

Optimisation of maize (*Zea mays* L.) physiological growth under field conditions by targeted water supplementation using a precision drip irrigation system

A kukorica (*Zea mays* L.) fiziológiai fejlődésének optimalizálása szántóföldi körülmények között célzott, precíziós csepegtető öntözőrendszerrel történő vízpótlással

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Received: June 19, 2025; accepted: February 5, 2026

ABSTRACT

The application of precision drip irrigation systems has gained extensive interest as a tool for improving crop yield, growth, and water-use efficiency. This study assessed the impact of precision drip irrigation on the physiological performance and growth of maize during the 2023 growing season. The experimental material included two maize hybrids, namely, FAO290 and FAO490. The examined physiological growth indicators included leaf area index (LAI), Normalized Difference Vegetation Index (NDVI), and relative chlorophyll content (SPAD). Data collection was conducted at four growth stages: V12, R1, R4, and R6. Irrigation had a significant effect on SPAD readings ($P < 0.001$), while it had no significant effect on either NDVI or LAI. In comparison with the control, the following values were recorded in irrigation treatments: 17.2%, 9.5%, and 11.4% for LAI, NDVI and SPAD, respectively. FAO490 showed better hybrid performance. Irrigated FAO490 showed 3.1%, 5.3% and 1.4% percent increase for LAI, NDVI, and SPAD values, respectively, compared to the FAO290 hybrid, concluding to a better physiological response to water supplementation of FAO490 compared to FAO290. The study justifies the impact of precision drip irrigation on maize physiological performance and growth, with FAO490 responding more favourably than FAO290. Therefore, the application of precision irrigation systems and the adoption of responsive hybrids act as coping strategies to improve maize growth under water-stressed areas and those with variable rainfall patterns.

Keywords: maize, Normalized Difference Vegetation Index, leaf area index, irrigation

ABSZTRAKT

A precíziós csepegtető öntözőrendszerek alkalmazása széleskörű érdeklődésre tart számot, mivel a terméshozam, a növekedés és a vízfelhasználás hatékonyságának javításának egyik legfontosabb eszköze. Tanulmányunkban a precíziós csepegtető öntözés hatását vizsgáltuk a kukorica fiziológiai teljesítményére és növekedésére. A kísérletet a Debreceni Egyetem Látókép Növénytermesztési Kísérleti Telepén végeztük a 2023-as vegetációs időszakban. A kísérletben két, FAO490 és FAO290 érésidevel jellemezhető kukoricahibridet vizsgáltunk. A vizsgált fiziológiai növekedési mutatók közé tartozott a levélfelület-index (LAI), a normalizált vegetációs differencia index (NDVI) és a relatív kloro-

filltartalom (SPAD). Az adatgyűjtés négy fejlődési stádiumban, V12, R1, R4 és R6 fenofázisban történt. Az adatokat GenStat v.19. szoftverrel varianciaanalízissel elemeztük. Az öntözés szignifikáns hatással volt a SPAD-ra ($P < 0,001$), ellenben az NDVI-ra és a LAI-ra nem gyakorolt statisztikailag igazolható hatást. Az öntözött kezelések 17,2%-kal, 9,5%-kal és 11,4%-kal magasabb LAI, NDVI és SPAD értékeket mutattak a kontrollhoz képest. A hibridek teljesítménye azt mutatta, hogy a FAO490 jobban teljesített, az öntözött FAO490 3,1%-os, 5,3%-os és 1,4%-os százalékos növekedést ért el a LAI, NDVI és SPAD értékek tekintetében a FAO290 hibridhez képest. Ez azt mutatja, hogy a FAO490 jobb fiziológiai választ adott az öntözésre, mint a FAO290. A vizsgálat igazolta a precíziós csepegtető öntözés hatását a kukorica fiziológiai teljesítményére és növekedésére, a FAO490 kedvezőbb reakcióját eredményezve. Ezért a precíziós öntözés és a megfelelő hibridek alkalmazása kulcsfontosságú a vízhiányos, illetve változó csapadékú területeken a kukorica növekedését javító termesztési stratégiák kidolgozásában.

Kulcsszavak: kukorica, Normalizált Differenciált Vegetációs index, levélterület index, öntözés

INTRODUCTION

Maize (*Zea mays* L.) is a highly demanded cereal globally due to its contribution to food security as a staple food, feeding livestock and a raw material for agricultural industries. Maize easily adapts to and grows in different agro-ecological regions. Most developing countries cultivate maize to improve food security and economic stability due to its yield potential (Shiferaw et al., 2011). Drought and water stress are two of the major factors that affect maize production (Pepó et al., 2008) due to the crop's sensitivity to these factors, mainly at important stages of growth, namely silking, tasseling, and grain filling. Scenarios of moderate drought have been documented to significantly affect the accumulation of biomass and yield of maize (Campos et al., 2004; Edmeades, 2013). Increased climate variability and shrinking water resources raise a major concern towards both maize production and growth (Mohammed et al., 2022). Therefore, to address these above-mentioned limitations to maize production, the adoption and application of efficient water management strategies, including precision drip irrigation under field conditions, should be the major focus to sustain maize production. However, the physiological responses of different maize genotypes to water availability depend on their genotypic variability, which justifies the importance of proper hybrid selection to optimise crop performance (Blum, 2009).

One of the major agricultural constraints is water scarcity (Ocwa et al., 2023), thus necessitating the implementation of efficient water use strategies for

heavy-feeder crops such as maize. Water application through traditional irrigation methods caused heavy water losses through evaporation, evapo-transpiration and runoff, affecting the overall water-use efficiency (WUE) of crops (Ssemugenze et al., 2024). The introduction of precision agricultural technologies, such as precision drip irrigation, has enhanced the water use efficiency of crops (Ocwa et al., 2024) since irrigation water is directly delivered to the crop root zone in a controlled manner, thus reducing water losses and augmenting the water uptake of crops (Lamm et al., 2007; Ayars et al., 1999). Kang et al., (2017) noted that drip irrigation improved water use efficiency of maize by 30–50% compared to furrow and sprinkler systems. Increased estimation of drought occurrences and rainfall unpredictability globally due to climate change necessitates the adoption of precision drip irrigation as a sustainable strategy to achieve higher crop yields with minimal water input (Feres and Soriano, 2007).

The evaluation of crop health and stress response depends on critical markers indicating physiological performance and growth (Horváth et al., 2021), namely plant height, Leaf Area Index (LAI), stem diameter, Normalized Difference Vegetation Index (NDVI), and Soil-Plant Analysis Development (SPAD). Leaf Area Index shows crop canopy development and photosynthetic potential, and high LAI values indicate higher light interception and greater accumulation of biomass (Maddoni and Otegui, 2004). NDVI, also known as leaf greenness, assesses

chlorophyll content and the vegetative vigor of the crop, indicating its responsiveness to the availability of water and nutrients (Hatfield and Prueger, 2010; Crespo et al., 2025). SPAD estimates the relative chlorophyll content signalling the nitrogen status and photosynthetic activity of the crop (Uddling et al., 2007). These growth parameters correlate with maize grain yield. Their sensitivity to environmental stress makes them critical markers for monitoring crop physiological performance and growth under different irrigation regimes (Dobos et al., 2012; Yadav et al., 2024).

The genetic variations of maize hybrids determine their response to water stress and irrigation conditions. Different hybrids have deeper root systems, high nutrient uptake, higher stomatal control, and efficient water use. Consequently, they have higher physiological performance and growth under water-limited conditions (Campos et al., 2004; Reynolds et al., 2005). Several studies have shown that hybrids that are drought-tolerant have higher SPAD and NDVI values under water stress conditions as they preserve the rate of photosynthesis while extending the grain-filling period (Aujla et al., 2007). Drought-tolerant hybrids grown under drip irrigation conditions maximised water use efficiency and produced high levels of biomass as they optimised the distribution of soil moisture and minimised evaporation losses (Tang et al., 2025). Therefore, assessment of hybrid performance when exposed to precision irrigation helps to identify suitable maize genotypes that perform better under varying water regimes. The study objectively investigates the impact of water supplementation through precision drip irrigation on the physiological performance and growth of two maize hybrids (FAO290 and FAO490) grown under field conditions.

MATERIALS AND METHODS

Experiment site

The experiment was set up during the 2023 growing season at Látókép Crop Production Experiment Site, University of Debrecen, Hungary.

Experimental materials

The two studied hybrids were FAO290 and FAO490.

The hybrid FAO290 is characterised by high tolerance to abiotic stress conditions and stable yield performance. It forms a uniform plant stand with consistent ear set, supporting reliable grain filling under drought-prone environments. Strong early vigor, good root development, and high stalk strength contribute to good standability and adaptability to intensive production systems.

The hybrid FAO490 is characterised by outstanding yield potential and a long growing season. It exhibits excellent tolerance to drought and dry environmental conditions and shows a stay-green phenotype of physiological maturity. The hybrid demonstrates high yield stability across different growing environments. Plants are significantly shorter than average, with ears set at a low height, contributing to good standability; lodging is not typically observed.

Soil sampling and sowing

Before sowing, soil sampling and laboratory analysis were conducted to assess the soil moisture content. Sowing was done on 20th April 2023 at a plant population of 74.000 maize plants/ha.

Experimental design, treatments and irrigation management

The experiment was laid out as a randomized split-plot field experiment. The size of the plot is 30 m². Surface drip irrigation lines were installed on 14th June 2023 at every crop row, supplying water at the intensity of 3 litres per hour. The irrigation system was controlled by the Hydrowise app. and managed by the meteorological station of the Experiment Site. The amount of irrigation water was 132 mm (June), 198 mm (July) and 44 mm (August) applied at different dates as shown in Table 1. Drip irrigation was dismantled on 22nd September 2023 when maize attained full growth and was ready for harvesting. Recommended agronomic management practices were done; weed management was done manually by hand

picking as soon as weeds emerged, row cultivation was done on 21st May 2023, while fertigation was done on 10th July 2023 using Megasol orange (25 kg fertiliser).

Table 1. Irrigation dates and amount of water (mm)

Date of Irrigation	Irrigated amount of water (mm)
18 June 2023	44
22 June 2023	44
25 June 2023	44
1 July 2023	44
5 July 2023	44
8 July 2023	22
10 July 2023	22
16 July 2023	22
21 July 2023	22
31 July 2023	22
4 August 2023	22
10 August 2023	22

Data collection stages

Data was collected at the V12, R1, R4, and R6 stages.

Field data collection

Leaf Area Index (LAI), Normalized Difference Vegetation Index (NDVI), and relative chlorophyll content (SPAD) were collected using the required equipment. Measurements were conducted from the field using the SPAD-502 Plus Chlorophyll Meter (Konica Minolta Inc., Tokyo, Japan) to measure the relative chlorophyll of the third last well-developed leaf and the opposite leaf at both vegetative and reproductive stages, respectively. The leaf transmittance coefficients of 650 nm and 940 nm were used to estimate SPAD values between 0 and 99. SS1 SunScan Canopy Analysis System (Delta-T Devices Ltd., Cambridge, UK) was used for measuring Leaf area index (LAI). Fifteen (15) measurements were collected from the field, and the average was calculated.

Statistical analysis

Data was analysed using ANOVA using Genstat software (19th edition) developed by VSN International (VSNi) and OriginLab (24th edition) developed by OriginLab Corporation, a software company based in Northampton, Massachusetts, USA, specialised in scientific graphing and data analysis tools.

RESULTS

Leaf Area Index (LAI)

Irrigation had no significant effect ($P=0.096$) on the leaf area index (LAI) of both maize hybrids studied (Figure 3). Hybrid and irrigation interaction showed no significant effect ($P=0.439$) on LAI (Figures 1 and 2). Although there were no statistically significant differences recorded, positive trends were noted using descriptive analysis. Comparing the LAI of both hybrids, the average LAI of FAO490 (6.03) was slightly higher than FAO290 (5.85). The leaf area index of irrigated treatments was consistently higher (6.41) than that of non-irrigated treatments (5.47), an indication of the positive impact of water supplementation through precision drip irrigation on the leaf area index of maize. Hybrid and irrigation interaction showed that irrigated FAO290 and FAO490 had the highest LAI value of 6.10 and 6.71, respectively, compared to non-irrigated FAO290 and FAO490, with the lowest LAI of 5.35 and 5.59, respectively. FAO490 showed better LAI under irrigated conditions, while FAO290 performed better under non-irrigated conditions. These findings showed the positive effect of precision drip irrigation on the canopy development of maize as the leaf area increased.

Normalized Difference Vegetation Index (NDVI)

Irrigation, hybrid and hybrid by irrigation interaction had no significant effect ($P=0.478$), ($P=0.222$), ($P=0.416$), respectively, on the NDVI (Figures 1, 2, and 3). Although there were no statistically significant differences, positive trends were noted using descriptive analysis. Comparing NDVI values of both hybrids, the average NDVI of the FAO490 hybrid (0.734) was slightly higher than that

of FAO290 (0.697), a clear indication of better canopy vigor. The NDVI value of irrigated treatments was consistently higher (0.748) than that of non-irrigated treatments (0.683), recording a positive effect of precision drip irrigation on NDVI of maize. Hybrid by irrigation interaction showed that irrigated hybrids of FAO290 and FAO490 had the highest NDVI values of 0.708 and 0.789, while non-irrigated FAO290 and FAO490 had the lowest NDVI values of 0.686 and 0.680, respectively. The irrigated FAO490 hybrid had better NDVI compared to

FAO290. Precision drip irrigation enhanced leaf greenness and vigor, mainly for the FAO490 hybrid, although no statistically significant differences were recorded.

Leaf Chlorophyll Content (SPAD)

Irrigation resulted in a significant difference ($P < 0.001$) in leaf chlorophyll content (SPAD) (Figure 3). Both hybrid and hybrid-irrigation interaction had no significant differences ($P = 0.561$) and ($P = 0.176$) on SPAD (Figures 1 and 2).

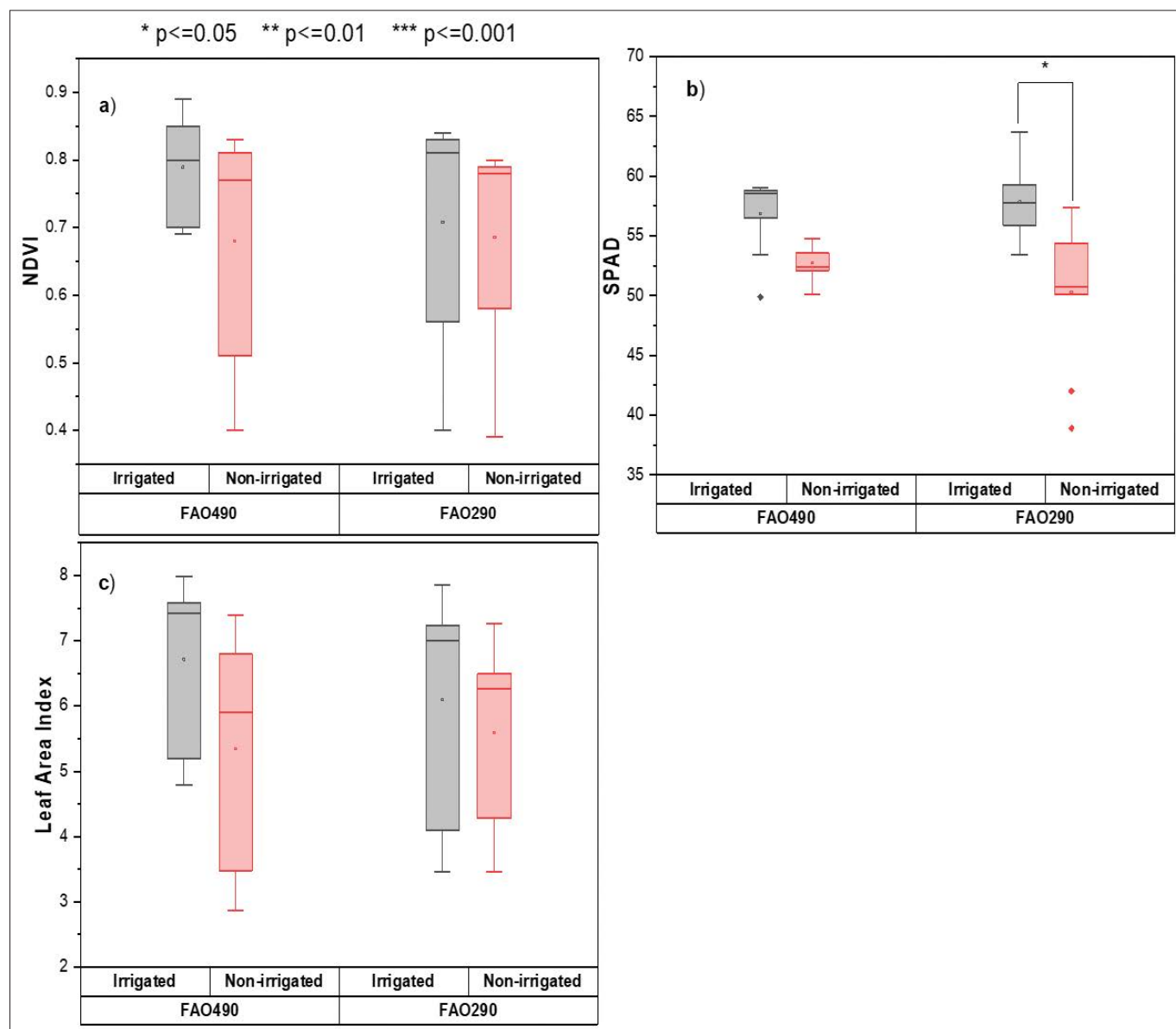


Figure 1. Hybrid by irrigation interaction effects on: a) NDVI, b) SPAD, and c) Leaf Area Index for the two studied maize hybrids

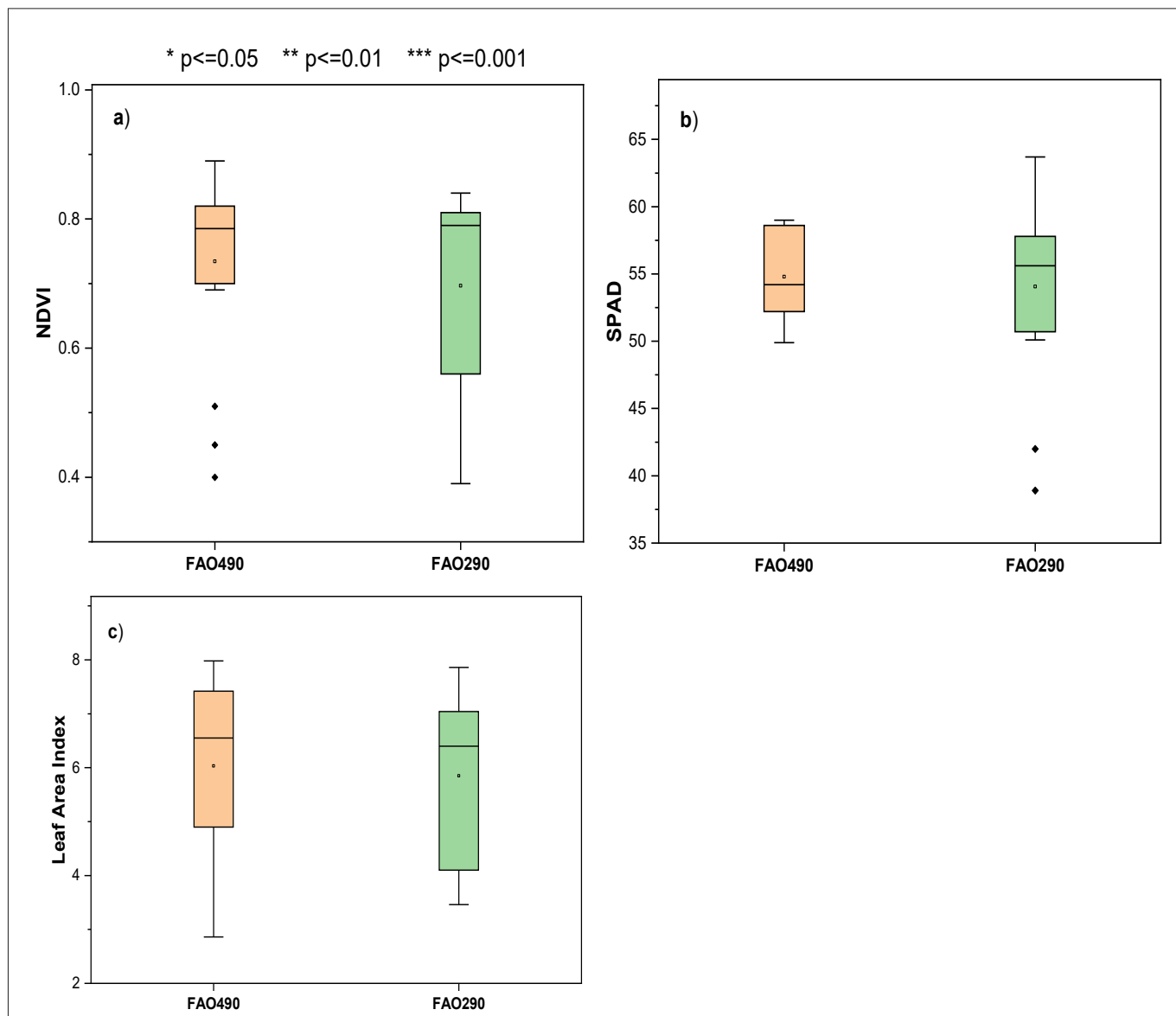


Figure 2. Showing hybrid effects on: a) NDVI, b) SPAD, and c) Leaf Area Index for the two studied maize hybrids

Comparing leaf chlorophyll content of both hybrids, the average SPAD of both hybrids was almost the same, FAO290 (54.06) and FAO490 (54.7), indicating a pronounced effect in both hybrids. The SPAD value of irrigated treatments was significantly higher (57.35) than that of non-irrigated (51.50), showing a positive effect of precision drip irrigation on the chlorophyll content of maize. Hybrid-irrigation interaction showed that ir-

rigated FAO290 and FAO490 had significantly higher SPAD values of 57.84 and 56.86 while non-irrigated FAO290 and FAO490 had the lowest SPAD values of 50.28 and 52.72, respectively. The significant difference of irrigation on SPAD shows how precision drip irrigation increased the concentration of leaf chlorophyll as an indication of improved physiological performance of different maize hybrids.

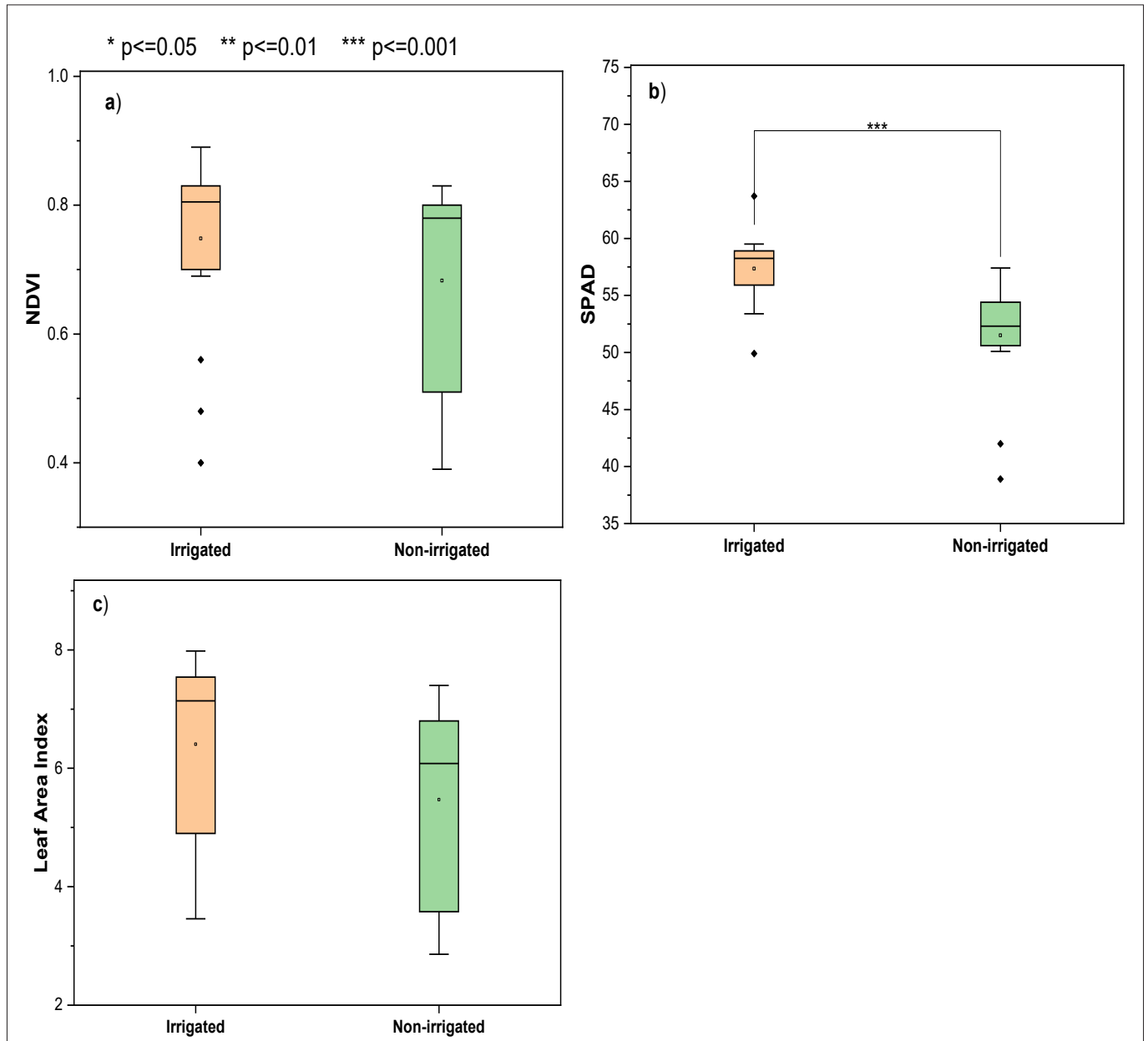


Figure 3. Showing irrigation effects on: a) NDVI, b) SPAD, and c) Leaf Area Index during the 2023 growing season

DISCUSSION

Although there is no significant effect of irrigation on LAI as recorded, irrigation resulted in a 17.2% increase, which indicates a positive trend. Optimal irrigation with nitrogen application led to increased LAI level during the growth period (Zhu et al., 2025). Leaf Area Index shows crop canopy development and photosynthetic potential, and high LAI values indicate higher light interception and accumulation of biomass (Maddonni and Otegui, 2004). Studies have recently highlighted how higher LAI values

show enhanced development of leaves, improved light interception and high canopy cover (Maddonni and Otegui, 2004). The hybrid FAO490 had a 3.1% higher LAI than FAO290, and this difference can be attributed to greater physiological resilience, better water use efficiency and more efficient nutrient use. These traits are of great importance in maize breeding research (Campos et al., 2004). However, Reynolds et al. (2005) noted that hybrid performance differences can be due to inherent

genetic variations, root architecture, water uptake and use efficiencies and chloroplast stability when plants are exposed to different water regimes.

A percentage increase of 9.5% as irrigation effect on NDVI showed how precision irrigation impacted the NDVI of maize. The hybrid FAO490, with 5.3% higher NDVI values compared to FAO290, showed differences in physiological growth. Tamás et al. (2023) noted a significant positive irrigation effect on the NDVI during a drought period. NDVI, also known as leaf greenness, assesses chlorophyll content and the vegetative vigor of the crop, indicating its responsiveness to the availability of water and nutrients (Hatfield and Prueger, 2010; Crespo et al., 2025). Drought-tolerant hybrids grown under drip irrigation conditions maximised water use efficiency and produced high levels of biomass as they optimised the efficient use of soil moisture and minimised losses (Tang et al., 2025). Literature indicates that higher NDVI indicates enhanced leaf greenness and canopy vigor, establishing a correlation with biomass production (Hatfield and Prueger, 2010). Several studies have shown that hybrids that are drought-tolerant have higher SPAD and NDVI values in water stress conditions as they preserve the rate of photosynthesis while extending the grain-filling period (Aujla et al., 2007). Basso and Ritchie (2015) noted that minimal improvements among physiological growth parameters led to improved growth and yield under precision water supplementation.

A positive significant difference ($P < 0.001$) in the recorded leaf chlorophyll content (SPAD) showed a great irrigation effect in maintenance and vitality of crop health during important growth stages. Nagy (2010) noted a significant effect ($P < 0.001$) of irrigation on SPAD values. Similarly, water treatments at the R1 stage had a significant effect ($P < 0.001$) on chlorophyll content (Széles et al., 2012). SPAD estimates the relative leaf chlorophyll content, signalling the nitrogen status and photosynthetic activity of the crop (Uddling et al., 2007). An increase of 11.4% in the chlorophyll content of maize due to irrigation is reflected in higher values within the leaves (Ling et al., 2011; Scagel et al., 2007). The hybrid FAO490

showed a 1.4 % higher SPAD value than FAO290, which indicates higher leaf nitrogen and chlorophyll contents in the hybrids, which, according to Uddling et al. (2007), might be attributed to improved rate and efficiency of photosynthesis, and delayed leaf senescence. Several studies have shown that drought-tolerant hybrids have higher SPAD and NDVI values in water stress conditions as they maintain the rate of photosynthesis while extending the grain-filling period (Aujla et al., 2007).

The hybrid by irrigation interaction did not show a significant difference. FAO490 had better SPAD and NDVI values under irrigated conditions, which indicated better performance under arid or semi-arid conditions that require the application of precision irrigation. Drought-tolerant hybrids grown under drip irrigation conditions maximised water use efficiency and produced higher biomass as they optimised the efficient use of soil moisture and minimised evaporation losses (Tang et al., 2025). Overall, this study justifies the impact of precision drip irrigation as a feasible precision agronomic tool aimed at improving maize physiological performance and growth under field conditions. Due to variable weather and climate and increased water scarcity across different agro-ecological regions, efficient water use and proper selection of maize hybrids are essential to promote sustainable production (Feres and Soriano, 2007; Blum, 2009).

CONCLUSIONS

These findings demonstrated the positive impact of precision drip irrigation on the improvement of maize physiological performance and growth, with a significant effect on leaf chlorophyll content (SPAD values), while leaf area index (LAI) and NDVI had minimal effect. Of the physiological and growth indicators studied, SPAD values had a positive statistically significant response to irrigation, i.e., the concentration of chlorophyll was enhanced by water supplementation, thus improving the photosynthetic rate of maize hybrids. No significant hybrids by irrigation interaction were recorded; however, the hybrid FAO490 consistently showed better perfor-

mances than FA0290 for almost all studied growth indicators. Under irrigation conditions, FA0490 showed higher values of LAI, NDVI, and SPAD. Accordingly, this hybrid had a better response to water supplementation through precision drip irrigation under field conditions. The study justifies the need to integrate precision drip irrigation systems for sustainable maize production, as it enhances growth mainly in water-constrained regions. The growth indicators examined directly influenced the accumulation of biomass and the yield potential of maize; therefore, objective irrigation could enhance maize growth performance, as well as nutrient and water use efficiency. Farmers in different regions should select responsive hybrids based on climatic variabilities, water scarcity, and plant genetic variability to maximize the irrigation effect. Precision irrigation and hybrid selection are important adaptive agronomic strategies ensuring improved sustainable maize production.

ACKNOWLEDGEMENT

This paper was supported by the János Bolyai Research Scholarship of the Hungarian Academy of Sciences (BO/00068/23/4).

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