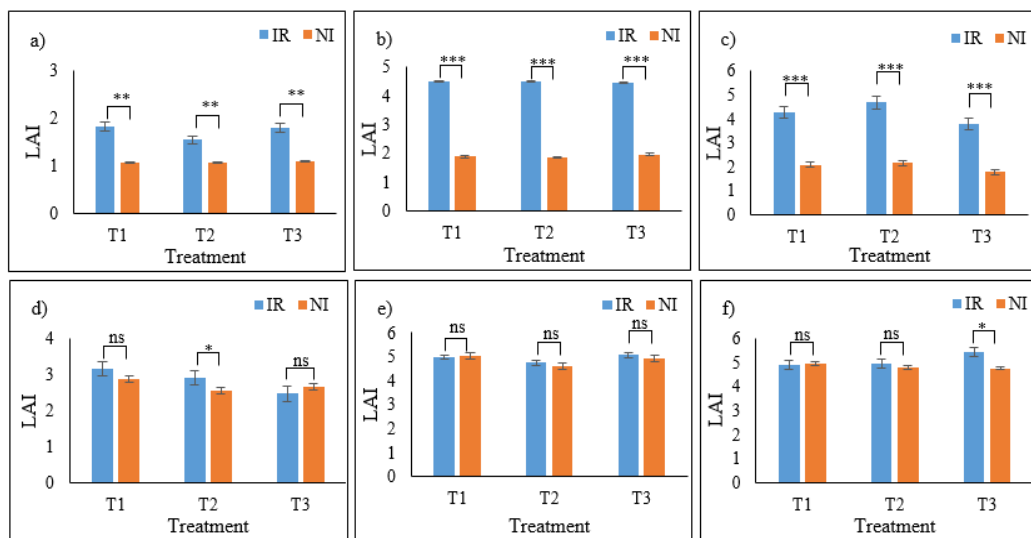


Figure 10 Comparative LAI performance of biostimulant and micronutrients treatments between Precision drip irrigation (IR) and non-irrigated (NI) conditions at different stages of maize growth in the two seasons. a) V12 (season 2022), b) VT (season 2022) c) R2 (season 2022), d) V12(season 2023), e) VT (season 2023), f) R2 (season 2023). T1 – biostimulant, T2 and T3 – chemical fertilizers containing different micronutrients, T4 – control. Significance levels: ns (not significant), *($p<0.05$), ***($p<0.01$), ****($p<0.001$). (Debrecen, 2022-2023).

4.2.1.4 Normalised difference vegetation index (NDVI) response to precision drip irrigation and biostimulant and micronutrients foliar application

Water management significantly ($p<0.05$) affected NDVI at the VT and R12 growth stages only in the 2022 growing season where precision irrigation significantly improved NDVI (Figure 11). In the 2022 growing season, the NDVI was significantly improved under precision drip irrigation which was 3.7% and 20.96% at the VT and R2 growth stages, respectively compared to non-irrigated conditions. Meanwhile, in the 2023 season growing season, though not significantly different, NDVI improved by 1.3% at the R2 growth stage compared to non-irrigated

conditions. Progressively, the NDVI decreased under both non-irrigated conditions and precision drip irrigation at R2 compared to other growth stages. According to *Tamás et al. (2023)*, during drought period, irrigation had a positive significant effect on NDVI. This agrees with the results of this study where NDVI was significantly improved by precision drip irrigation only in the 2022 season where extreme drought was evident.

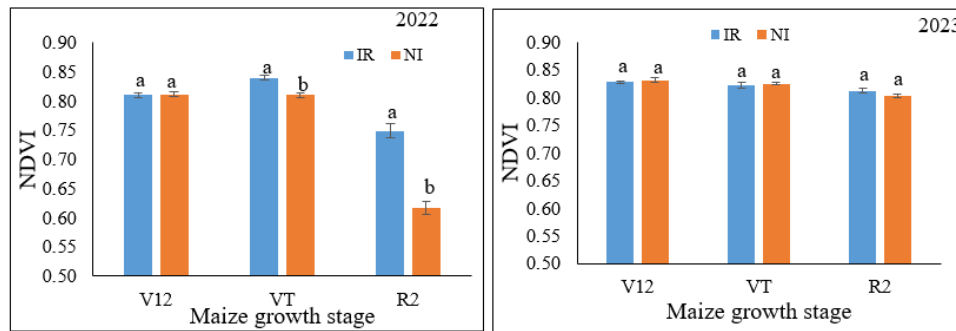


Figure 11 Response of NDVI to water management in 2022 and 2023 seasons at different growth stages of maize.

On otherhand, there were no significant differences ($p>0.05$) between the individual effects as well as the interactions between the biostimulant complex and micronutrient \times water management. However, on seasonal basis, all treatments had reduced NDVI in the 2022 growing season at the R2 growth stage (Figure 12). The comparative analysis by a t-test of T1, T2 and T3 performance between precision drip irrigation and non-irrigated conditions showed significant improvements only at the VT and R2 growth stages in the 2022 growing season. As such at the VT growth stage, only T2 elicited an improvement of NDVI by 6.3% while at the R2 growth stage, T1, T2 and T3 elicited an improvement of 26.0%, 22.6%, and 23.1%, respectively. In the 2023 the growing season, no significant improvements were recorded. The comparative NDVI of each treatment at each growth stage between the two water regimes is shown in Figure 13. *Balaout et al. (2022)* reported a positive effect of foliar nutrients application on the NDVI with a marked improvement of 8 % and 25 % at silking and physiological maturity stages, respectively. Similarly, another study revealed a higher effect of nitrogen fertilization on NDVI in the whole vegetative period of the experiment (*Tamás et al., 2023*). According to *Zelenák et al. (2022)*, the fact that maize plants exhibited high NDVI during the 12 leaf, silking and physiological maturity period, shows that biostimulant application enhanced the health of maize hybrids. This agrees with the results of this study where optimal effects by T1, T2 and T3 were seasonally

conspicuous at the VT and R2 growth stages.

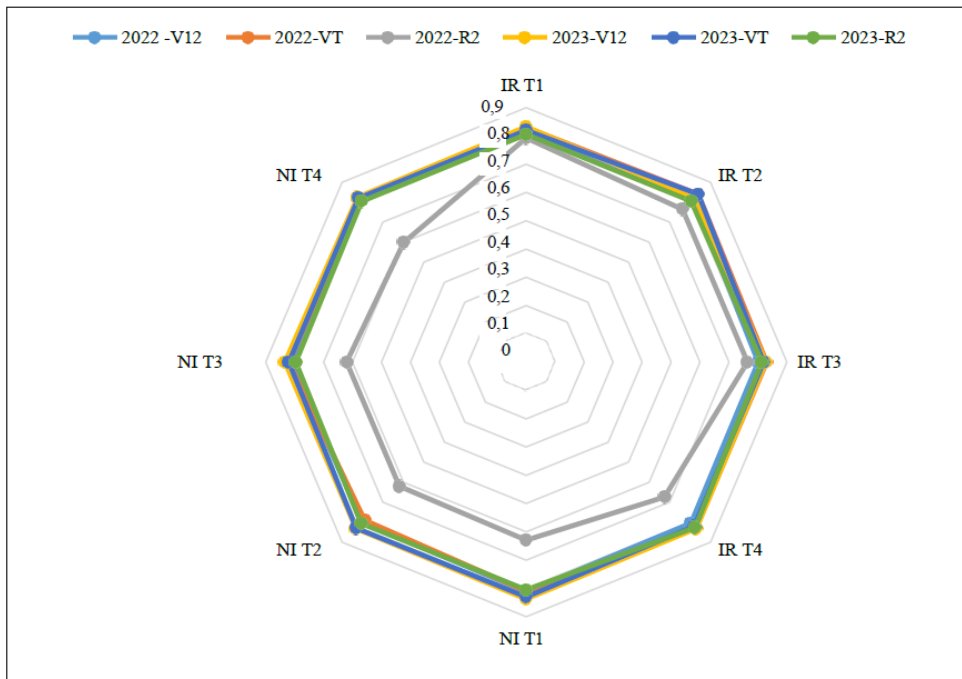


Figure 12 Seasonal overview of NDVI under water management, biostimulant complex and micronutrients at different maize growth stages in 2022 and 2023 seasons. IR – precision drip irrigation, NI – non-irrigated conditions. T1 – biostimulant, T2 and T3 – chemical fertilizers containing different micronutrients, T4 – control. (Debrecen, 2022-2023).

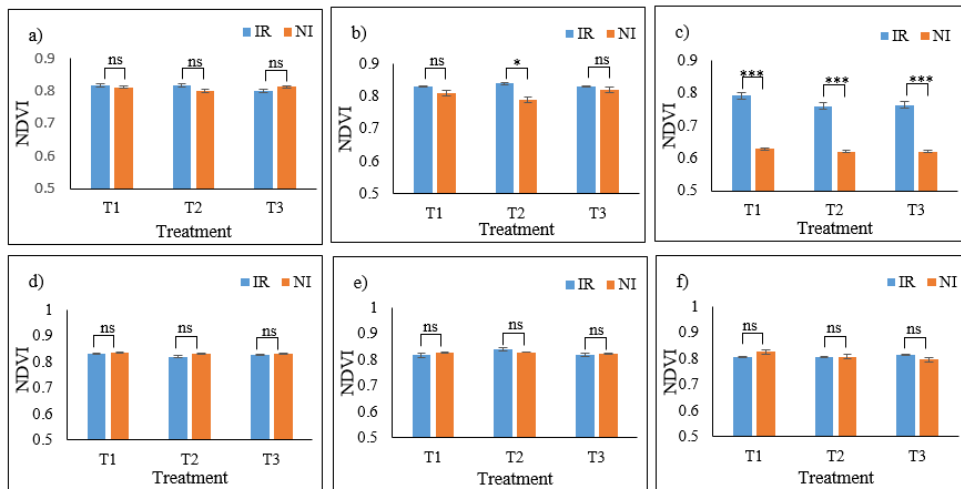


Figure 13 Comparative NDVI performance of biostimulant and micronutrients treatments between precision drip irrigation (IR) and non-irrigated (NI) conditions at different stages of maize growth in the two seasons. a) V12 (season 2022), b) VT (season 2022) c) R2 (season 2022), d) V12 (season 2023), e) VT (season 2023), f) R2 (season 2023). T1 – biostimulant, T2 and T3 – chemical fertilizers containing different micronutrients, T4 – control. Significance levels: ns (not significant), *($p < 0.05$), **($p < 0.01$), *** ($p < 0.001$). (Debrecen, 2022-2023).

4.2.1.5 Soil Plant Analysis Development (SPAD) response to precision drip irrigation and biostimulant and micronutrients foliar application

The SPAD was significantly ($p < 0.05$) affected by water management at V12 and R2 growth stages in both seasons (Figure 14). In the 2022 growing season, precision drip irrigation reduced SPAD by -7.7% at the V12 growth stage while an increase of 43.1% was registered at R2 growth stage as compared to non-irrigated conditions. However, in the 2023 growing season, precision drip irrigation optimized SPAD by 3.2% and 2.9% at the V12 and R2 growth stages, respectively compared to non-irrigated conditions. The reduction of SPAD in V12 could be result of the overlapping effect of excess moisture shortly after precision drip irrigation installation, and later improvement in the next stages was due to the right moisture content that corresponded with the requirement of maize in those stages. According to *Liu et al.* (2023), at flowering stage, SPAD was improved by 3.8% and by 3.7% at maturity stage by drip irrigation. According to *Chen et al.* (2024), irrigation treatment 945 m³/hm² had lower SPAD compared to only 1275 m³/hm² in 2019. However, in 2020, it registered increase of 3.96%, 5.12%, 11.10%, 12.64% and 19.90%, respectively, compared to the 1275 645, 315, 1 605 m³/hm² irrigation amounts and rain-fed (control) at tasseling and silking growth stages. Similarly, *Gu et al.* (2021) also reported that the quantity of irrigation significantly affected maize SPAD values (chlorophyll content) with medium irrigation being higher than lower and high irrigation by 13.8% at ear stage and up to 12.9% in the filling stage.

Generally, both the NDVI and SPAD as leaf greenness indicators were optimised by irrigation at the R2 growth stage in the 2022 growing season. The high severity of drought stress effects made treatment effects detectable. Earlier, it was reported that in agriculture, NDVI indicates greenness of the vegetation and vigor (*Ouhaddou et al.*, 2024) and SPAD value indicates the chlorophyll content of the plant hence higher SPAD show better plant nutrition (*Mumtaz et al.*, 2020). Therefore, irrigation effects on SPAD and NDVI were optimal in the season with high drought and temperature stress.

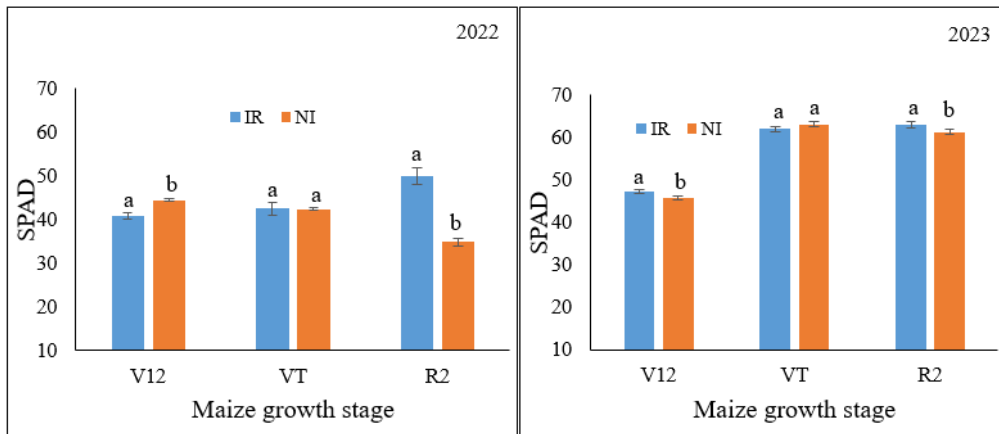


Figure 14 Effect of water management on SPAD at different stages of maize growth in 2022 and 2023 seasons.

The effect of biostimulant and micronutrients were only significant ($p = 0.04$) at the R2 growth stage in the 2023 growing where the SPAD values of T1, T2, and T3 were 64.5, 63.9, and 62.8 compared to 61.2 in the control. In this case, the treatments elicited SPAD improvements of 5.4%, 4.4%, and 2.6%. For other stages in both seasons, although positive effects was evident, the SPAD values under the biostimulant, and micronutrient treatments were not significantly different from the control. Earlier, *Balaout et al.* (2022) reported a positive effect of foliar nutrients application on the SPAD with a marked improvement of 12 % and 4 %, at 12-leaf and silking stages, respectively. Meanwhile, another study showed that the interactive effect of nitrogen fertilization and water management had a significant positive effect on SPAD (*Guo et al., 2021*). A study by *Zelenák et al.* (2022) showed a positive effect of biostimulant application on the SPAD values with the highest (62.8) value obtained in Ivola maize hybrid at silking stage. The comparison by the t-test of the biostimulant and micronutrients effects between the precision drip irrigation and non-irrigated conditions showed variation in the direction of effects. For example, in the 2022 growing season, there was a significant reduction in the SPAD values in T1, T2 and T3 treatments by -5.9%, -8.0%, and -8.1% under precision drip irrigation at the V12 growth stage. However, at the R2 growth stage, all the three treatments improved SPAD by 39.9%, 48.9%, and 41.8%. In the 2023 growing season, the significant improvements were only evident at the V12 stage where T1 and T2 optimized SPAD by 4.3% and 4.2%. The comparative SPAD values of each treatment at each growth stage between the two water regimes is shown in Figure 15.

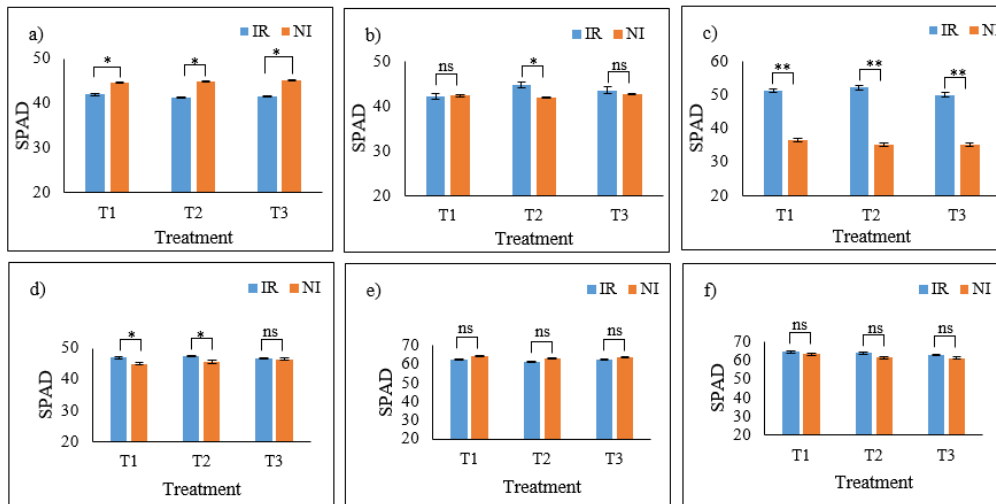


Figure 15 Comparative SPAD performance of biostimulant and micronutrients treatments between precision drip irrigation (IR) and non-irrigated (NI) conditions at different stages of maize growth in the two seasons. a) V12 (season 2022), b) VT (season 2022) c) R2 (season 2022), d) V12 (season 2023), e) VT (season 2023), f) R2 (season 2023). T1 – biostimulant, T2 and T3 – chemical fertilizers containing different micronutrients, T4 – control. Significance levels: ns (not significant), *($p < 0.05$), **($p < 0.01$), *** ($p < 0.001$). (Debrecen, 2022-2023).

4.2.2 Variation of chlorophyll fluorescence and quantum photochemical yield (photosynthetic efficiency) of maize due to water management, and foliar biostimulant and micronutrients application

There were significant ($p < 0.05$) differences on chlorophyll fluorescence parameters and quantum photochemical yield between precision drip irrigation and non-irrigated conditions in both seasons. The values of F_M' , F_q' , $\Phi PSII$, and ETR under precision drip irrigation at the V12 were lower compared to non-irrigated conditions in the 2022 growing season. However, a remarkable optimization effect at the VT stage was recorded by precision drip irrigation with 23.4%, 33.5%, 10.4%, and 10.4% improvement of F_M' , F_q' , $\Phi PSII$, and ETR, respectively. Later, conspicuous significant improvement of $\Phi PSII$ and ETR by 6.7% and 6.9%, respectively by precision drip irrigation was recorded at the R2 stage. In the 2023 growing season, the significant effects were evident at the VT and R2 growth stages. As such, the improvement of 11.5%, 15.2%, 2.9% and 3.8%, of F_M' , F_q' , $\Phi PSII$ and ETR were observed at the VT growth stage, and similar trend of effects were recorded at the R2 growth stage. This compares with earlier study by Wang *et al.* (2023a) showed that high-temperature + elevated water content of the soil treatments significantly enhanced variable fluorescence, maximal quantum efficiency, actual photosynthetic rate, and net photosynthetic rate, and reduced canopy temperature by 1- 3 °C. The report emphasized that elevating soil moisture content during grain

filling stage enhances photosynthesis and general adaptation to the warming influence of climate change in maize production (Wang *et al.*, 2023a).

In terms of overall progression of F , F_m' , F_q' , Φ PSII, and ETR across the three stages, F_m' , F_q' , Φ PSII, and ETR exhibited gradually increasing response while F showed notable reduction at the VT stage and increased by R2 stage (Figure 16). Increase in minimum fluorescence shows undesirable effects on photosynthesis (dos Reis *et al.*, 2019). However, for both seasons, F_m' , F_q' , Φ PSII, and ETR parameters exhibited opposite patterns. Although between the two water regimes, F_m' , F_q' , Φ PSII and ETR parameters were divergent, optimal water stress amelioration by precision drip irrigation was evident. Abiotic stresses including water stress undesirably affects the biosynthesis of chlorophyll and photosystem efficiency (Sharma *et al.*, 2020). In addition, drought or water stress causes reduction of electron transport rate (Zivcak *et al.*, 2013; Hu *et al.*, 2023) and hence irrigation is necessary to reverse the effects. Xu *et al.* (2019) also indicated that higher irrigation quotas significantly improved the actual and maximum photosynthetic efficiency of PSII compared to the control. With deficit water supply, a study by Chen *et al.* (2023), revealed that deficit irrigation at 75 % field capacity had higher photochemical quenching, effective quantum yield (Φ PSII), and electron transfer rate compared to 50 % field capacity and the control, while 50 % field capacity had higher maximal quantum efficiency (F_v/F_m) than 75 % field capacity. Generally, Jaswal and Sandal (2024) emphasized the importance of effective water supply and management through irrigation in mitigation the negative effects of reduced water content on maize productivity. Besides, just eradicating reduced moisture stress, irrigation also delays leaf senescence hence prolonging photosynthetic capacity of maize leaves (Wang *et al.*, 2023b). Therefore, improvement of chlorophyll fluorescence parameters and quantum photosynthetic yield validates the significance of precision irrigation in enhancing maize productivity under abiotic stress especially drought or water stress, and heat stress.

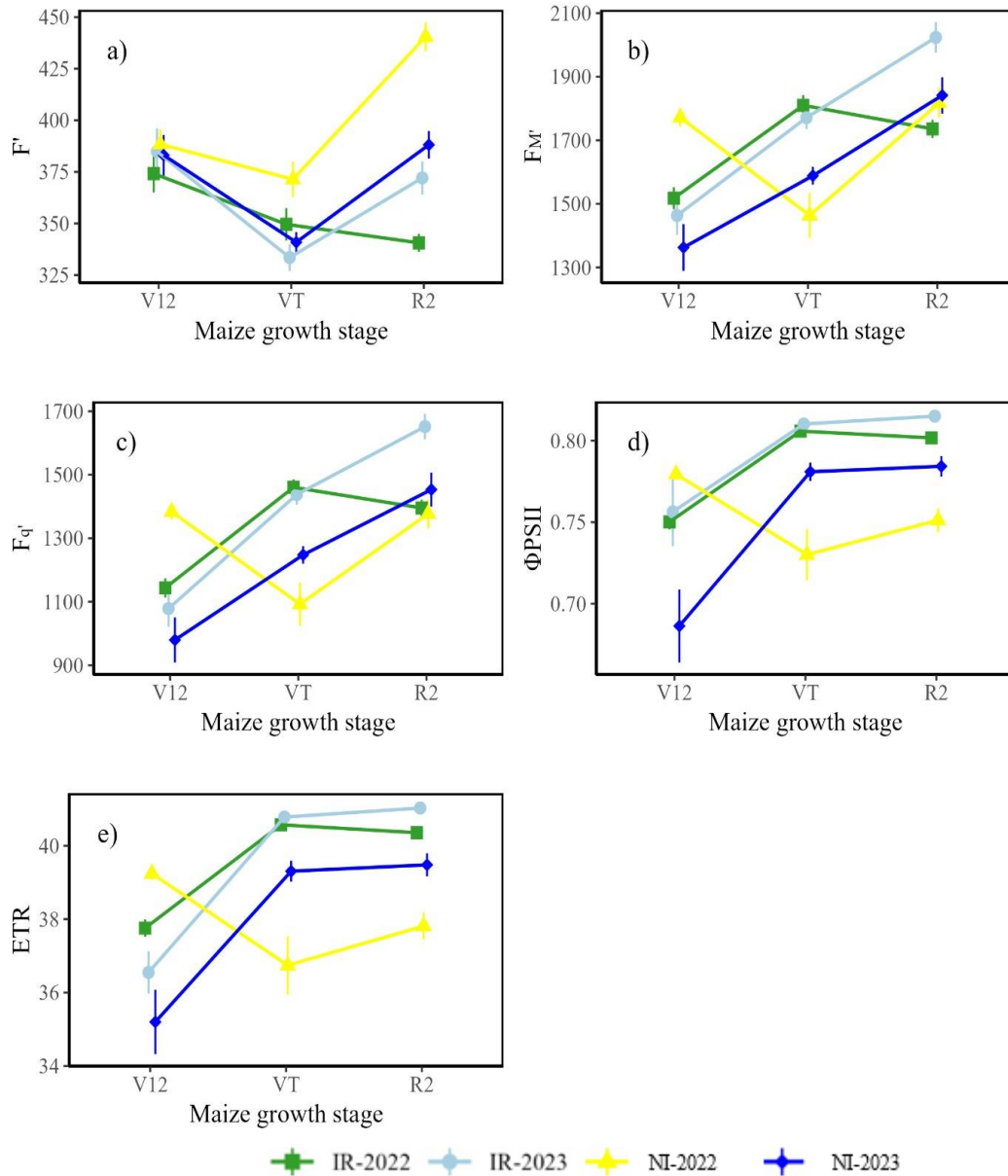


Figure 16 Chlorophyll fluorescence parameters and photochemical yield dynamics under precision irrigation (IR) and non-irrigated (NI) conditions at different maize growth stages in 2022 and 2023 growing seasons. a) F' (steady-state fluorescence signal under actinic light prior to saturation pulse), b) F_M' (maximal fluorescence under actinic light at steady state photosynthesis when all the reaction centers are closed), c) F_q' (fluorescence difference between F_M' and F'), d) Φ_{PSII} (quantum photosynthetic yield (efficiency) of photosystem II, e) ETR (electron transport rate). Vertical bars indicate the standard error.

The variation in F' , F_M' and F_q' in reaction to foliar biostimulant as well as micronutrient treatment was only conspicuous in some growth stages. However, there were no significant ($p>0.05$) effects on F' , and as such in all the stages, the recorded treatment values of F' ranged from 320 to 410 under non-irrigated conditions and from 335 to 435 under precision drip irrigation. Meanwhile, the effects on F_M' were significantly different ($p<0.05$) at VT and R2 stages of growth under the two water management regimes in seasons 2022 and 2023. Therefore, under non-irrigated conditions at the R2 growth stage in season 2022, considerably higher F_M' values of 1870, 1833 were recorded in T1 and T2 compared to 1795 and 1773 in T3, and T4 (control) while F_M' values ranged from 1659 – 1733 under precision drip irrigation since the treatments did not significantly differ. On the otherhand under precision drip irrigation in the growing season 2023, T1, T2 and T3 treatments had higher F_M' of 1887, 1730 and 1831 compared to 1636 in the control. Contrary, under non-irrigated conditions, T1 had F_M' of 1670 which was significantly different (higher) from 1512, 1569 and 1603 in T2, T3 and the control. Accordingly, similar trend of F_M' was observed in the R2 growth stage. Similarly, for the parameter F_q' , were significant ($p<0.05$) at R2, and VT and R2 stages of growth in the 2022 and 2023 growing seasons. Therefore, at the R2 growth stage in 2022 season, higher F_q' value of 1413 was recorded under T1 compared to 1397, 1343 and 1355 under T2, T3 and the control, respectively, under non-irrigated conditions while no significant differences were observed under precision drip irrigation. Meanwhile, at the VT growth stage under precision drip irrigation in the 2023 growing season, T1, T2, and T3 had higher F_q' of 1544, 1403, and 1491 as compared to the control (1313). Equally, the treatments T1, T2, and T3 under non-irrigated conditions had higher F_q' of 1327, 1177 and 1230 as compared to the control (1257). At the R2 growth stage, higher F_q' of 1721 was maintained by T1 compared to T2 (1539), T3 (1681) and the control (1665). Correspondingly, higher (1530) F_q' was maintained by T1 compared to T2 (1269), T3 (1581) and the control (1434) under non-irrigated conditions. The t test analysis of the effect of T1-T3 on F' and F_M' between the water management regimes are summarized in Figure 17 and 18.



Figure 17 Comparative F' performance of biostimulant and micronutrients treatments between precision drip irrigation and non-irrigated (NI) conditions at different stages of maize growth in the two seasons. a) V12 (season 2022), b) VT (season 2022) c) R2 (season 2022), d) V12 (season 2023), e) VT (season 2023), f) R2 (season 2023). T1 – biostimulant, T2 and T3 – chemical fertilizers containing different micronutrients, T4 – control. Significance levels: ns (not significant), *($p < 0.05$), **($p < 0.01$). (Debrecen, 2022-2023). Uncompared treatments were not significantly different.

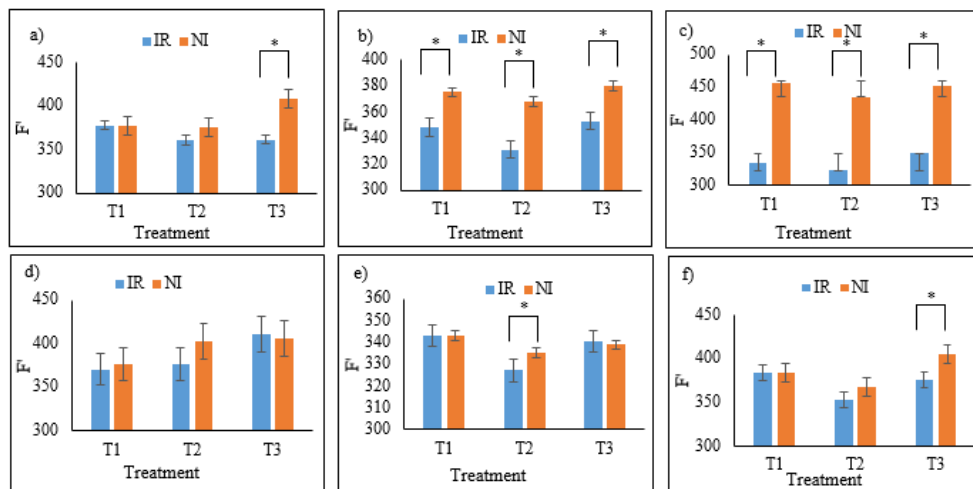


Figure 18 Comparative FM' performance of biostimulant and micronutrients treatments between precision drip irrigation and non-irrigated (NI) conditions at different stages of maize growth in the two seasons. a) V12 (season 2022), b) VT (season 2022) c) R2 (season 2022), d) V12 (season 2023), e) VT (season 2023), f) R2 (season 2023). T1 – biostimulant, T2 and T3 – chemical fertilizers containing different micronutrients, T4 – control. Significance levels: ns (not significant), *($p < 0.05$), **($p < 0.01$). (Debrecen, 2022-2023). Uncompared treatments were not significantly different.

For Φ PSII, biostimulant and micronutrients individual effects in each water management regime were not significantly different, albeit the existence of significant interactive differences between water management \times foliar biostimulant and micronutrients application at VT as well as R2 growth stages, respectively. In season 2022, at the VT growth stage under drip precision irrigation, T1 had significantly higher Φ PSII as compared to T2 and T3 under non-irrigated condition. Also, T3 improved Φ PSII under precision irrigation when compared with the value recorded under non-irrigated condition. Correspondingly, at R2 growth stage, higher values of Φ PSII were recorded in all treatments T1, T2 and T3 as compared to the values under non-irrigated condition. In addition to the above, T1, T2 and T3 under precision drip irrigation in the growing season 2023 had higher Φ PSII values as compared to non-irrigated condition (Figure 19). *Chen et al. (2016)* emphasized the importance of correct fertilizer (nutrients) application improving photosynthetic efficiency and reducing photodamage under water or drought stress. *Wu et al. (2013)* recommended that nitrogen delayed under water logging conditions enhance photosynthetic efficiency and reduces photodamage of maize seedlings. According to *Abd El-Mageed et al. (2021)*, foliar application of silicon improved stomatal conductance and photosynthetic efficiency signifying silicon ability to enhance drought tolerance by maize. On the same note, foliar Zn-lysine application mitigated water stress effect on photosynthetic efficiency, water relations and yield of maize cultivars (*Shehzad et al., 2022*). *Wang et al. (2009)* noted that although zinc application did not improve drought stress adaptation by maize, it improved photosynthetic rate under irrigated conditions due to increased stomatal conductance and consequently intercellular CO₂ concentration. In this study, although the individual effects within each water management regime were suboptimal, zinc application exhibited positive on both quantum photosynthetic yield and electron transport rate especially in the VT and R2 growth stages of maize. Similarly, the positive effect of biostimulant application on both quantum photosynthetic yield and electron transport rate suggest possibilities achieving optimum effect if applied in combination with other nutrient inputs. This is because although the biostimulant used in being a complex lacked some micronutrients including zinc, boron, manganese, iron and others, which are important in maize nutrition. In this study, boron and molybdenum (T3) produced a positive effect. Earlier, a review by *Haque (2024)* showed that application

of boron enhances leaf area, which has a direct nexus with interception of photosynthetically active radiation resulting in higher photosynthetic efficiency and biomass accumulation. Additionally, besides improving photosynthetic capacity of maize, boron also ameliorates stress especially under water deficit conditions (Naeem *et al.*, 2017). This strongly suggests existence of possibilities to improve the efficacy of these nutrient inputs used in this study on maize photosynthetic capacity through combined application. Earlier, Chen *et al.* (2023) revealed that sole application of chitin had higher photochemical quenching and F_v/F_m compared to other chemical treatments. Luiz Piati *et al.* (2023) noted reduced effect of biostimulants under higher doses in one season, hence emphasized the need for combined application and testing of application times. However, generally, the authors showed that foliar biostimulant application boosted and/or stimulated physiological activity in maize. However, Gajula *et al.* (2025) recorded minimal synergistic benefits between combined nitrogen levels and biostimulant application. Overall, Privantu *et al.* (2023) echoed that biostimulants boosted maize physiological performance under both abiotic stress (water stress) and optimal environmental conditions.

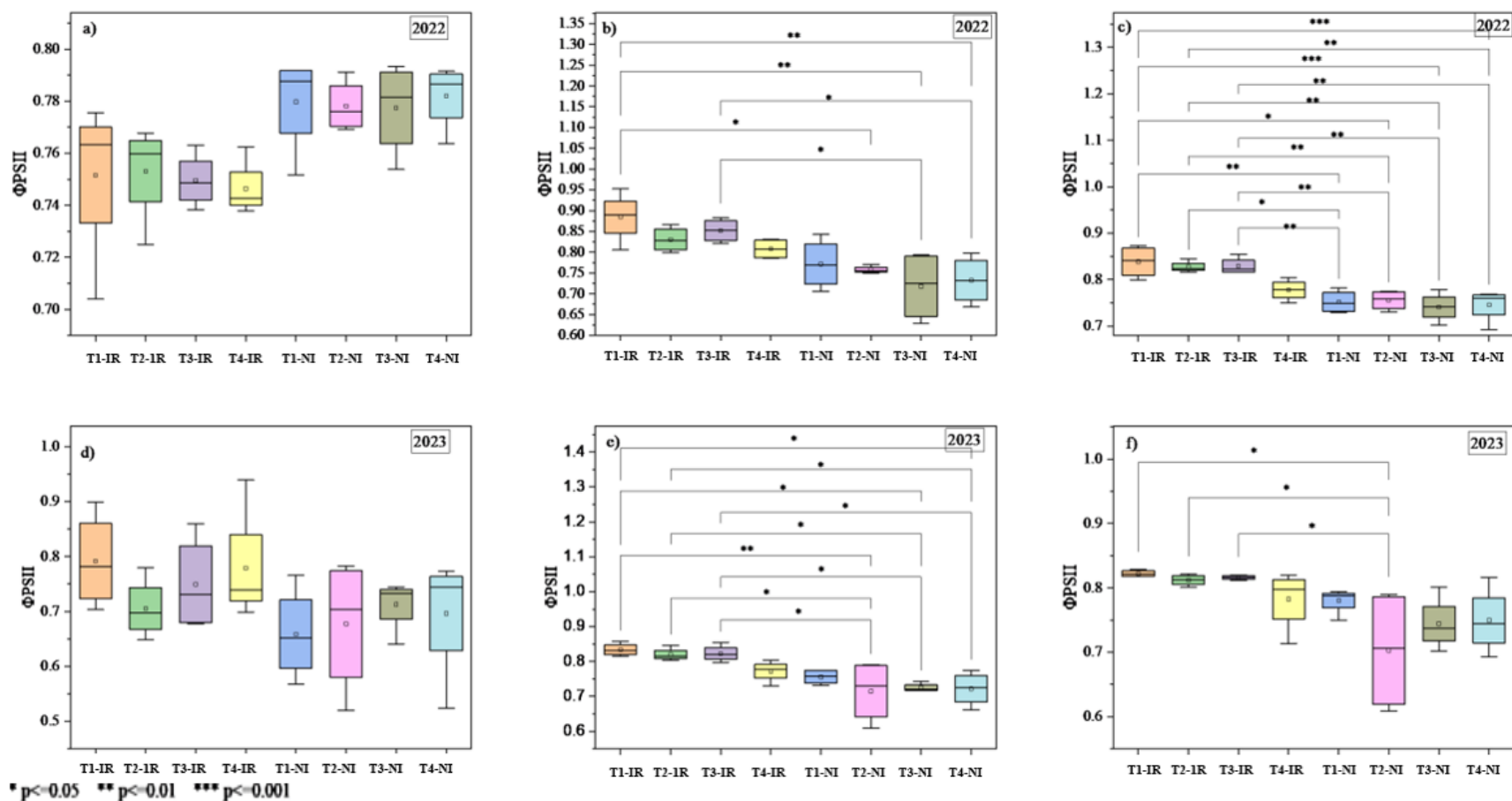
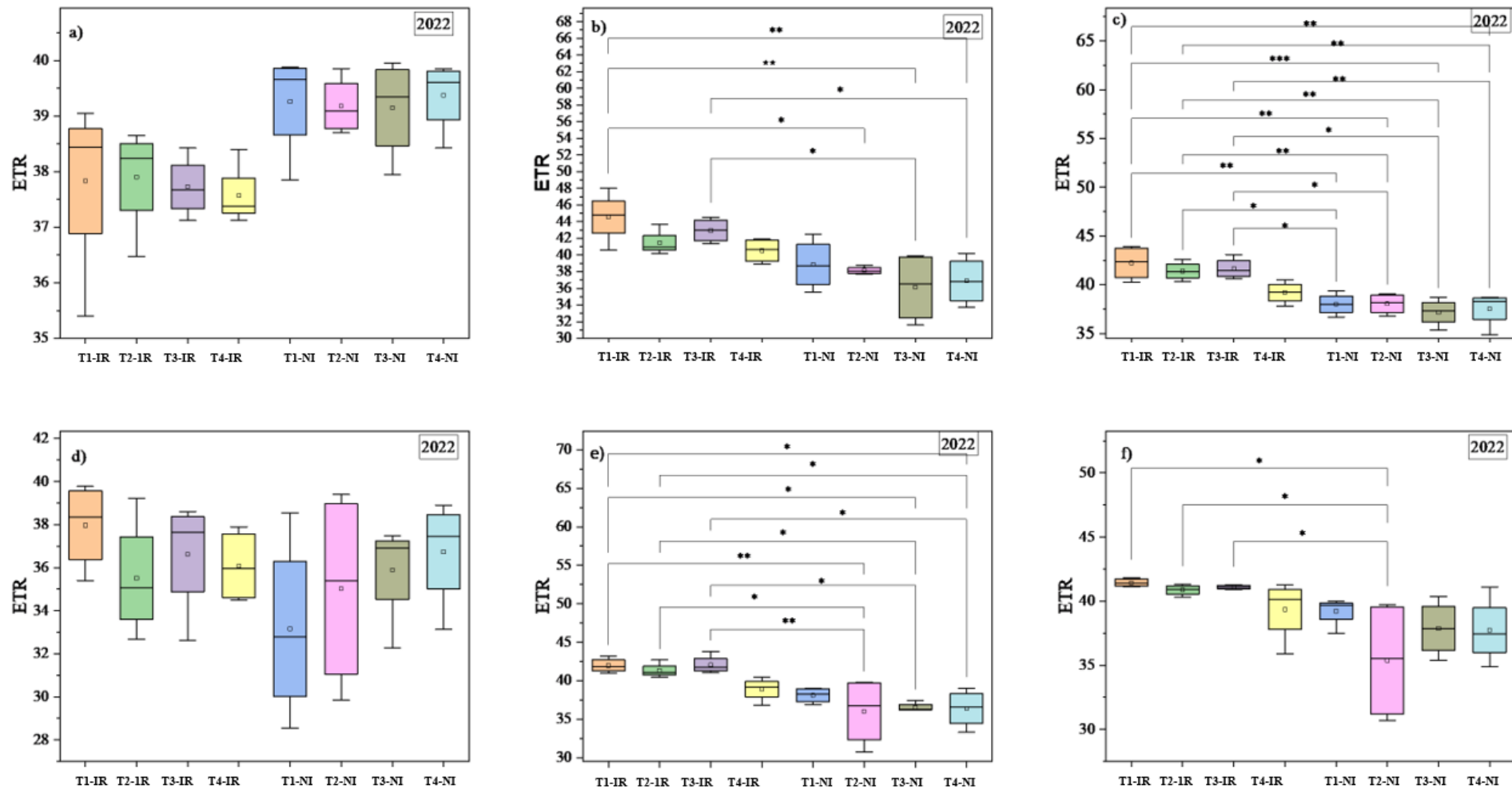


Figure 19 Quantum photosynthetic yield (efficiency) of photosystem II (Φ_{PSII}), under biostimulant and micronutrient treatments for precision drip irrigation (IR) and non-irrigated (NI) conditions at different stages of maize growth. a) V12 (season 2022), b) VT (season 2022) c) R2 (season 2022), d) V12 (season 2023), e) VT (season 2023), f) R2 (season 2023). T1 – biostimulant, T2 and T3 – chemical fertilizers containing different micronutrients, T4 – control. Significance levels: ns (not significant), * (p<0.05), ** (p<0.01), *** (p<0.001). Uncompared treatments did not differ significantly. (Debrecen, 2022-2023).

Similarly, the direction of response of ETR was similar to Φ PSII, where interactive effects showed significantly higher ETR in T1, T2, and T3 treatments under precision drip irrigation as compared to non-irrigated conditions. Most importantly, T1 maintained a higher ETR at the VT and R2 growth stages in both seasons (Figure 20). Overall, the biostimulant and micronutrients foliar application optimized photochemical yield under precision drip irrigation compared to non-irrigated conditions (Figure 21, 22). This corroborates with results of earlier studies. For example, a study showed that foliar Zn-lysine application mitigated water stress effect on photosynthetic efficiency, water relations and yield of maize cultivars (Shehzad *et al.*, 2022). Wang *et al.* (2009) noted that although zinc application did not improve drought stress adaptation by maize, it improved photosynthetic rate under irrigated conditions due to increased stomatal conductance and consequently intercellular CO₂ concentration. For biotimulants, dos Reis *et al.* (2019) discovered that the derivatives from chitosan enhanced photosynthetic activity and electron transport yield in PSII. Similarly, the biotimulating effect of moringa extracts improved fluorescence parameters under irrigation (Abidi *et al.*, 2023). Additionally, Chen *et al.* (2023) revealed that sole application of soil-treated chitin had higher photochemical efficiency compared to other chemical treatments. In this study, biostimulant complex was rich in amino acids, nitrogen and fulvic acid, which positively affected the photosynthetic activity. Nitrogen promotes efficient operation of the photosynthetic systems by increasing the chlorophyll content and enzymatic activity (Nasar *et al.* 2022; Nematpour and Eshghizadeh, 2023). Besides, Niu *et al.* (2023) explained that amino acid glycine betaine plays a critical role in regulating plants growth and development processes. In fact, optimum amino acid biostimulants application exhibits evidence of sustaining agricultural production (Cheng *et al.*, 2024). In general, this study shows that the effectiveness of the biostimulant and micronutrients increases with precision supply of adequate water. In other words, optimum agronomic efficiency from exogenously applied nutrients is achievable through adequate moisture supply at the nutrient and water sensitive stages of maize growth.



* $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$

Figure 20 Electron transport rate (ETR) under biostimulant and micronutrient treatments for precision drip irrigation (IR) and non-irrigated (NI) conditions at different stages of maize growth. a) V12 (season 2022), b) VT (season 2022) c) R2 (season 2022), d) V12 (season 2023), e) VT (season 2023), f) R2 (season 2023). T1 – biostimulant, T2 and T3 – chemical fertilizers containing different micronutrients, T4 – control. Significance levels: ns (not significant), * ($p < 0.05$), ** ($p < 0.01$), *** ($p < 0.001$). Uncompared treatments did not differ significantly. (Debrecen, 2022-2023).

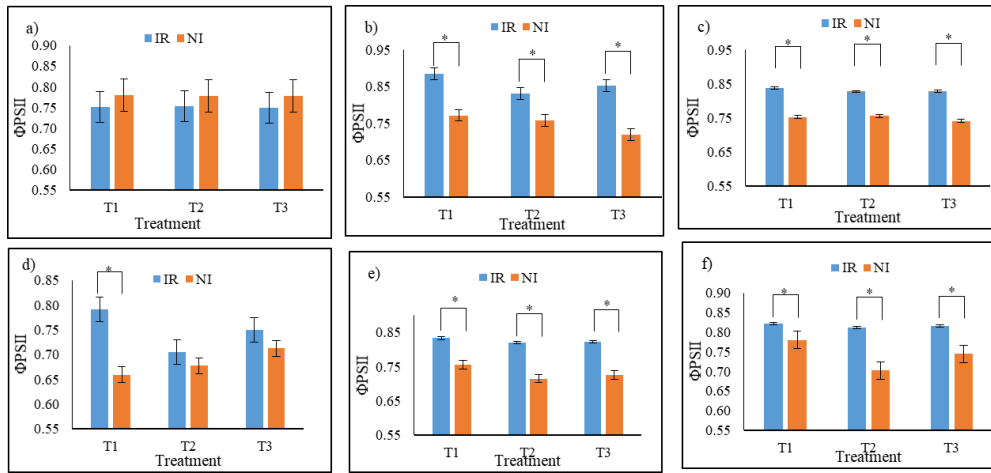


Figure 21 Comparative Φ PSII performance of biostimulant and micronutrients treatments between precision drip irrigation (IR) and non-irrigated (NI) conditions at different stages of maize growth in the two seasons. a) V12 (season 2022), b) VT (season 2022) c) R2 (season 2022), d) V12 (season 2023), e) VT (season 2023), f) R2 (season 2023). T1 – biostimulant, T2 and T3 – chemical fertilizers containing different micronutrients, T4 – control. Significance levels: ns (not significant), *($p < 0.05$), **($p < 0.01$). (Debrecen, 2022–2023). Uncompared treatments were not significantly different.

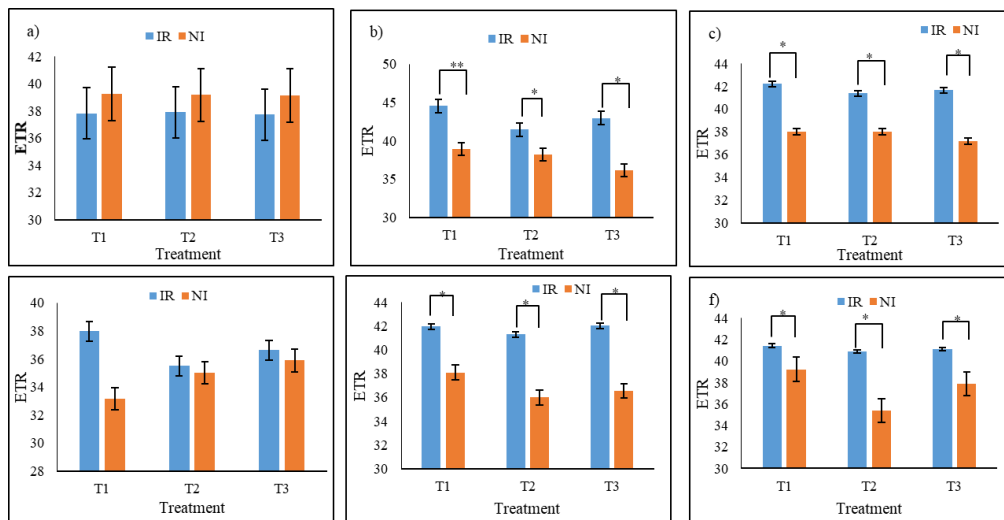


Figure 22 Comparative ETR performance of biostimulant and micronutrients treatments between precision drip irrigation and non-irrigated (NI) conditions at different stages of maize growth in the two seasons. a) V12 (season 2022), b) VT (season 2022) c) R2 (season 2022), d) V12 (season 2023), e) VT (season 2023), f) R2 (season 2023). T1 – biostimulant, T2 and T3 – chemical fertilizers containing different micronutrients, T4 – control. Significance levels: ns (not significant), *($p < 0.05$), **($p < 0.01$). (Debrecen, 2022–2023). Uncompared treatments were not significantly different.

4.2.2 Water management and biostimulant and micronutrients foliar application effect on yield components

4.2.3. 1 Number of seeds per cob, weight of 1000 seeds and cob weight

The cob weight, 1000 seed weight, and seed number per cob were significantly ($p < 0.05$) affected by water management. The seed number per cob was 538 under precision drip irrigation compared to 164 under non-irrigated conditions in growing season 2022. This shows that precision drip irrigation improved seed number per cob by 228.1%. Similarly, in 2023 growing season, precision drip irrigation had 506 seeds per compared to 468 under non-irrigated conditions. This indicates precision drip irrigation to optimize seed number per cob by 8.1% (Figure 23). For the case of biostimulant and micronutrients, their individual effects were not significantly different in under each water management regime. As such, treatments T1, T2 and T3 had 573, 529 and 571 seeds per cob compared to 478 in the control under precision drip irrigation while under non-irrigated conditions, T1, T2 and T3 had 142, 194 and 177 seeds per cob compared to 144 in the control. This trend was repeated in the 2023 growing season. On the same note, for weight of 1000 seeds, 363.3 and 534.7 g were recorded under precision drip irrigation compared to 268.3 and 505.2 g under non-irrigated conditions in the 2022 and 2023 growing seasons, respectively. This shows improvement of 1000 seed weight in the two years by 35.3 and 5.8%, respectively (Figure 24).

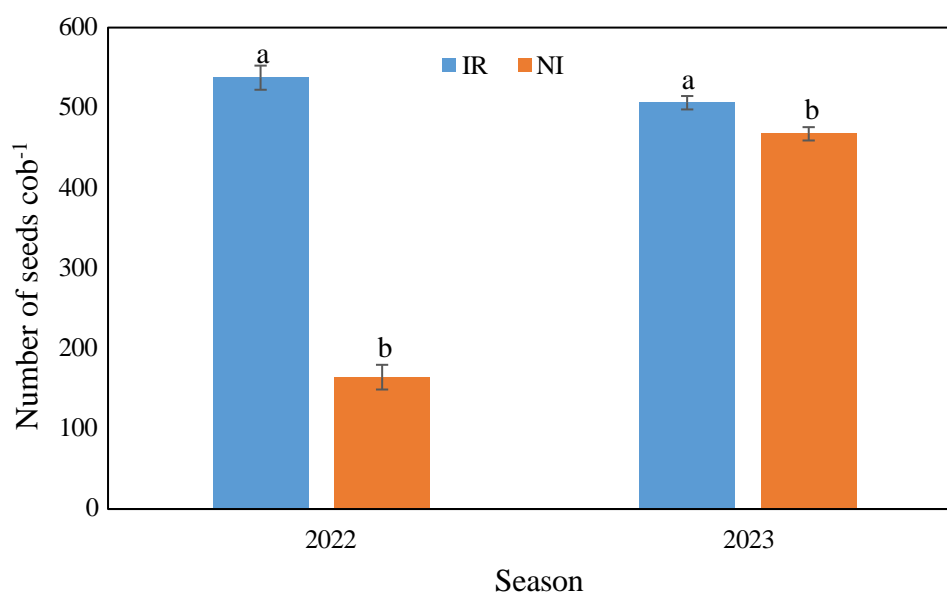


Figure 23 Seed number cob⁻¹ (a) as affected by water management in 2022 and 2023 seasons. . IR – precision drip irrigation, NI- non-irrigated conditions.

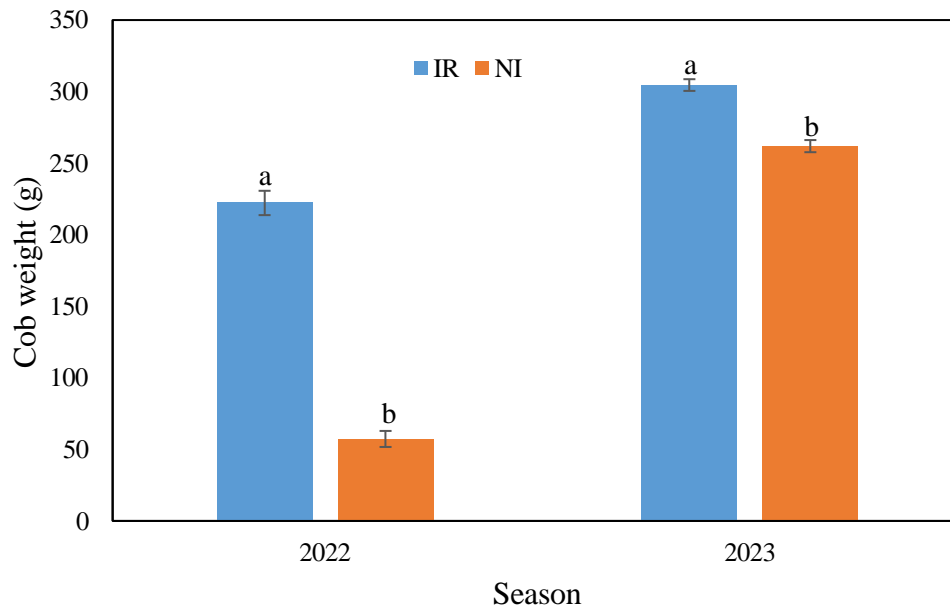


Figure 24 Cob weight as affected by water management in 2022 and 2023 seasons. IR – precision drip irrigation, NI- non-irrigated conditions.

The interaction between water management regimes \times biostimulant and micronutrients was significant only in the 2023 growing season. As such, T2 had the higher performance under precision drip irrigation with 1000 seed weight of 569.9 g (Figure 25). According to *Zelenák et al.* (2022), foliar biostimulants application improved 1000 seed weight by 22.8% and 6% in the Ivola and Mv Marfi maize hybrids, respectively. Relatedly, *Chinasho et al.* (2023) showed that blended fertilizer application produced higher performance in terms of seed number per cob and 1000 seed weight. For the case of cob weight, precision drip irrigation had 222.2 and 304.6 g cob weight, which was significantly higher than 57.2 and 261.9 g under water stress. Earlier study showed that irrigation quantity did not significantly affect yield components, though medium irrigation had heavier cobs which were 30.8% and 4.2% heavier than lower and higher irrigation quantity treatments, respectively (*Gu et al., 2021*). Meanwhile the biostimulant and micronutrients individual effects within each water regime were not significantly different. However, when the treatment effects between the two water regimes were compared, under precision drip irrigation, T1, T2 and T3 had cob weight of 237.8, 226.0, and 230.0 g compared to 49.8, 68.4 and 63.2 g under non-irrigated conditions in the 2022 growing season. In the 2023 growing season, T1, T2 and T3 had cob weights of 316.4, 310.8, and 300.8 g under precision drip compared to 260.7, 266.18 and 274.9 g under non-irrigated conditions, respectively. This implies

that the efficacy of T1, T2 and T3 to improve cob weight is promising under precision drip irrigation.

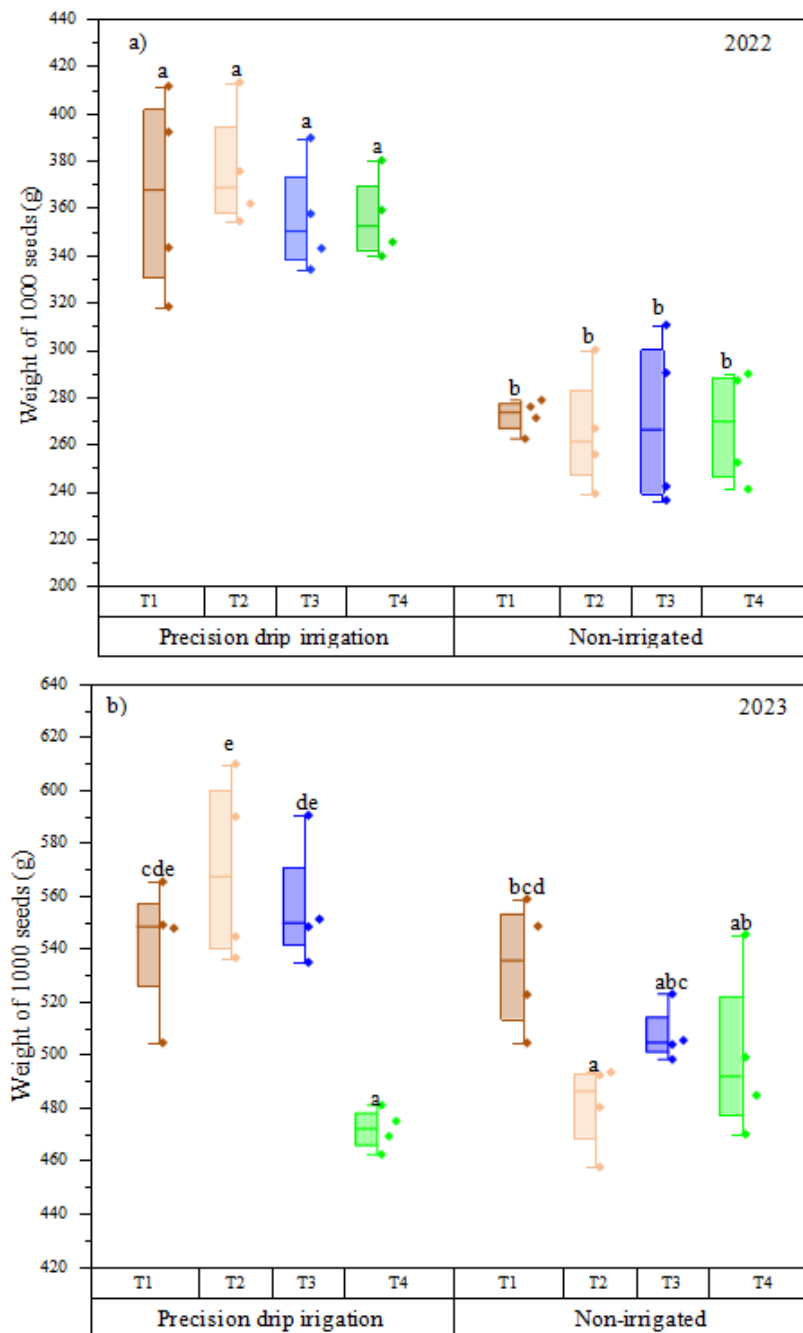


Figure 25 Water management and biostimulant, and micronutrients interactive effects on the weight of 1000 seeds. T1 – biostimulant, T2 and T3 – chemical fertilizers containing different micronutrients, T4 – control. Different lowercase letters indicate treatment significant differences by Tukey test at $p < 0.05$. (Debrecen, 2022-2023).

4.2.3. 2 Cob diameter, length and weight of seeds per cob

The cob diameter, length and weight of seeds per cob were significantly optimized by precision drip irrigation compared to non-irrigated condition (Figure 26). In the 2022 growing season, under precision drip irrigation, the cob diameter was 48.3 mm compared to 34.1 mm under non-irrigated conditions. This represents 41.6% cob diameter optimization by precision irrigation. In the 2023 growing season, under precision drip irrigation, the cob diameter was 52.0 mm compared to 50.0 mm under non-irrigated conditions. This represents 4.0% cob diameter optimization by precision irrigation. For the case of the biostimulant and micronutrients in the 2022 growing season, the individual and interactive effects between water management \times biostimulant and micronutrients were not significant. Under precision drip irrigation, cob diameter was 49.1, 48.6 and 49.4 mm in T1, T2 and T3 as compared to 46.3 mm in the control. Similarly, under non-irrigated conditions, cob diameter was 33.2, 35.0, and 34.9 mm in T1, T2 and T3 compared to 33.5 mm in the control, respectively. However, comparing the performance of the biostimulant and micronutrients between precision drip irrigation and water stress showed slightly higher cob diameter under of treatments T1, T2 and T3 under precision drip irrigation.

For the case of cob length in the 2022 growing season, under precision drip irrigation, the cob length was 19.5 cm compared to 11.5 cm under non-irrigated conditions. This represents 69.6% cob length optimization by precision irrigation. In the 2023 growing season, under precision drip irrigation, the cob length was 21.0 cm compared to 19.0 cm under non-irrigated conditions. This represents 10.5% optimization by precision irrigation. For the case of the biostimulant and micronutrients in the 2022 growing season, the individual and interactive effects between water management \times biostimulant and micronutrients were not significant. Under precision drip irrigation, cob length was 20.4, 19.9 and 20.3 cm in T1, T2 and T3 compared to 17.5 cm in the control. Similarly, under non-irrigated conditions, cob length was 11.5, 12.1, and 11.5 cm in T1, T2 and T3 compared to 10.3 cm in the control, respectively. However, comparing the performance of the biostimulant and micronutrients between precision drip irrigation and non-irrigated conditions showed slightly higher cob length under of treatments T1, T2 and T3 under precision drip irrigation. Similar trend was followed in the 2023 growing season. *Chinasho et al.* (2023) showed that blended fertilizer application produced

higher performance in terms of cob length.

For the weight of seeds (kernels) per cob, in the 2022 growing season, under precision drip irrigation, the weight of seeds per cob was 196.2 g compared to 45.5 g under non-irrigated conditions. The represents 331.2% optimization by precision irrigation. In the 2023 growing season, under precision drip irrigation, the weight of seeds per cob was 269.0 g compared to 234.8 g under non-irrigated conditions. The represents 14.6% optimization by precision drip irrigation. For the case of the biostimulant and micronutrients in the 2022 growing season, the individual and interactive effects between water management \times biostimulant and micronutrients were not significant. Under precision drip irrigation, weight of seeds per cob was 209.8, 199.6, and 204.0 g in T1, T2 and T3 compared to 171.4 g in the control. Similarly, under non-irrigated conditions, weight of seeds per cob was 39.0, 53.7, and 49.6 g in T1, T2 and T3 compared to 39.5 g in the control, respectively. However, comparing the biostimulant and micronutrients performance between non-irrigated conditions and precision drip irrigation showed slightly higher weight of seeds (kernels) per cob under treatments T1, T2 and T3 under precision drip irrigation. Similar trend was followed in the 2023 growing season.

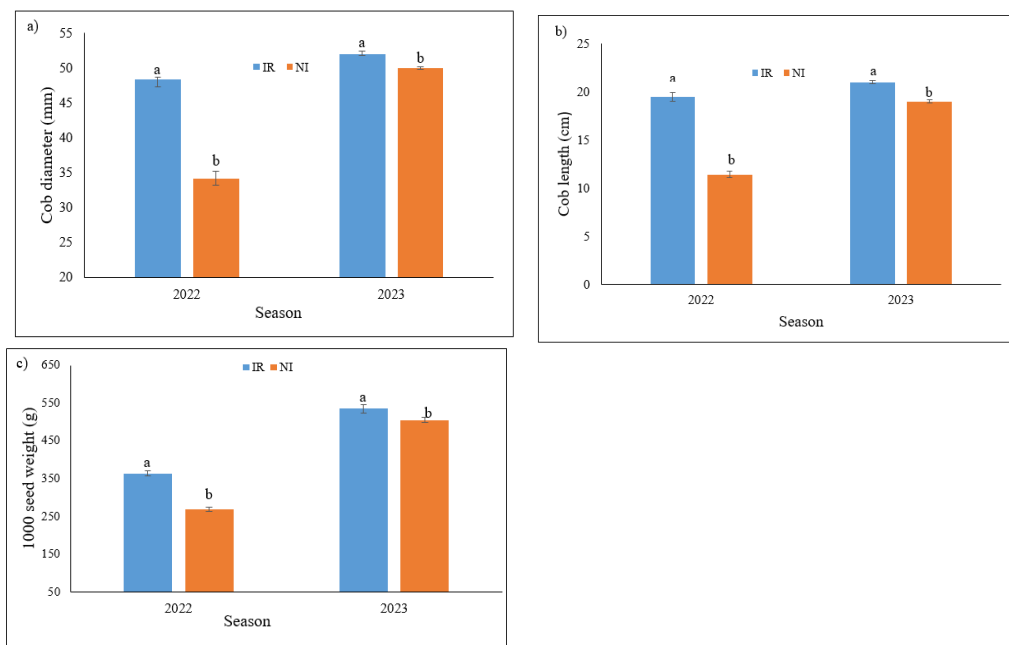


Figure 26 Cob diameter (a), cob length (b) and weight of 1000 seeds (c) under non-irrigated (NI) conditions and precision drip irrigation (IR) (Debrecen, 2022-2023).

4.2.3 Overall response of grain yield to water management, and biostimulant and micronutrients foliar application

Precision drip irrigation, and biostimulant and micronutrient foliar application significantly ($p < 0.05$) enhanced maize yield. Specifically, the yield of 13.3 and 19.4 t ha⁻¹ was recorded under precision drip irrigation compared to 3.8 and 17.3 t ha⁻¹ under non-irrigated conditions in the two seasons (Figure 27). This implies that 9.5 t ha⁻¹ and 2.1 t ha⁻¹ yield improvements were produced by precision drip irrigation in the seasons 2022 and 2023, respectively. In other words, precision drip irrigation enhanced grain yield in both seasons, although the highest optimization effect was evident in 2022 due to high water and heat stress. Besides, in the 2022 season, low precipitation was received in the growing period of maize. A study by *Gombos and Nagy (2023)* showed that the location where this study was conducted (Debrecen) had high temperatures and severe drought thus affecting maize yield. High or low water gradients reduce photosynthetic efficiency (*Zhao et al., 2019*) which affects yield. A report by *Da Ge et al. (2010)* showed that in absence of irrigation, high water stress severity decreases maize grain yield by 375.2%. This yield reduction as hastened if the temperature is elevated (*Niu et al., 2024*) due to interrupted absorption and assimilation of nutrients. Accordingly, *Xu et al. (2023a)* revealed that the yield of maize varieties tolerant to drought reduced with decrease in the drip irrigation quota. Additionally, drip irrigation saved 30% of water input and improved overall yield of maize compared to surface irrigation system (*Ibrahim et al., 2022*). According to *Rasool et al. (2020)*, drip irrigation saved circa 60% of the water and significantly improved grain yield attaining up to 9.9 t ha⁻¹ compared to the furrow irrigation method. Meanwhile, rainfed maize production buttressed with drip irrigation had higher photosynthetic efficiency, resulting into 53% yield increment (*Bai and Gao, 2020*). Generally, irrigation in areas with water stress enhances crop productivity (*Li et al., 2024b*).

The biostimulant as well as micronutrients application significantly ($p < 0.05$) improved yield in 2023 season, irrespective of the water management regime. Thus, the recorded yield for 2023 season was 18.7 t ha⁻¹ in both T1 and T2, and 18.6 t ha⁻¹ in T3 as compared to 17.5 t ha⁻¹ in the control. In other words, T1 and T2 produced yield improvement of 1.2 t ha⁻¹ (6.9%) and T3 had 1.1 t ha⁻¹ (6.3%). Putting this in general context, it appears that compared to the control, each of the treatments T1,

T2 and T3 produced an overall yield improvement of 1.0 t ha⁻¹. Meanwhile for the growing season 2022, the biostimulant and micronutrients application had yield between 8.4 – 8.6 t ha⁻¹ compared to 7.1 t ha⁻¹ in the control. As such, though the positive effect was also evident in the growing season 2022, biostimulant as well as micronutrient application effects were suboptimal (Figure 28).

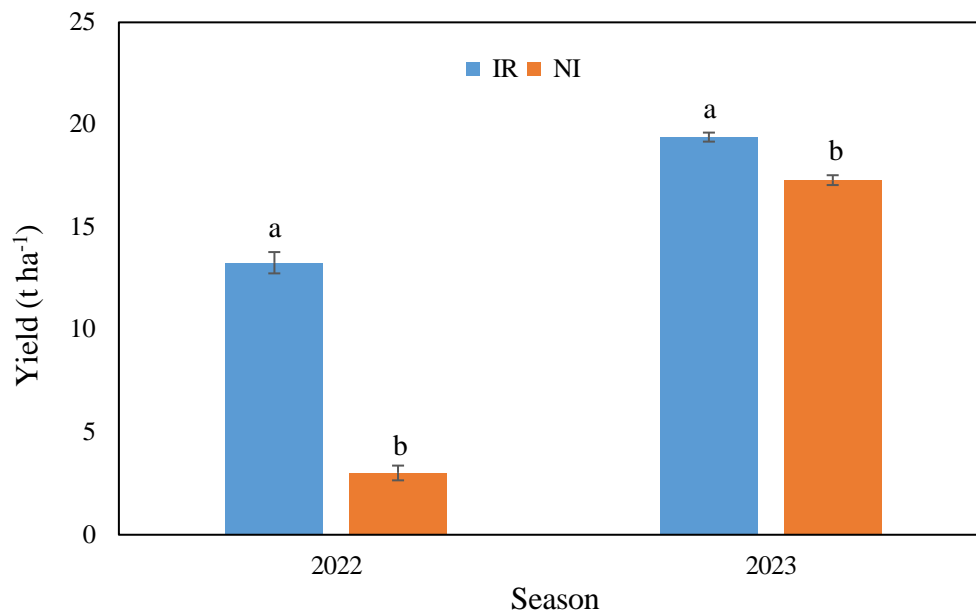


Figure 27 Variation in maize grain yield as affected by water management in 2022 and 2023 seasons. IR - precision drip irrigation, NI - non-irrigated conditions

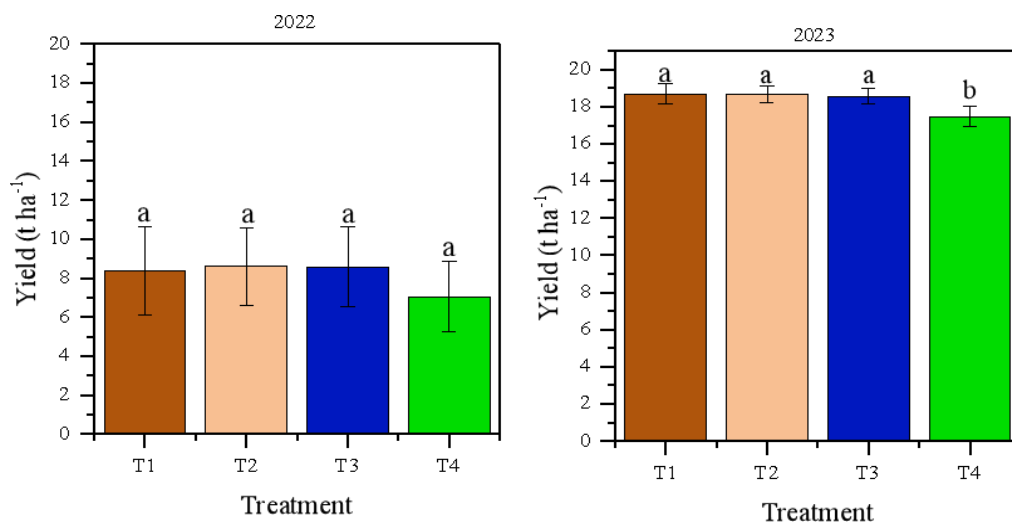


Figure 28 Overall effect of biostimulant and micronutrient foliar application on yield. T1 – biostimulant, T2 and T3 – chemical fertilizers containing different micronutrients, T4 – control. Error bar is the standard error. Different lowercase letters on the bars indicate treatment significant differences in each season by Tukey test at $p < 0.05$. (Debrecen, 2022-2023).

Analysing the biostimulant and the micronutrients effects between the two water management regimes shows higher yield under precision drip irrigation. For example, T1 had yield of 14.2 and 20.8 t ha⁻¹ under precision drip irrigation as compared to 2.5 and 17.4 t ha⁻¹ under non-irrigated conditions in the growing season 2022 and 2023, respectively. The treatments T2 and T3 followed similar trend (Figure 29), suggesting the reversal of negative effect of water stress by the treatments. Yield reduction under water stress is due to carbon starvation arising from stomatal closure (*Sharma et al., 2020*). Since the yield and yield components were optimized by the treatments under precision drip irrigation, it is clear that efficacy of biostimulants and micronutrients; zinc, molybdenum, boron in enhancing carbon assimilation and dry matter accumulation is high under precision drip irrigation depending on the prevailing climate conditions of a given growing season. In this case, utilisation of precision techniques that adjust nutrients and moisture supply vis-à-vis plant demand becomes paramount. This remediates scenarios where either biostimulants or micronutrients application yields contradicting results. For example, a 75% yield improvement by zinc under irrigation was reported by *Elshamly et al. (2024)* while other authors reported zinc not to significantly effect yield between water stress and irrigated plots (*Hussain et al., 2020; Idrees et al., 2024*). A study by *Abdo et al. (2022)* revealed a 25.4%, 13.6%, 32.2% yield enhancement by biostimulants containing sole amino acids, humic acids, and amino acids + humic acids. Also, foliar biostimulants application was reported to increase yield by 13.4% of Mv Marfi maize hybrid (*Zelenák et al., 2022*). Similarly, foliar Blend® with a myriad of nutrients optimized grain yield by 6.6% due to improved nutrient uptake (*Francis et al., 2016*). However, a review by *Ocwa et al. (2024a)* revealed that obtaining sustainable yield improvement by biostimulants may require integrated application. In this study, overall effects of biostimulants and micronutrients were only evident in 2023 season. However, the treatments effects compared between precision drip irrigation and non-irrigated conditions were consistently different for the two seasons where T1 and T3 had conspicuously better performance under precision irrigation. However, the treatments T1, T2 and T3 were applied once on the basis that if their performance was to be consistent and significantly higher in both seasons, then they would be recommended. However, it turned out that these treatments had similar positive effects, differing from only the control. In this circumstance, it is worthwhile to test

varying combinations of T1, T3 and T3 to ascertain potential synergistic effects. The results of the soil analysis revealed that the soil had inadequate nitrogen but adequate in zinc. This suggests that a single T1 application was not able to meet the nitrogen demand of maize plants required for optimal productivity, implying to options; increasing nitrogen supply through soil application while maintaining single application of T1, though the sustainability of this suggestion could have concerns related to the flow of nitrogen to water bodies hence pollution concerns. The second option is to have multiple applications of T1 in phenophases sensitive to nitrogen. This also requires further studies to determine the exact application times required to produce optimum effects under precision irrigation. Based on this, it appears that the optimum productivity potential of the tested biostimulant was not achieved. Therefore, as further investigations are suggested, careful attention has to be tailored to other compounding factors that affect the efficacy of biostimulants. Generally it is reported that crop response to biostimulants is influenced by biostimulant formulation and application method, climate conditions (*Długosz et al., 2020*), plant factors (*Berta et al., 2014*), among other factors. Again, since zinc was adequate in the soil in this study, there is need to test the effectiveness of T2 in soils, which are deficient in zinc under precision irrigation regimes. Application of zinc at later stages of maize growth in soil with adequate zinc has limited effect on plant development (*Capo et al., 2024*). From tasseling onwards zinc application only biofortifies the grain (increase zinc concentration) with no improvement in grain yield (*Wang et al., 2012*). Zinc is an essential micronutrient that plays key roles in regulation of metabolic processes including photosynthetic carbon assimilation by maize (*Sun et al., 2021; Idrees et al., 2024*). *Hussain et al. (2020)* reported comparable maize yield in plots fertilized with zinc and potassium with the plots without fertilization but well irrigated and recommended investigations involving irrigation scheduling. Nevertheless, *Idrees et al. (2024)* revealed zinc supplementation to enhance yield components as compared to non-zinc treatment under water stress and well irrigated conditions. Similarly, dry matter accumulation and economic yield was reported to be enhanced by zinc under 75% irrigation (*Elshamly et al., 2024*). Besides, irrigation, nutrients sources, and zinc availability in the soil, it's also reported that different hybrids have varying response to application of zinc (*Mohsin et al., 2014; Potarzycki et al., 2016; Capo et al., 2024*). Since this study tested T2 with only one maize hybrid, a study involving testing the

efficacy of T2 with different maize hybrids with varying maturity dates is recommended.

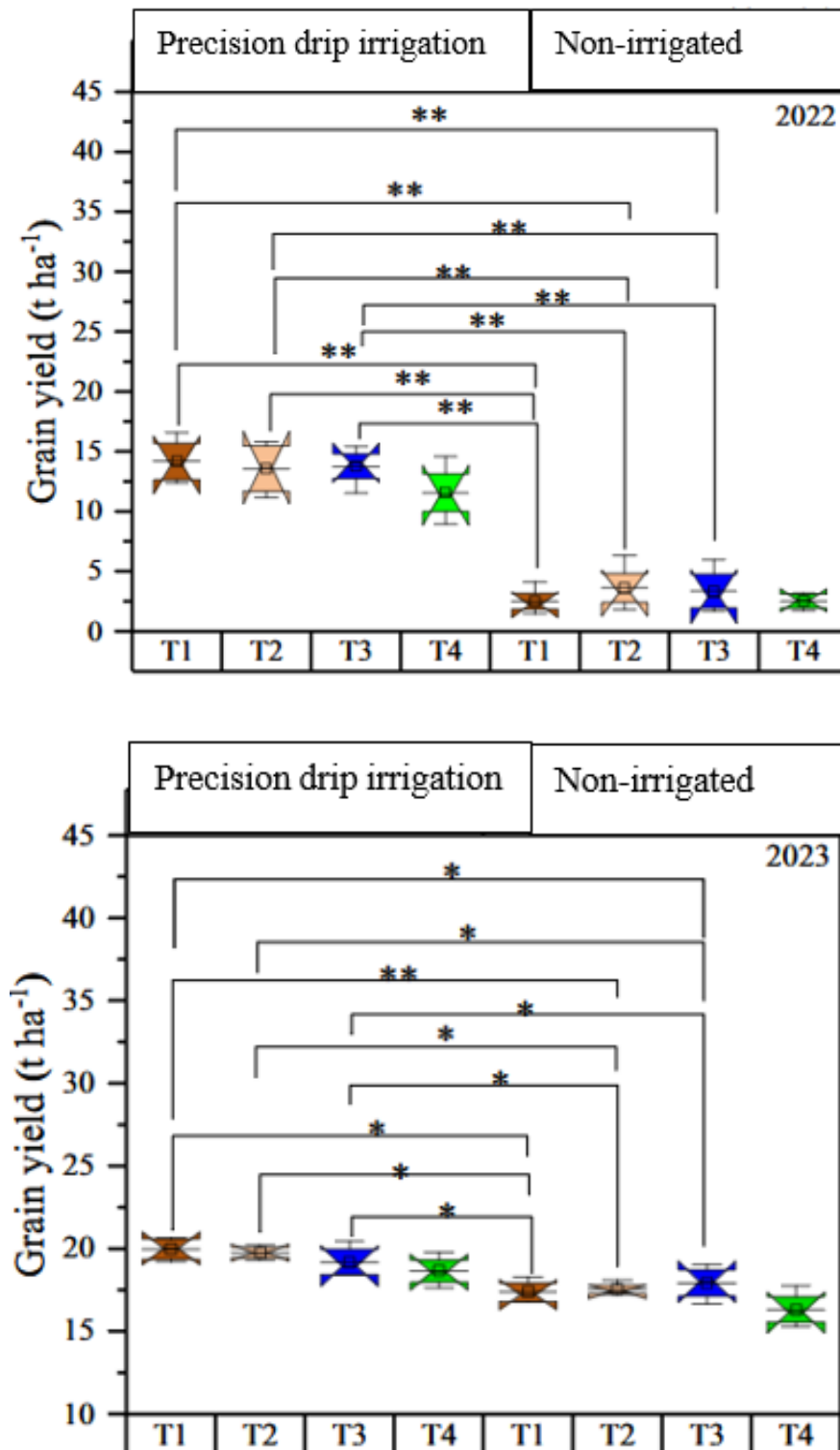


Figure 29 Biostimulant and micronutrients affect maize grain yield under precision drip irrigation and non-irrigated conditions in 2022 and 2023 seasons. T1 – biostimulant, T2 and T3 – chemical fertilizers containing different micronutrients, T4 – control. * and ** means significant differences by Tukey test at $p < 0.05$ and $p < 0.01$, respectively. Comparisons made only where significant differences were detected. (Debrecen, 2022-2023).

4.2.4 The nexus between photochemical yield parameters and grain yield

The results indicated a positive correlation between F_M' , F_q' , Φ PSII and ETR and a negative correlation between F' and Φ PSII, ETR and yield. Contrary, F' had a significant negative correlation with grain yield, ETR and Φ PSII, and positive correlation with F_M' . Additionally, F_M' had no correlation with grain yield. From this correlation analysis (Figure 30). To put this in context, the yield, Φ PSII and ETR positive correlation is an evidence of Φ PSII and ETR being useful indicators of micronutrients and biostimulants application as well as drip irrigation effect on maize yield and overall productivity. In context, it's apparent that ETR and Φ PSII are promising potential parameters that can be used for both stress diagnostics as well as indicators of yield. However, earlier, *Jin et al. (2023)* observed a positive relationship between photosynthesis and chlorophyll fluorescence with a considerable increase under water stress. However, variation in the photochemical parameters across maize growth stages suggests that these parameters can be used to detect and mitigate the negative effects of water stress on maize yield and yield components in the early stages. If correctly implemented, this enhances the sustainability of agronomic interventions, as early corrective measures facilitate the achievement of planned crop yield.

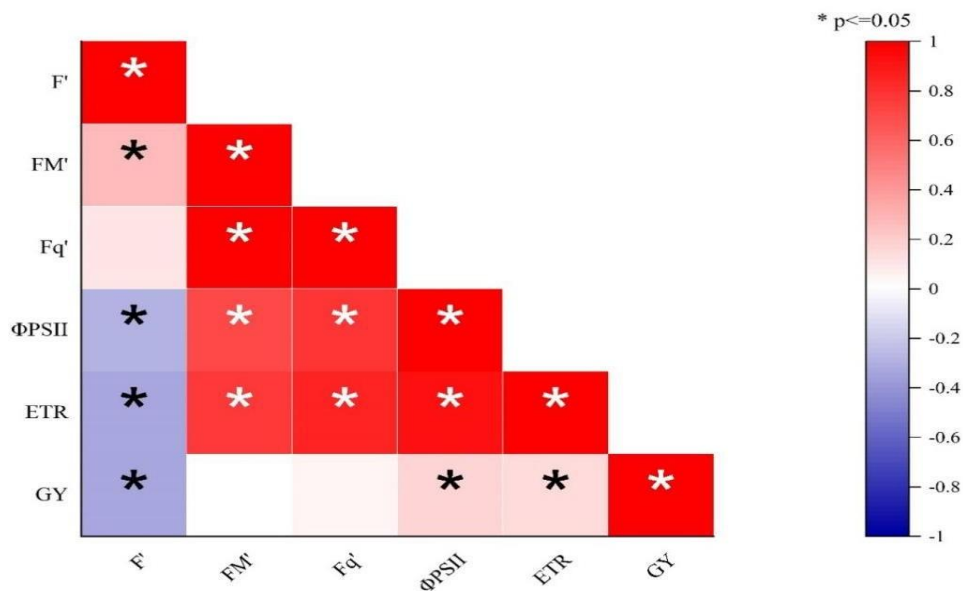


Figure 30 Correlation between quantum efficiency of photosystem II, chlorophyll fluorescence, and maize yield. F' (minimal fluorescence), F_M' (maximal fluorescence), F_q' (fluorescence difference between F_M' and F'), Φ PSII (quantum photosynthetic yield or efficiency of photosystem II), ETR (electron transport rate), GY (Grain yield).

4.2.5 Grain quality as affected by precision drip irrigation and biostimulant and micronutrients foliar application

Grain quality attributes significantly differed between the water management regimes only in the 2022 growing season. In the 2022 growing season, precision drip irrigation had grain oil, protein, and starch content of 3.0%, 5.2% and 56.9% compared to 2.7%, 7.3% and 54.6% under non-irrigated condition. This shows 0.3 and 2.3% improvement in oil and starch content, and -2.1% reduction in protein content by precision drip irrigation. In the 2023 season, grain oil, protein and starch content was 3.3%, 6.1% and 62.4% under precision drip irrigation compared to 3.5%, 6.6% and 63% under non-irrigated condition, respectively. In this case, though there were no significant differences, protein grain content in 2023 growing season was till reduced by -0.5%. The results of moisture content are also presented in Table 6. Overall, the season 2022 had intensive drought hence statistically proven differences in some quality parameters unlike 2023 where grain quality parameters were not easily affected by irrigation because the precipitation was closer to the normal crop/maize production requirements. For example, in the 2022 growing season, precision drip irrigation had grain protein, and starch content of 5.2% and 56.9% compared to 7.3% and 54.6% under water stress. This shows 2.1% reduction in protein content and 2.3% improvement in starch content by precision drip irrigation. Because of high drought or water stress in the 2022 growing season, maize exhibited a high water use efficiency and photosynthesis. Additionally, availability of water increases utilization of plant nutrients such as nitrogen, potassium, zinc, among others, resulting in a high assimilate accumulation and partitioning to the yield components. Earlier, *Kresović et al. (2018)* showed that irrigation significantly increased magnesium, iron, zinc, and potassium utilisation, and consequently grain yield. In connection to this, it became evident that reduction of protein under precision drip irrigation (high protein content under water stress) was because starch and protein are negatively correlated. This is validated by *Kálmán et al. (2023)* who showed a negative correlation between grain protein content and dry matter accumulation.

Table 6 Grain quality attributes under precision drip irrigation (IR) and non-irrigated conditions (NI) (Debrecen, 2022-2023).

Water management regime	2022			
	Oil (%)	Protein (%)	Starch (%)	Moisture (%)
IR	3.0±0.04 ^a	5.2±0.70 ^a	56.9±0.23 ^a	23.8±0.80 ^b
NI	2.7±0.06 ^b	7.3±0.10 ^b	54.6±0.55 ^b	21.4±0.17 ^b
Water management regime	2023			
	Oil (%)	Protein (%)	Starch (%)	Moisture (%)
IR	3.34±0.03 ^a	6.1±0.06 ^a	62.4±0.13 ^a	16.1±0.10 ^a
NI	3.45±0.05 ^a	6.6±0.08 ^a	63.0±0.13 ^a	14.3±0.10 ^b

In terms of biostimulant and micronutrients effects, on the other hand, there were limited individual effects of T1, T2 and T3 on grain quality attributes under both precision drip irrigation and non-irrigated conditions (Table 7).

Table 7 Effect of biostimulant and micronutrients application on grain quality attributes under precision drip irrigation (IR) and non-irrigated conditions (NI) in the 2022 growing season.

IR				
Treatment	Oil (%)	Protein (%)	Starch (%)	Moisture (%)
T1	3.0 ^a	5.3 ^a	57.0 ^a	21.5 ^a
T2	3.0 ^a	5.3 ^a	57.1 ^a	21.0 ^a
T3	3.0 ^a	5.1 ^a	56.7 ^a	21.6 ^a
T4	3.1 ^a	5.1 ^a	56.7 ^a	21.7 ^a
NI				
T1	2.6 ^a	7.3 ^a	53.3 ^a	26.0 ^a
T2	2.8 ^a	7.0 ^a	56.1 ^b	21.7 ^b
T3	2.8 ^a	7.4 ^a	55.9 ^b	21.8 ^b
T4	2.6 ^a	7.5 ^a	53.2 ^a	25.7 ^a

However, it was evident that the protein content under T1, T2 and T3 was lower under precision irrigation compared to non-irrigated conditions. Also, in the 2023 growing season, both the individual and interactive effects of biostimulant and micronutrients on grain attributes under both water regimes were not significantly different (Table 8).

Table 8 Effect of biostimulant and micronutrients application on grain quality attributes under precision drip irrigation (IR) and non-irrigated conditions (NI) in the 2023 growing season

IR				
Treatment	Oil (%)	Protein (%)	Starch (%)	Moisture (%)
T1	3.3 ^a	6.3 ^a	62.3 ^a	16.2 ^a
T2	3.4 ^a	6.2 ^a	62.6 ^a	16.2 ^a
T3	3.4 ^a	6.0 ^a	62.4 ^a	16.0 ^a
T4	3.3 ^a	6.1 ^a	62.6 ^a	16.1 ^a
NI				
T1	3.4 ^a	6.5 ^a	63.0 ^a	14.3 ^a
T2	3.4 ^a	6.6 ^a	62.9 ^a	14.4 ^a
T3	3.3 ^a	6.6 ^a	62.7 ^a	14.7 ^a
T4	3.5 ^a	6.4 ^a	63.2 ^a	14.2 ^a

These results contradict earlier studies that showed optimal grain quality improvement by biostimulants. This could be as a result of the varying composition of the biostimulant and the conditions under which it was tested. A study by *Tejada et al.* (2018) showed that maize quality was optimized by foliar fertilisation with biostimulant synthesized from chicken feathers. A study by *Ördög et al.* (2021) revealed the protein content of 9.4% from the biostimulant constituted from *Nostoc piscinale* cyanobacteria compared to 8.2% in the control. Conversely, humic acid at varying application rates enhanced grain oil content of maize (*Niaz et al.*, 2016). A systematic review by *Ocwa et al.* (2024a) revealed that protein, oil and starch improvement by different categories of biostimulants ranged from 0.1-3.7, with most evaluated studies depicting limited significant differences. In these regards, it appears that a research lacuna exists on how to improve the oil, protein and starch content of maize using biostimulants and micronutrients.

5. CONCLUSIONS

Precision drip irrigation exhibited optimal effects on growth parameters. Plant height was optimized by an average of 165% and 5.7% in the two seasons. Stem diameter was only optimized by 9.4% at R2 growth stage in 2022, and by average of 7.4% in the 2023 growing season. The LAI was only improved at the VT and R2 growth stages by 134.2% and 121.0% in the 2022 season. Therefore, optimal precision effects of drip irrigation on plant height and LAI were high with increased drought stress.

Looking at the nitrogen content of the plant as evidence by the SPAD values, precision drip irrigation reduced SPAD by -7.7% at the V12 growth stage and increased it by 43.1% at the R2 stage in 2022 season that was characterized by severe water stress and high temperature. In 2023 season with limited water stress and average temperature, precision drip irrigation optimized SPAD by 3.2% and 2.9% at the V12 and R2 growth stages, respectively. The comparative biostimulant and micronutrient effect also revealed a significant reduction in the SPAD values in T1, T2 and T3 treatments by -5.9%, -8.0%, and -8.1% under precision drip irrigation at the V12 growth stage. However, at the R2 growth stage, all the three treatments improved SPAD by 39.9%, 48.9%, and 41.8%. In 2023 growing season, the significant improvements were only evident at the V12 stage where T1 and T2 optimized SPAD by 4.3% and 4.2%. Overall, these results indicates that the overlapping effect of excess moisture shortly after application reduces SPAD values since all the reductions occurred at V12 growth stage that preceded the stage of irrigation installation.

Precision drip irrigation improved chlorophyll fluorescence, quantum photosynthetic yield and yield of maize in a season with severe drought and heat stress as well as in the season with above average favourable climate conditions.

In context, since irrigation water was supplied according to the weather conditions and moisture level in the soil in a precision manner that matched the requirements of maize at different growth stages, water was saved and water use efficiency was increased. This highlighted the impetus for the utilisation of precision drip irrigation as opposed to conventional methods such as border irrigation and furrow irrigation, which are wasteful under the current water shortage crisis and unpredictable

climate.

Precision drip irrigation had suboptimal effects on grain quality, although there was a conspicuous reduction in grain protein content by -2.1% and -0.5% in 2022 and 2023 seasons, respectively as well as 0.4% reduction in oil content in 2022 season. Also, precision drip irrigation improved starch by 2.3% in 2022 season. On the other hand, the biostimulant (T1) and micronutrients treatments (T2 and T3) effects on oil, starch and protein content of grain were all suboptimal.

The biostimulant and micronutrients had optimal effects on steady state fluorescence, and maximal fluorescence but suboptimal sole effects for quantum photosynthetic yield and electron transport rate. However, the interaction between precision drip irrigation and biostimulant and micronutrients exhibited a significant effect on the quantum photosynthetic yield and electron transport rate performance.

The sole biostimulant and micronutrient application had suboptimal optimization effect on growth parameters while the effect on grain yield was seasonal. However, comparative analysis of biostimulant and micronutrient application in the two water regimes showed better performance under precision drip irrigation, suggesting the synergy between adequate timely moisture supply and utilization of nutrients supplied.

The experimental site soil had a weak nitrogen category and as such, it appeared that the biostimulant was not able to supply adequate nitrogen required to achieve sole optimal effects on the overall productivity. This necessitates a study tailored to 2 – 3 application times at critical stages of maize under season specific precision irrigation, and/or testing the 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.

The fact that the soil in the experimental site had sufficient zinc implies that suboptimal sole effects of T2 need verification by testing the efficacy of T2 in soils deficient of zinc under season specific precision drip irrigation in pedoclimate conditions. This would validate the efficacy of T2 in enhancing vegetative and overall yield productivity of maize.

The extreme discrepancy between the temperature and precipitation in the two

seasons (including the preliminary study) resulted into variations in results of the effects of the biostimulant (T1) and micronutrients treatments on some parameters assessed making it difficult to draw conclusive evidence for the utilization of the tested products. This necessitates prolonged studies in several locations under pedoclimate conditions or heterogeneous soil and climate conditions to confirm the biostimulant effects under pedoclimate conditions. This is because of inconsistencies and variability of efficacy of different biostimulant products under field conditions.

From the results of this study, it appears that precision drip irrigation primarily influenced overall productivity of maize while the application of biostimulant, and micronutrient application showed positive effect. Therefore, additional studies related to application times, integration with minimal chemical fertilizer application, and testing their efficacy with more maize hybrids under diverse crop agroecosystems is required.

6. NEW SCIENTIFIC RESULTS

This study establishes the following new results:

1. Precision drip irrigation at the VT and R2 growth stages has the capacity to enhance plant height, and LAI by an average of 85.3%, and 127.6%, respectively. However, the optimisation efficacy increases with increase in the severity of water stress and elevated temperatures that seasonally differ.
2. Grain quality attributes including oil, starch, and protein content are only significantly affected by precision drip irrigation in seasons where drought and temperature stress are high, for this study in 2022 season where there was 0.3% and 2.3% improvement in oil and starch content, and -2.1% reduction in protein content by precision drip irrigation.
3. The response of quantum photosynthetic yield and electron transport rate to nutrients supplied by the biostimulant and chemical fertilizers improves with precision supply of moisture at sensitive stages of maize depending on the overall climate conditions of the given season. T1 had significantly higher (0.9 or 90%) Φ PSII as compared to T2 and T3 under non-irrigated conditions at the VT growth stage. Since quantum photosynthetic yield was positively correlated with grain yield, it can be used as a good indicator of the efficacy of biostimulants and micronutrients on vegetative and yield productivity and as a guide to make necessary nutrient supply corrections during active phenophases of maize.
4. The biostimulant (T1) as well as micronutrients (T2 and T3) application significantly improved yield irrespective of the water management regime with each treatment producing an overall yield improvement of close to 1.0 t ha⁻¹. Comparatively, T1 had yield of 14.2 and 20.8 t ha⁻¹ under precision drip irrigation as compared to 2.5 and 17.4 t ha⁻¹ under non-irrigated conditions in the growing seasons 2022 and 2023, respectively. In this, the fact that all the three treatments under water regimes had positive impact on yield suggest the need to have integrated application to achieve their optimum effect. Additionally, the biostimulants (T1) and micronutrients (T2 and T3) produced suboptimal effects on grain quality attributes under both precision drip irrigation and non-irrigated conditions.

7. PRACTICAL UTILIZATION OF RESULTS

1. Utilization of precision drip irrigation based on season specific climate conditions. This study demonstrates a clear difference in the amount of irrigation water supplied to maize during the two seasons since water supply was remotely controlled via a mobile phone application (Hydrawise application (Hunter)). The growing season 2022 used additional 55.6 mm of water compared to 2023 since it had higher drought intensity. In this regard, season specific precision drip irrigation ensures judicious utilization of water since no irrigation is started when the probability of rain reaches 80%. This saves water as compared to irrigation methods that supply moisture in a generic routine.
2. Guide to careful moisture supply just after irrigation installation, since in this study, even with 15 days gap in the installation of irrigation systems in the two seasons, chlorophyll content still reduced at V12 leaf stage that preceded irrigation and nutrients supply.
3. Early detection of efficacy of exogenously supplied nutrients on the productivity of maize. The suboptimal sole efficacy of the biostimulant and micronutrients on quantum photosynthetic yield and electron transport rate aligned with the results of final grain yield. In this case, if a deficiency of a nutrient is detected at the growth stage, then correction through extra supply can be implemented to reduce the anticipated negative effect on the final grain yield.
4. Identified grey areas of research for the tested biostimulant and micronutrients in Hungary. The fact that the soil was deficient in nitrogen based on soil tests means that there is need to develop appropriate nitrogen supply mainly through soil application based on the nitrate directive by the EU, and in case additional nutrient supply is needed, then foliar fertilisation could be used in appropriate doses. However, rigorous investigations are required to ascertain appropriate soil chemical nitrogen supply that can be combined with foliar biostimulant application to obtain optimum maize productivity while protecting the environment. In addition, this study guides that foliar zinc application in zinc rich soil is counterproductive.

8. SUMMARY

Climate change precipitates rapid propagation of drought worldwide. In addition, there is continuous depletion of nutrients in the soil. As such, depending on the geographical location, the severity of their effect threatens food crop production and consequently human livelihood. This research investigated the efficacy of precision drip irrigation and newly developed biostimulants, and micronutrients from chemical fertilizers on the productivity of maize. Two water regimes were included in the study i.e precision drip irrigation and non-irrigated conditions. Nutrient treatment sources were T1 (non-microbial biostimulant containing major and trace elements), T2 (chemical fertilizer containing zinc), T3 (chemical fertilizer containing majorly boron and molybdenum), and the control (T4). Data was collected on growth parameters, chlorophyll fluorescence parameters, quantum photosynthetic yield or efficiency of photosystem II (Φ PSII or Y(II)), electron transport rate (ETR), and yield and yield components and grain quality. Precision drip irrigation significantly ($p < 0.05$) improved plant height, chlorophyll content (SPAD), NDVI, chlorophyll fluorescence, Φ PSII, and ETR, yield and yield components. In the two seasons, precision drip irrigation improved yield by 250% (9.5 t ha^{-1}) and 12.1% (2.1 t ha^{-1}). Although grain starch content was positively affected, there was reduction in protein content under precision drip irrigation by -2.1 and -0.5% in the two seasons. The sole biostimulant and micronutrients effects were optimal for chlorophyll fluorescence while interactive effects showed improved Φ PSII, and ETR under precision drip irrigation at VT and R2 growth stage., Between water management regimes, biostimulant had the highest yield optimization effect under precision drip irrigation in the 2022 season with elevated water stress. However, since the grain yield of T1, T2, and T3 was not significantly different when compared to each other except the control, suggests further studies. The biostimulant and micronutrients effect on grain quality attributes were suboptimal. From the results of this study, it appears that precision drip irrigation primarily influenced overall productivity of maize while, although the application of biostimulant, and micronutrient application showed positive effect, additional studies related to application times, integration with minimal chemical fertilizer application, and testing their efficacy with more maize hybrids under diverse crop agroecosystems is required.

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10. PUBLICATION LIST



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Subject: PhD Publication List

Candidate: Akasairi Ocwa
Doctoral School: Kálmán Kerpely Doctoral School
MTMT ID: 10086967

List of publications related to the dissertation

Foreign language scientific articles in Hungarian journals (1)

1. **Ocwa, A.**, Ssemugenze, B., Harsányi, E.: Seed treatment with *Bacillus* bacteria improves maize production: a narrative review.
Acta agrar. Debr. 2024 (1), 105-111, 2024. ISSN: 2416-1640.
DOI: <http://dx.doi.org/10.34101/ACTAAGRAR/1/12043>

Foreign language scientific articles in international journals (3)

2. **Ocwa, A.**, Mohammed, S., Mousavi, S. M. N., Illés, Á., Bojtor, C., Ragán, P., Rátonyi, T., Harsányi, E.: Maize Grain Yield and Quality Improvement Through Biostimulant Application: a Systematic Review.
J Soil Sci Plant Nutr. 24, 1609-1649, 2024. ISSN: 0718-9508.
DOI: <http://dx.doi.org/10.1007/s42729-024-01687-z>
IF: 3.4 (2023)
3. **Ocwa, A.**, Bojtor, C., Illés, Á., Ssemugenze, B., Balaout, I., Rátonyi, T., Széles, A., Harsányi, E.: 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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4. **Ocwa, A.**, Harsányi, E., Széles, A., Holb, I., Szabó, S., Rátonyi, T., Mohammed, S.: A bibliographic review of climate change and fertilization as the main drivers of maize yield: implications for food security.
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5. **Ocwa, A.**, Ssemugenze, B., Kuunya, R., Gumisiriya, C., Balaout, I., Bojtor, C., Illés, Á., Harsányi, E.: Improving the agronomic performance of maize: differential responses to precision irrigation.
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6. Ssemugenze, B., **Ocwa, A.**, Kuunya, R., Gumisiriya, C., Bojtor, C., Illés, Á., Nagy, J.: Physiological Growth Improvement of Maize (*Zea mays* L.) through Foliar Fertilisation under Irrigated Conditions.
In: Proceedings of the Plants 2025: From Seeds to Food Security, Sciforum MDPI, Barcelona, 1, 2025, (Plants 2025 Conference, ISSN 2223-7747 ; 2025)
7. **Ocwa, A.**, Ssemugenze, B., Harsányi, E.: Bibliometric analysis of cereal grain quality.
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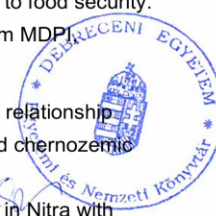
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Total IF of journals (all publications): 41

Total IF of journals (publications related to the dissertation): 6,8

The Candidate's publication data submitted to the Tudóstér have been validated by DEENK on the basis of the Journal Citation Report (Impact Factor) database.

25 April, 2025



11. ACKNOWLEDGEMENT

This academic journey has been successfully because of immense support from different stakeholders. My appreciation goes to the government of Hungary through Tempus Foundation for the Stipendium Hungaricum Scholarship and all the support rendered during the whole study period. Also, my gratitude goes to the government of the Republic of Uganda through the Ministry of Education and Sports for support. To my supervisor Prof. Dr. Harsányi Endre, your mentorship and overall support can not be quantified, thank you very much.

My appreciation also goes to administration and staff of Kálmán Kerpely Doctoral School, Institute of Land Use, Engineering and Precision Farming Technology for all the support and guidance that enabled this academic journey to be successful.

In a special way, I want to thank Dr. Mohammed Safwan, Dr. Bojtor Csaba, Dr. Illés Árpád, Dr. Seyed Mohammad Nasir Mousavi, and Mr. Fejer Peter from the Institute of Land Use, Engineering and Precision Farming Technology for the support in experimental work, scholarly writing, and guidance in the overall Ph.D. journey. Your experiences kept me steady.

To my wife Mrs. Namusisi Annet Ocwa, and our beloved children; Miss: Imukeka Jordan Ocwa, Adie Michelle Ocwa, and Amita Angel Ocwa, you endured tough life in my absentia, but your love and support kept me focused.

To my colleagues and/or friends: Ssemugenze Brian, Ahmed Abdelhakam Esmail Mohamed, Juhász Csaba, Kuunya Ronald, Nyandi Muhoja Sylvester, Sawadi Ndunguru Francisco, Melash Anteneh Agezew, Reda Gebrehaweria Kidane, Edep Tito, Kabaale Fred Peter, Ibtissem Balaout, Hajer Sidahmed, and Costa Gumisiriya, thank you very much for the life experiences shared including your support.

I also want to appreciate Dr. Awio Thomas of Africa Rice Centre, and Prof. Bosco Bua of Kyambogo University for the inspiration, support, and encouragement.

Finally, to everyone who is not listed here but provided support, thank you very much.

12. DECLARATION

I prepared this dissertation within the framework of Kálmán Kerpely doctoral school of University of Debrecen, in order to obtain the doctoral (Ph.D.) degree of the University of Debrecen.

Debrecen, 2025/05/09.....

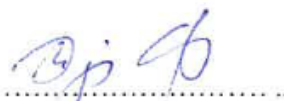


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DECLARATION

I certify that **Akasari Ocwa**; a doctoral candidate 2021-2025 and within the above-mentioned Doctoral School carried out his work under my guidance/direction. The independent contribution of the candidate to the results included in the dissertation, the dissertation is the independent work of the candidate. I suggest / recommend the acceptance of the dissertation.

Debrecen, 2025/05/09.....



the signature of the supervisor