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EVALUATION OF FOLIAR FERTILIZATION ON MAIZE GROWTH, YIELD, GRAIN QUALITY AND QUANTITY UNDER IRRIGATED AND NON-IRRIGATED CONDITIONS

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1. INTRODUCTION

Maize (*Zea mays L.*) ranks among the oldest cereal crops with a significant contribution to the livelihood of humankind (*Hearn, 2014*). The crop's origin can be traced to Southern Mexico approximately 9,000 years ago. Teosinte a well-known wild ancestor from which maize was domesticated through plant selection, breeding and cultivation (*Awika, 2011*). Maize formed a major part of pre-columbian civilizations due it's widespread to America which later found its way to Europe, Asia and Africa through the Columbian exchange during the 15th and 16th centuries (*Kennett et al., 2020*). Due to favourable weather and agro-climatic conditions across the different agro-ecological regions, the crop easily adapted thus high cultivation and production. Since then to date, maize ranks among the most important cereals produced globally as a staple crop for both subsistence and industrial reasons.

FAO, (2017) estimated that the total global population will be 9.7 billion people approaching 2050, a call for increased nutritious food production. The recent cereal production statistics of 2024 recorded 2,853 million tonnes *(FAO, 2024),* major contributor to world food security (Laskowski et al., 2019), the three major cereals include wheat, rice, and maize (Table 1, *FAO, 2024*). According to FAO report of 2021, the estimated global protein intake and food calories were 37% and 42%. Therefore, to meet the high food requirement of the growing population, maize production as a major cereal should be enhanced (*Shiferaw et al., 2011*; *Poole et al., 2021*). The versatility of maize crop makes it a primary staple food for human consumption across all continents however it also contributes to sustainability of the livestock and animal industry since it's a major animal feed, the industrial and biofuel sectors also benefit tremendously from maize crop as primary production raw material (*Hearn, 2014*; *Ranum et al., 2014*; *Grote et al., 2021*). Maize differs from other cereals due to its high growth and yield potential, quality thus a valuable economic crop globally. Rice and wheat commonly known for production and consumption across Asia and Europe respectively, maize survives and adapts well in all corners of the world. Maize being a highly adaptive crop to different weather conditions, agro-ecological regions and cropping systems justifies its global significance.

Table 1 showing global production statistics of three major cereal crops by year 2023

Cereal	Cultivation area (million ha)	Production (million tonnes)	Average yield (t/ha)
Maize	200	1217	6.09
Wheat	220.7	789	3.57
Rice	160	538.8	4.7

FAO, 2024

The global maize cultivation and production is estimated at approximately over 200 million hectares and 1.2 billion metric tonnes annually respectively (*García-Lara et al., 2019*; *FAO, 2023*). The four major cereals include maize (1,151.36 tonnes), wheat (783.8 tonnes), rice (502.98 tonnes) and barley (150.48 tonnes) (*FAO, 2023*). Global statistics distribute the regional maize production share as America (49.6%), Asia (32%), Europe (10.9%), Africa (7.4%) and Oceania (0.1%) (Figure 1) while the five biggest maize producers as United States, China, Brazil, Argentina, and India (*FAO, 2021*) thus contributing tremendously to the world's food basket, food and feed markets as well as international grain trade (*Horváth et al., 2021*). Europe contributes almost 7.4% to the global maize production (*FAO, 2021*), purposely for both grain and silage. Prior to year 2022, highest maize producers of Europe were France, Romania, Hungary, Italy, and Ukraine. Agriculture in Europe benefits from advanced mechanisation and technology and research justifying the continental contribution to global maize production. However, challenges of climatic variability affect agriculture in general and maize production (*Ocwa et al., 2023*) thus causing cultivation changes and adaptation of better resource management strategies.

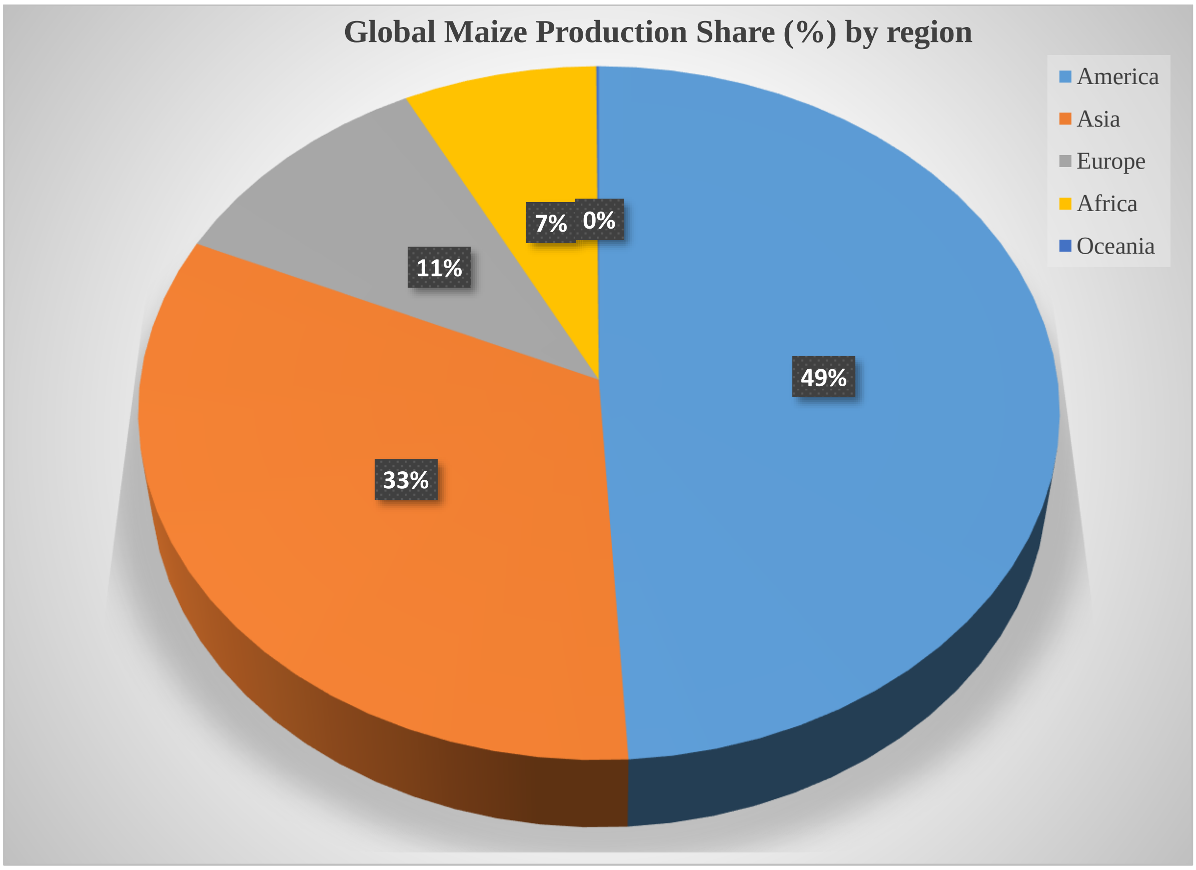


Figure 1 Global Maize Production Share (%) by region (*FAO, 2024*)

Wheat, barley, and maize (Figure 2) are majorly produced for consumption and export in Hungary (*Nagy, 2008*). Maize covers an estimated 1 million hectares of land, with a record 6–8 million tonnes as annual production and a significant increase has been registered over the last 23 years (Figure 3). Hungarian maize is utilised and distributed among exportation (48%), livestock feed (33%), agro-processing industry (18%), and seed production (1%) (*HCSO, 2022*). Food, livestock feed and several products namely, canned maize, isosugar, maize mush, as well as ethanol and distiller's grain are the major industrial products from maize in Hungary (*Széles et al., 2019*). To furnish above needs, optimum maize production is paramount to the economy and livelihood of Hungary. Maintenance of high maize grain yield and other cereals needs fertile arable land and sustainable agronomic practices such as fertilization (*Pakurar et al., 2004*; *Nagy, 2012*), water supplementation and irrigation (*D'Haene et al., 2007*; *Széles et al., 2012a*), favourable agro-climatic conditions (*Nagy, 1997*, 2010; *Bojtor et al., 2021*).

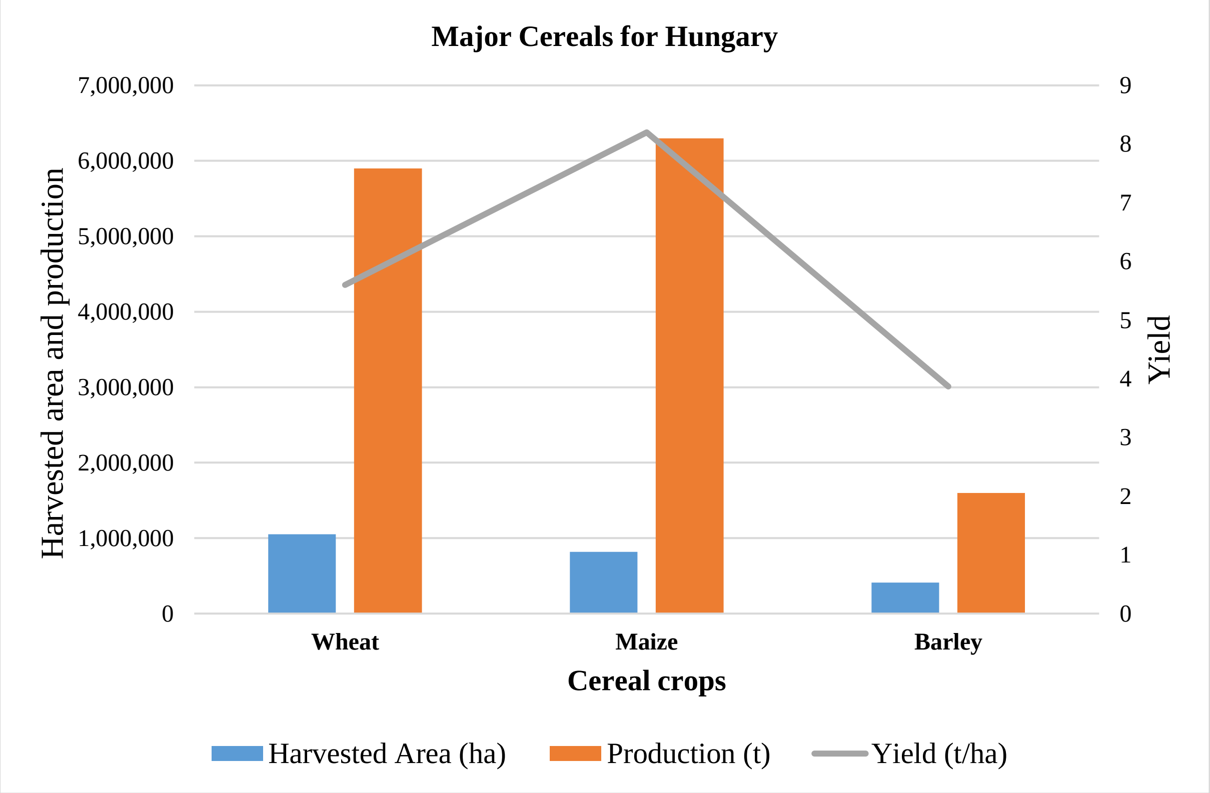


Figure 2 Major cereal production statistics for Hungary by year 2023 (Source: *HCSO, 2024*)

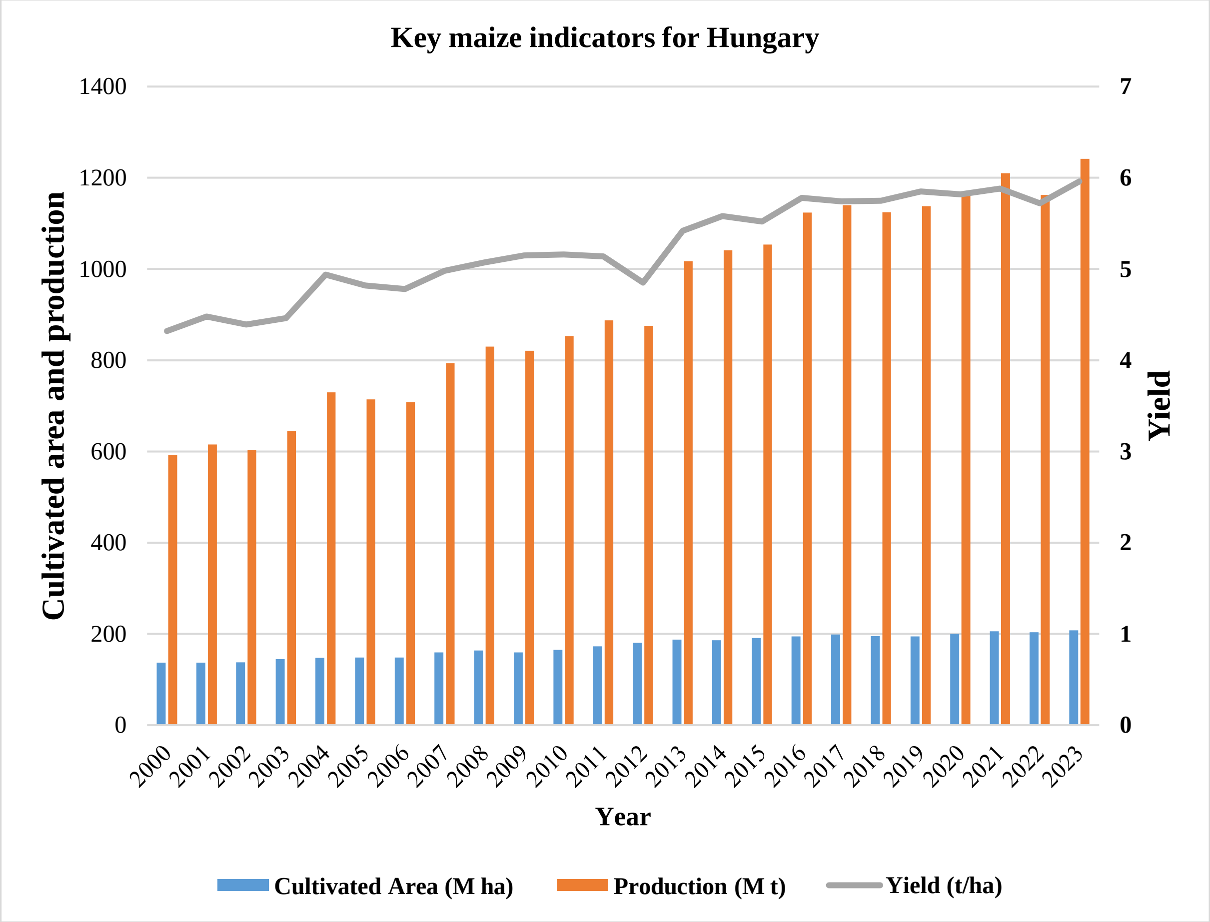


Figure 3 Key maize indicators for Hungary from 2000 to 2023 (Source: *HCSO, 2024*)

1.1 Factors that determine of maize production

Hybrid: Maize variety enhances yield (*Pepó & Karancsi*, *2017*), and growth, improved drying abilities (*Nagy et al.*, *1999*, *Széles et al.*, *2012b*, *Szabó et al. 2022*), improved digestibility and grain qualities (Torres et al., 2016), tolerance to cold stress conditions (*Sinka et al., 2021*), tolerance to high moisture stress conditions (*Khatibi et al., 2022*). Some maize hybrids (FAO340 and FAO410) are highly stable due to fertilisation (*Mousavi et al., 2020*). While others are highly tolerant to drought conditions such as KSC206, KSC704, KSC705 and KSC706 (*Shojaei et al., 2022*). Therefore, proper selection of maize varieties boosts maize growth, yield and quality when exposed to varying plant stresses in Hungary.

Major maize pathogens, pests and diseases across Hungary such as entomogenous nematode, western corn rootworm, aspergillus flavus, mycotoxins, Diabrotica Virgifera, beetles, Heterorhabditis Megidis, and weeds affect maize production. Due to adverse effects witnessed, several pest and diseases control programmes (*Szőke et al., 2011*) have been initiated to counter such detrimental effects on maize yields.

Drought conditions: Climate change has emerged as a disastrous factor affecting maize production causing global food shortages and poverty (*Elbeltagi et al., 2020*). High drought spells, reduced precipitation and increased temperatures have been recorded across European countries (*Spinoni et al., 2015*; *Alsafadi et al., 2020*), causing high production losses among farmers. Hungary has recently faced frequent drought spells affecting overall agricultural production (*Bartholy et al., 2007*), and severity of climate change expected to worsen during the 21st century (*Gálos et al. 2007*). There is a growing need to develop climate adaptation measures (*Ahmadalipour et al., 2019*; *Zhu et al., 2019*). Such measures are important to boost crop production and major cereal yields such as maize (Mohammed et al., 2022). Climate adaptation measures such as precision farming techniques, and selection of drought tolerant varieties (*Cherkasov et al., 2009*; *Balogh et al., 2020*; *DeLay et al., 2022*). The need for supplemental irrigation to improve yield (*Hamdy et al., 2003*; *Oweis & Hachum, 2009*), since provision of irrigation in maize fields enhances water use efficiency (*Kresović et al., 2016*). Application of precision dripping irrigation enhances ventilation and moisture of the soil (*Illés et al., 2021*).

Stress: Maize plant stresses affect yield (*Tóth et al., 2022*). Plant growth requirements including light, water, plant nutrients, precipitation and temperature affect maize production are major growth and yield enhancers (*Zhu, 2016*). Therefore, research should address availability of favourable factors through efficient utilisation by plants.

Soil fertility: Most of Hungarian soil has greatly lost its properties thus reduced maize production (*Pepó, 2006*). This calls for target measures that improve nutrient availability thus enhanced maize yield (*Pepó et al., 2006*; *Grassini et al., 2011*). Application of fertilisers such as NPK improves maize growth, development and yield (*Bojtor et al., 2021*). Micronutrients such as nitrogen greatly improve maize yield and protein synthesis (*Sangoi et al., 2001*; *Pikul et al., 2005*; *Tilman et al., 2011*), as well as partial compensation of adverse agro-technical plant requirements (*Nagy, 2006b*), but these plant nutrients should be supplied optimally at different growth stages (*Zang et al., 2007*; *Alley et al., 2009*).

Maize requires a good supply of nutrients and moisture at critical growth stages as this determines physiological maturity (*Wang et al., 2021*; *Illés et al., 2022*). Industrial development of foliar fertilisers in Hungary has taken centre stage to counter soil nutrient and moisture deficiencies detected by the application of precision agriculture technologies. Assessment of such foliar fertilisers, their efficiency and effectiveness are vital as this addresses the knowledge and production gap between research and farmers as the final consumers. Recent studies have focused on studying single micronutrient effect such as nitrogen, phosphorous, zinc, iron, boron etc with less focus on the combined effect of micronutrients through foliar fertilisation on maize. Therefore, our study hypothesis is how the efficient application of a combination of different foliar products under precision drip irrigation systems enhances physiological growth, yield and yield components, and grain quality. The study objectives are:

a) Determine the effect of precision drip irrigation and foliar fertilisation on physiological growth traits of maize.

b) Assess the yield and yield components of maize under foliar fertilisation and precision drip irrigation.

c) Evaluate the grain quality response to foliar fertilisation and precision drip irrigation.

d) Correlation analysis between physiological growth traits, yield components and overall grain yield.

2. LITERATURE REVIEW

2.1 Maize breeding in Hungary, maize varieties/hybrids and their characteristics

Breeding of maize hybrids opened the chapter of Hungary's maize research through crossing different varieties in 1933 by Rudolf Fleischmann who managed to develop 12 cross hybrid varieties. Research led by László Berzsenyi-Janosits yielded 171 varieties by 1948 (*Russell, 1984*), however state registration conducted in 1953 recognised only four hybrids and these included *Óvári* 1, *Óvári* 3, *Óvári* 4, *Óvári* 5. This great research breakthrough was the genesis of maize hybrid research for Hungary. Martonvásári 5 (Mv 5) hybrid was developed through inbred line crossing by Endre Pap a native of Mindszentpuszta during the year 1953 (*Jánossy et al., 1957*). The development and registration of Mv 5 marked the first maize hybrid in Hungary and Europe (*Jánossy et al., 1957*; *Russell, 1984*). Martonvásári 5 (Mv 5) hybrid has different traits such as higher grain yield, higher stability and adaptability, mid-early maturing and ripening variety thus an important and favourable maize variety grown in most regions of Hungary and other European countries (*Ssemugenze et al., 2024*). The above maize research breakthroughs initiated the establishment of maize hybrid experimental stations in different parts of Hungary; In 1958, Debrecen, Mezőnagymihály, Baja, Boly, Murony, Mezőhegyes, whereas between 1959-1964, Hódmezővásárhely, Szenttamás, Dalmand, Mosonmagyaróvár, Cegléd and Mezőfalva, (*Russell, 1984*; *Jánossy et al., 1957*; *Berko & Horváth, 1993*) were established. Such infrastructural development laid a strong foundation for maize research to thrive in Hungary.

Since Mv 5 registration in 1953, almost every region of Hungary had adopted production of hybrid maize by 1964 (*Berko & Horváth, 1993*). Recent research showed hybrid performance in Hungary; Maize hybrids that are early maturing like GK Siló and Mv Vilma perform well in northern parts of Hungary while mid and late maturing hybrids such as Sze 403 and Mv Hópehely have high biomass and grain yield potential adopting well in the southern regions (*Russell, 1991*). The yield potential of hybrids was 7–11% (*Frey, 1971*) and 49% (*Kovács & Szundy, 1991*) for hybrids developed in the 1960s compared to those developed before. A higher yield difference was recorded between 1980's maize hybrids (66.4%, 4.21 t/ha) compared to the 1930's open-pollinated varieties including 'Jubileum' and 'Debreceni sárga' characterised by adaptability and moderate yields (*Badu-Apraku et al., 2023*) with a 27.5% (2.28 t/ha) yield (*Russell, 1984*). Hybridisation in maize improved the plant stocking density compared to varieties developed through open pollination in 1930s (*Russel 1991*). This set the research direction and investment into development of maize hybridisation thus boosting Hungary’s maize production. Hybrids FAO340 and FAO410 have higher stability due to NPK application (*Mousavi et al., 2019a, 2019b, 2020; Mousavi & Nagy, 2021*), single cross maize hybrids such as SC647, KSC206, KSC704, KSC705, Szegedi 386, Mv NK 333, and KSC706 have higher drought tolerance traits (Khatibi *et al.* 2022), Sushi, SY Minerva, P0217, Fornad, DKC4792, Loupiac, and Armagnac have higher specific response to nutrients (*Szabó et al., 2022*), Gyöngyhajnal, Nugát 72, Strongstar, and Sweetstar have a higher tolerance to cold stress (*Sinka et al., 2021*), P9494 and SY Afinity hybrids had a higher grain yield potential due to application of NPK fertilisers (*Illés et al., 2021*). Maize hybridisation has improved yield, stability, grain quality traits, stress resistance, resource-efficient cropping systems and a solution to changing climate (*Pepó, 2006; Pepó et al., 2008; Badu-Apraku et al., 2023*). Hungarian bred maize hybrids possess a higher plasticity thus high adaptation across diverse types of soil and climatic regions within Central Europe according to genotype-by-environment interaction studies by *Davis et al., (2025)*.

Recently the integration of precision agriculture and digital phenotyping into maize research has enabled application of tools to evaluate the physiological, yield and grain traits including chlorophyll content, plant canopy, root architecture thus improved selection for plant stress resilience and yield efficiency (*Széles et al., 2024*). Application of molecular genetics such as marker-assisted selection (MAS) and genomic sequence (GS) has improved maize production in Hungary through the identification of QTLs responsible timely flowering, drought, heat, salt and cold tolerance, and disease resistance (*Gelybó et al., 2018*). Maize breeding programs in Hungary have registered success through development of high-yielding, and resilient maize hybrids. The future of maize breeding lies in integration of genomics, precision digital agriculture, and application of sustainable crop management practices.

2.2 Irrigation methods

The global cropland area equipped with irrigation recently hit almost 22.5 percent by the year, 2022 accounting for ~354 million hectares. Irrigation systems in Hungary covers an estimated area of 300,000 ha however, an average of 100,000 ha represent the actual irrigated area (*FAO, 2016)* (Table 2). The three main irrigation types of Hungary include sprinkler irrigation (83.75%), surface irrigation (13.41%) and micro irrigation (2.84%) with sprinkler systems the most used irrigation technology (Figure 4). The climatic zones of Hungary include warm temperate dry and cold temperate dry according to the Hungarian Meteorological Service

(HMS), 2019. The annual precipitation of Hungary has shown to be lower compared to the annual evapotranspiration which has resulted into drought spells for the previous years (*Huzsvai et al., 2020, 2022)*. There has been an increased frequency and intensity of droughts in Hungary in previous years. The increased global water scarcity calls for improved and application of efficient irrigation technologies and management systems to counter high drought incidences (*Tsang & Jim, 2016*). Maize water requirement must be distinguished from static water demand and absolute water consumption. Maize is referred to as a moderate water consumer (450-550 mm) with a daily water consumption ranging between 45-55 m^3/ha. Maize static water requirement (average 67-79%) refers to the percentage pore soil volume filled with water and the air percentage used. *Pepó & Sárvári, (2011)* noted that the maize transpiration coefficient refers to the used amount of water (350 l/kg) required in production of dry matter (1kg).

Table 2 showing irrigated area of Hungary

Year	Irrigated land area (hectares)	Percentage irrigated land area of total agricultural land (%)
2010	44,858	0.88
2011	101,046	1.98
2012	124,944	2.45
2013	118,934	2.33
2014	99,335	1.94
2015	80,529	1.58
2016	97,741	1.91
2017	101,405	1.98
2018	96,849	1.90
2019	101,097	1.98
2020	111,850	2.19
2021	110,506	2.16
2022	133,126	2.61

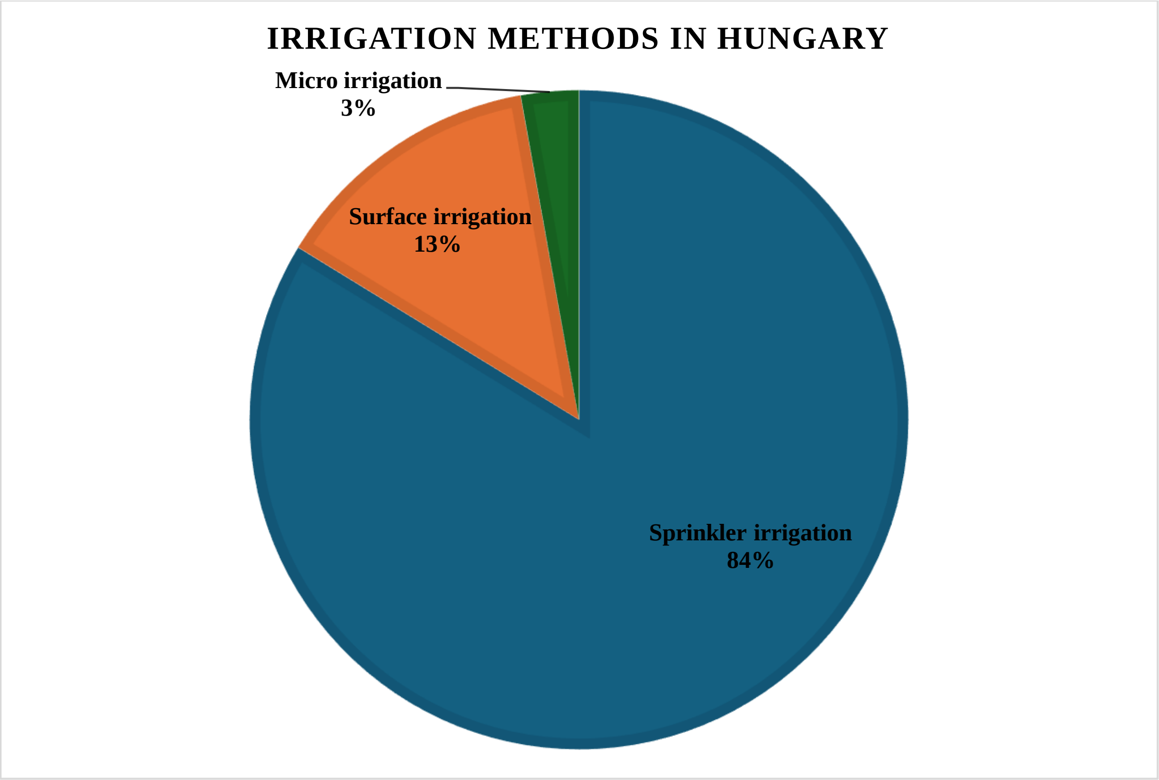


Figure 4 Irrigation methods majorly practiced in Hungary

Linear irrigation among the dominant irrigation methods of Hungary occupies (65%), while rain gun irrigation systems and centre pivot irrigation cover 16% and 15% respectively (*Dukes, & Perry, 2006)*. Linear irrigation saves 50% of irrigation water compared to surface and sprinkler irrigation methods (*Zakari et al., 2014; Szabo et al., 2021*). Challenges associated with linear irrigation include the high channel density associated with the Hungarian Great Plain. Most linear irrigation machines are outdated with less availability of GPS thus preventing variable-rate irrigation (VRI). This means that Hungarian farmers carryout irrigation at a constant irrigation rate, with minimal consideration of the field spatial heterogeneity causing overirrigation and underirrigation (*Kumar et al., 2017*). Precision irrigation including variable-rate irrigation (VRI), improves efficiency of water application thus ensuring optimal water supply (*Evett et al., 2006*). The University of Debrecen collaborating with Magtar Kft developed the first lateral mobile irrigation machine equipped with VRI in Hungary. This system has proved to achieve high and homogeneous irrigation uniformity, and a percent Christiansen uniformity coefficient (93±2), percent distribution uniformity (88±2) and variation coefficient (9±2). The system achieved a satisfactory irrigation accuracy; mean absolute error, mean bias error, and normalized root mean square error. The system recorded a lower percent over irrigated and under irrigated of 1.4%±2% and 0.4% ±0.3% respectively. There were significance differences ($p<0.05$) of irrigation uniformity and accuracy when the system was tested in several cropping zones along the pipeline between irrigation water depths. Therefore, this lateral VRI mobile irrigation machine achieved irrigation uniformity and accuracy of schedules in crop fields enhancing saving water during irrigation (*Szabó et al. 2023*).

Dripping irrigation offers an effective ventilation of soil with suitable soil moisture content (*Ghamarnia et al., 2013*). Drip irrigation, through a process known as fertigation or chemigation, enables the precise application of fertilizers and other essential agricultural chemicals directly to a plant's root zone. This reduces groundwater pollution due to leaching of fertilisers and toxic materials (*Yufenga et al., 2021; Yang et al., 2023*). Precision drip irrigation has modified modern irrigation efficiency thus optimisation of water consumption, improvement of irrigation method under field pressures thus increased productivity among other irrigation methods (*Merry, 2003; Yang et al., 2018*). Micro-sprinkler irrigation offers a suitable way of microclimate modification. Micro-irrigation influences fruit micro-climatic parameters namely, temperature, air, and humidity. Irrigation has an evaporative cooling effect thus modifies the surface temperature of plant mainly when the temperature of air is higher (~20°C) (*Iglesias et al., 2005*).

2.3 Bibliometric review of irrigation and fertilisation in Hungary

Figure 5 shows the bibliometric network visualisation generated by VOSviewer showing the main research areas and trends related to irrigation studies. The map is structured around keyword co-occurrence, where node size represents the frequency of terms and link strength indicates the degree of association between topics. “Irrigation” appears as the central and most dominant node, highlighting its pivotal role in the literature, and is strongly connected to key themes such as “crop management”, “water”, “evapotranspiration”, and “climate change”. The clusters reveal the interdisciplinary nature of irrigation research in Hungary. Agronomic themes are reflected by terms such as “soil”, “growth”, “biomass”, “maize”, and “nitrogen”, while environmental and climatic aspects are represented by “temperature”, “water requirements”, and “responses”. Technological advancements are also evident, with emerging keywords like “machine learning”, “artificial intelligence”, “GIS”, and “prediction”, indicating a growing integration of digital tools in irrigation management. Additionally, terms such as “drip irrigation”, “groundwater”, and “salinization” highlight concerns related to water use efficiency and sustainability. Overall, figure 5 demonstrates that irrigation research is increasingly shifting towards integrated, technology-driven approaches aimed at improving water use efficiency and ensuring agricultural sustainability under changing environmental conditions.

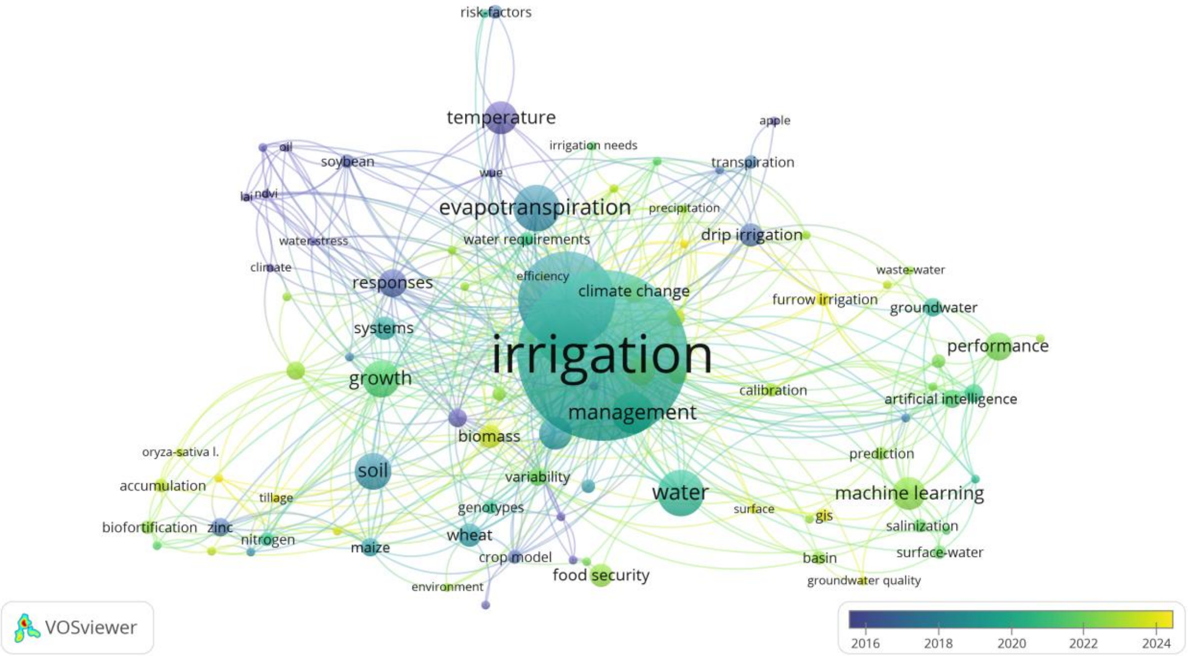


Figure 5 Recent research studies on irrigation, and effects on yield, quality and stress alleviation in Hungary indicated in yellow and green colours.

Source: Vosviewer analysis of recent literature from Web of Science database by author

Figure 6 illustrates the structure and evolution of research on foliar fertilisation, micronutrient management, and their effects on maize production. The map is based on keyword co-occurrence, where node size reflects the frequency of terms and link strength indicates the degree of association between research topics. The central position of “maize”, “yield”, and “foliar application” highlights their dominant role in the literature, with strong connections to “soil”, “nitrogen”, “grain yield”, and “quality”, indicating the close relationship between nutrient management and crop productivity. Distinct thematic clusters can be identified, including plant physiological processes (“photosynthesis”, “chlorophyll”, “translocation”), stress-related responses (“drought”, “salinity”, “abiotic stress”, “tolerance”), and nutrient-specific research (“zinc”, “boron”, “iron”, “manganese”, and “biofortification”). The network also reveals growing attention to advanced approaches such as “nanoparticles”, “biostimulants”, and “foliar fertilization technologies”, reflecting innovation in nutrient delivery systems. Overall, the figure demonstrates that current research is increasingly integrating foliar fertilisation with plant physiology and stress adaptation strategies to enhance maize yield, nutritional quality, and resilience under changing environmental conditions.

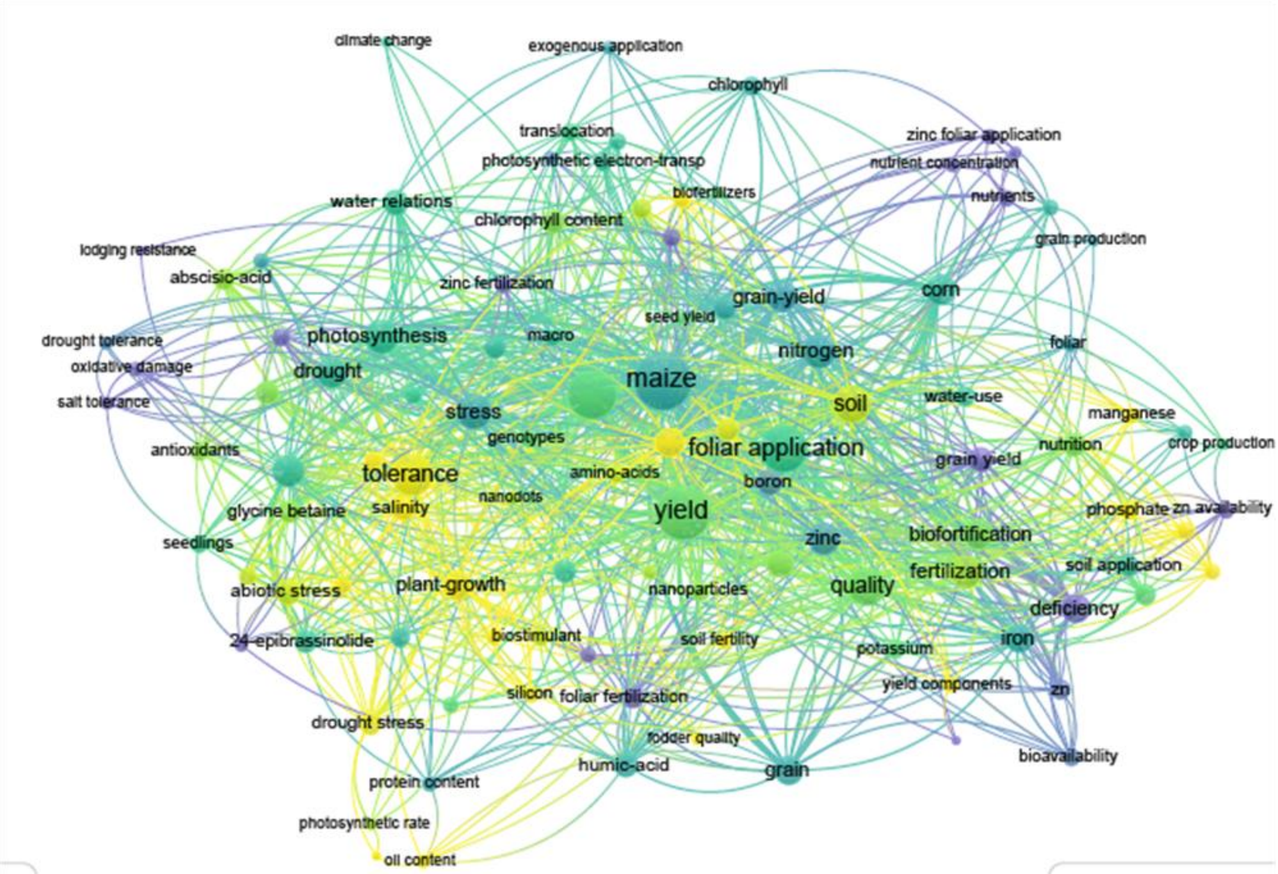


Figure 6 Recent research studies on foliar fertiliser application, micronutrients applied and effects on yield, quality and stress alleviation in Hungary indicated in yellow and green colours. Source: Vosviewer analysis of recent literature from Web of Science database by author.

2.4 Fertiliser application methods

A fertiliser refers to any material that contains nutrients different forms that is soluble or other forms that have been prepared in natural and synthetic form and origin applied directly to soil or plant tissues supplying nutrients to plants to support growth. Fertilisers include D.A.P, Urea, N.P.K, Super Phosphate (*Brady & Weil, 2016*).

Broadcasting method: This fertiliser method also known as shying that involves uniform spreading of fertilisers over the field. It’s mainly suitable for crops sown through seed broadcasting. After ploughing of land, the fertiliser is broadcast by mixing it with soil manually or using different machinery such as soil ploughs and cultivators (*Zhang, 2012*). Broadcasting fertilisation offers several advantages like uniformity of nutrient application across the soil surface, ease of operation, simplicity and scalability (*Brady & Weil, 2016*). Broadcasting fertilisation method is mostly and widely used fertilisation method by farmers mainly practising under surface irrigation. Shortcomings of broadcasting method include high volatility, loss of nitrogen, and non-uniformity of fertilizer due to soil erosion and rapid water flow attributed to field irrigation. Once solid fertilisers are spread all over the surface of basin along the basin length which induces and risks fertilisers being carried away by irrigation water to the basin tail in a process termed as backward warping. This leads to fertilisation inefficiencies and pollution of near water bodies. *Potcho et al. (2022)* noted that a high loss of nutrients due to leaching, volatilization, and surface runoff thus reduction of fertilizer-use efficiency mainly nitrogen-based fertilisers such as urea. Farmers easily adopt broadcasting method due to its low-cost effectiveness and availability of alternative placement techniques however deep placement, fertigation and banding fertilisation methods have high significant uptake of nutrients and yield output when applied across different cropping systems as well limiting emission of greenhouse gasses (*Zhang et al., 2020*).

Deep fertiliser placement/application

Fertiliser placement involves placing the fertiliser closely to the plant in form of spots or bands. Spot fertiliser placement involves placing the fertiliser approximately 5cm (2 inches) from the seed or 5cm into the soil to avoid leaving being left exposed on the soil surface causing fertiliser losses (*Du et al., 2018*). Spot placement commonly used for crops including cereals and vegetables because of the large seed size. Band fertiliser placement involves placing fertilizers in bands on row sides about 5cm below the seed and 5cm away from the seed/plant. More appropriate for crops with high insensitivity to direct fertiliser contact (*Wu et al., 2017*). Deep fertiliser application maintains and enhances nutrient use efficiency by plants through improvement total above-ground biomass and grain yield when compared to other surface broadcasting methods (*Li et al., 2020*). This method reduces fertilizer application volumes however maintaining crop yield in maize (*Guo et al., 2016*). Burying the fertiliser into the soil close to the plant root increases fertiliser absorption by plants promoting plant growth during the early development stages (*Zhu et al., 2019*). When nitrogen fertilisers are applied through deep fertilisation, it reduced emission of CH_4 and NO by 40% and 54% respectively in rice fields (*Du et al., 2018*).

Fertigation: Fertigation refers to dissolving fertilisers into irrigation water supplying it through an irrigation system to crops (*Adamsen et al., 2005*). Under this method, fertilisers are incorporated into irrigation water in an open or closed system so that they are applied at once (*Ibrahim et al., 2016*). Open fertigation system mainly applies for both furrow and flood types of irrigation which involves lining and unlinking of open ditches and gated pipes. On the other hand, closed fertigation systems include sprinkler and trickle irrigation systems (*Li et al., 2021*). Through fertigation, macro and micro-nutrients are applied to the plants such as nitrogen and sulphur whereby these fertilisers dissolve into the irrigation water then transported through the stream to the soil and absorbed by the plants. Fertigation saves fertiliser application costs since it utilises relative less expensive irrigation water. High levels of fertiliser application aimed at intensifying agricultural production and productivity increases pollution due to increased nutrient levels in both underground and surface waters (*Dixon et al., 2022*). Thus, efficient plant nutrient management through careful application of fertilisers is required, efficient irrigation systems where irrigation water is precisely delivered around plant roots through methods like fertigation enabling rapid and uniform distribution and uptake of plant nutrients. Irrigation water with dissolved fertilisers is delivered to the crop field whereby devices are used to control the timing and amount of fertiliser being applied (*Xie et al., 2020*). Fertigation is applicable to different planting patterns and agro-climatic conditions due to its accuracy and flexibility of the irrigation management systems. Advantages of fertigation include saves time and labour, and higher efficiency levels as fertilisation time can be controlled thus improving both the spatial and temporal soil water and nitrogen distribution enhancing irrigation and fertilization uniformity (*Dixon et al., 2022*). A study comparing the performance of both broadcasting and fertigation fertilisation method, based on uniformity and efficiency of fertilisation, and fertiliser amount. It was found that fertigation had a 14.5%, 14.3%, and 8.4% compared to broadcasting method (*Singh et al., 2019*). However, fertigation requires a high-cost investment to equip required facilities such as fertilising tanks and pumps and thus difficult to apply on non-cash crops and other subsistence farmlands under surface irrigation (*Dixon et al., 2022*).

Foliar application method

Fertilisers are applied directly to the plant foliage in form of a liquid spray where absorption of limited quantities of nutrients occurs (*Patil & Chetan, 2018*). Foliar fertilisation serves as a precision sustainable and management tool to apply nutrients to crops in liquid form (*Jemo et al., 2015; Froese et al., 2020*). It mitigates the plant stress impacts at critical growth stages as fertilisers can be easily applied anytime to fix a given stress (*Niu et al., 2021*). This method of fertiliser application provides essential plant nutrients as well as tolerance and alleviation of different stress factors, enhances chlorophyll content, rate of photosynthetic activity, improves crop resistance to pests and diseases (*Elmer & White, 2016*).

Through the precious application of nutrients at the required time and right quantities optimises plant growth. Foliar application minimises the time of absorption of nutrients by the plant and when fertiliser application was done (*Pinciroli et al., 2019; Tóth et al., 2022*). When *Waraich et al., (2011)* applied required nutrients at grain initiation stage through foliar method, it optimised grain number per plant. Due to foliar application of nano-sized fertilizers, quick nutrient deficiencies where fixed mainly under severe conditions under which root absorption was constrained (*Peirce et al., 2019*). Swift absorption and assimilation of nutrients has been documented with nitrogen supplied as urea at 100% absorption rate in less than four hours (*Patil & Chetan, 2018*). Phosphorus application through leaves improved fertiliser use efficiency and its grain concentration (*Mcbeath et al., 2011; Brankov et al., 2020; Gorlach et al., 2021*). Foliar nutrient application enhanced nutrient use and absorption hence maximising crop yields, cob length, cob diameter and grains per row, increased starch and protein content of grains (*Amanullah et al., 2013; Ivanov et al., 2019; Racz et al. 2021*). Generally, foliage nutrient application offers higher absorption of rate compared to other fertilisation methods.

2.4.1 Comparison of foliar nutrient application with other fertiliser application methods

Using ZnO-NP fertiliser, a study compared foliar fertiliser application with broadcasting, banding, seed coating and soil-drenching fertilisation methods on maximisation of maize growth and yield grown in the field (*Hayat et al., 2023*). The fertiliser was applied at a level of; soil-drench (150 mg kg^{-1}), seed coating (100 mg kg^{-1}), and foliar (50 mg kg^{-1}) respectively. The total phosphorous uptake improved in all the methods, foliar fertilisation with the lowest amount of fertiliser applied managed to record a 6–11% and 16–20% increase in growth of maize and plant biomass respectively (*Ali et al., 2016*). Compared to seed coating methods, phosphorous foliar application increased cob length, plant height (2%), and seed emergence rate, maize growth and yield significantly improved (*Thakur et al., 2023*). This proved that foliar fertilisation required the less amount of fertiliser to effectively produce better results compared to other fertiliser application methods.

Comparison of foliar fertiliser application with soil application showed that there a significant positive effect on chlorophyll fluorescence parameters due to foliar application ($r = 0.8414$), while on the other hand chlorophyll content, plant mineral uptake (Fe and Zn) had a significant positive effect under soil application ($r = 0.6965$) according (*Ling & Silberbush, 2002; Dölger et al., 2024*) while maize plant growth and grain yield improved significantly due to both foliar and fertigation methods (*Stewart et al., 2021*). Basal and foliar nutrient application methods had no positive effect on maize growth and leaf nutrients according to (*Buligon et al., 2023*). When granular phosphorous was applied instead of foliar phosphorous application effectively raised the levels of phosphorous in the soil with minimised adverse effects (*Wasaya et al., 2021*). Maize growth improved when grown on permanent beds after substituting traditional granular application with foliar application of nitrogen (*Lamlom et al., 2024*). Foliar fertilisation offers an edge over other fertiliser application methods.

Comparing foliar fertilisation with splitting, fertigation, and soil application using potassium (K) fertilisers. Foliar potassium fertilisation improved growth of maize, grain yield, quality and yield-related traits. Analysis of net and cost benefit ratio proved that foliar application performed better than other methods (*Gazoulis et al., 2023*). Other studies concluded that; boron foliar application compared with basal fertilisation method recorded a 19.6% grain yield increase (*Wasaya et al., 2012*). alternate fertilisation reduced weed biomass by 28% with a 56% maize yield increase compared to conventional fertilisation according to (*Murawska et al., 2017*). Foliar nutrient application has proved more efficient over traditional nutrient fertilisation methods. Foliar fertilisation offers an alternate way to overcome challenges such leaching, soil pH, volatilisation, nutrient lock-up hence rapid nutrient absorption and utilisation by plants thus addressing plant nutrient deficiencies during critical stages of plant growth (*Ssemugenze et al., 2025*), an effective strategy boosting plant health and productivity. Several studies have as well documented foliar fertilisation as an effective and efficient supplemental approach to soil fertiliser application methods.

2.5 Grain yield stability and quality improvement through foliar application of nutrients

Nutrient replenishment has boosted maize yield (*Pepó, 2006*) across Hungary amidst declining soil quality (*Grassini et al., 2011*) thus impacting maize production. During short periods of growth, maize yields are enhanced through NPK fertiliser application (*Árendás et al., 2010*; *Tilman et al., 2011; Bojtor et al., 2021*). Precision fertiliser advancement like foliar application to plants controls supply of nutrients at different growth stages (*Zang et al., 2007; Alley et al., 2009*), mitigates pollution of environment and soil (*Wu & Liu, 2008*). Due to fertiliser application, maize rotation reduces by 50% (*Berzsenyi et al., 2000*). Unfavourable agro-technical requirement of plant nutrients can be catered for through fertilisation (*Nagy, 2006b*). Therefore, nutrient supplementation at different crop growth stages achieves the required yields.

Jakab et al. (2018) conducted a study in 2016 assessing foliar fertilisation effect on maize yield and quality using three different foliar fertilisers. The results showed that the yield obtained under foliar fertilisation (11.61-12.86 t ha^{-1}) was higher than that of control (11.37 t ha^{-1}). Though the difference wasn't significant, application of foliar products increased corn yield and grain quality. *Potarzycki & Grzebisz, (2009)* applied foliar zinc fertiliser at an optimal rate of 1.0 to 1.5kg Zn ha^{-1} on maize at 5th leaf stage. There was an 18% grain yield difference between foliar treatment and NPK-only treatments (*Jakab & Komarek, 2017*). The total nitrogen uptake and maize yield significantly increased due to zinc foliar application at 1.0 kg Zn ha^{-1}. Foliar fertilised plots recorded a 17.8% for number of kernels per plant and nitrogen uptake ($R^2 = 0.79$) compared to the NPK plot.

Tóth et al. (2022) evaluated the physiological and biochemical processes fodder corn by foliar application of zinc (Zn) and amino acids. The physiological parameters included relative chlorophyll content, and PSII effectiveness; biochemical processes included ascorbate peroxidase, guaiacol peroxidase, and superoxide dismutase activities, the malondialdehyde and proline concentration. Maize yield increment due to different foliar treatments was Zn (10%), Zn+AS1 (6%), and Zn+AS2 (10%). Foliar treatment improved cob and ear weight compared to the control. There was a positive significant effect on relative chlorophyll content due to Zn-treatment at different weeks of application according to *Ghani et al., (2022)*. Foliar application of Zn-containing fertilisers increased the activity of superoxide dismutase (SOD) which was an indicator of higher grain yield (t ha^{-1}) and cob weight (*Rajasekar et al., 2017*).

Artyszak et al. (2025) compared the effect of silicon-based products on maize yield and quality applied through both foliar and soil. NPK was applied to the soil at 100% and 50% levels. The composition of soil silicon-based fertilisers included Mg (46 g kg^{-1}), Si (200 g kg^{-1}), Mn (45 g kg^{-1}) and Ca (181 g kg^{-1}) applied at 100, 300, and 500 kg ha^{-1}, doses. Foliar fertiliser composition was Si (336 g dm^{-3}), and Ca (207 g dm^{-3}). The study evaluated different parameters namely, grain yield, dry matter content, moisture content, grain quality and yield components. A 17.5% grain yield increment was recorded due to soil fertilization dose (500 kg ha^{-1}), 16.4% yield increment due to foliar application at a fertilisation dose (300 kg ha^{-1}), and 17.8% yield increment due to combination of soil fertilisation + foliar application at a fertilisation dose at a dose (500 kg ha^{-1}). Grain yield due to 50% and 100% NPK treatment was (+11.9%) and (+12.6%) when compared with control. There was significant and beneficial effect on the grain quality parameters such as protein and fat content however a reduction in starch content was recorded.

Limon-Ortega & Baez-Perez, (2024) conducted an experiment in the Mexican volcanic belt testing performance of three phosphorous treatments applied through foliar spraying, and granular application by both (band and broadcasting methods) compared to control. The interaction of growth year and phosphorous treatment had a significant effect on agronomic efficiency (AE), recovery efficiency (RE) and grain yield. Year effect greatly affected grain quality parameters such as bulk density and 1000 grain weight. Foliar phosphorous application affected yield, agronomic efficiency (AE), recovery efficiency (RE) compared granular phosphorous application. There was a 26% decrease of the initial soil phosphorous (46 mg/kg) because of foliar phosphorous application. Therefore, replacement of the granular phosphorous with foliar phosphorous application offers a viable option to improve soil phosphorous level with minimal environment effects on maize performance.

Field and on-farm trails on micronutrient conducted in the USA between 2013-2015, 26 testing foliar application effect of micronutrients on maize yield at different nutrient concentrations. Foliar spraying was conducted from V6 to V14 growth stages at different farm locations with 10.9 to 16.4 Mg ha^{-1} of yield. Minimal positive significant grain yield was recorded. Micronutrient concentrations applied at 4 to 9 mg Zn kg^{-1} improved the growth of maize leaves at 5 of 17 sites while 87 to 119 g Zn ha^{-1} rate improved leaf growth at 2 of 17 sites. Only Mn ($r = 0.54$) had a direct relationship with grain yield compared to others. Sites that had iron deficiencies recorded a 0.4 Mg ha^{-1} due to application of Fe at 123 g ha^{-1}. Thus, maize yield can be increased due to foliar iron application mainly under Fe deficient soils *(Stewart et al., 2020).*

Ssemugenze et al. (2025) conducted a review to synthesise literature on application of foliar fertilisation and its effect on maize. A strong positive ($R^2 = 0.7842$) relationship was noted in publication trends on maize foliar fertilisation. The review noted that the major micronutrients applied to maize through foliar sprays included zinc, nitrogen, potassium, iron, phosphorous, and manganese *(Kovacevic et al., 2006).* It was noted that the timely foliar nutrient application offered a viable option to correct different soil nutrient deficiencies thus sustainable supply of nutrients due to different abiotic and biotic stresses. Parameters such as grain quality, kernel size, and grain weight were impacted at flowering and grain filling stages due to foliar fertiliser application. *Rácz et al. (2021)* studied the effect of Nitrogen (N) stabilizer (Nitrapyrin) and foliar fertiliser application on stress indicators amongst three maize fodder hybrids (*Zea mays* L., FAO490, Kite Zrt.). The treatments included control, Nitrapyrin, foliar fertilizer, Nitrapyrin + foliar fertilizer). This study measured the rate of lipid peroxidation, proline content, and chlorophyll content. The study findings showed that Nitrapyrin impacted on use and efficiency of nitrogen in maize as indicated by reduction in activity of proline, MDA, and SOD with increased rate of photosynthesis resulting from improvement from nutrient supply of Nitrapyrin and foliar fertilisation.

2.6 Physiological growth improvements due to foliar nutrient application

Maresma et al. (2016) studied plant height and SPAD using UAV for grain yield prediction when maize was side dressed in nitrogen fertilisers applied before flowering stage. Both inorganic nitrogen doses and inorganic-organic nitrogen combinations were applied. Wide Dynamic Range Vegetation Index (WDRVI) was used as a spectral index explaining final grain yield of different nitrogen treatments. The application of extra nitrogen at an optimum rate of 239.8 kg N ha^{-1} showed no significant effect on plant height, WDRVI, and NDVI yielding a grain yield (16.12 Mg ha^{-1}). The study ranked plant height and vegetation indices and were used as predictors of yield at V12 physiological growth stage.

Balaout et al. (2022) conducted an experiment at Látókép Experimental Station of Plant Production in the year 2021 to study different foliar fertilisers namely, Zinc, Natur Plasma T biostimulant, Sulphur Mono additives, Natur Active complex. Two maize hybrids to include FAO350 and FAO510 were sprayed with foliar fertilisers at the 8th leaf stage examining treatment effect at physiological critical growth stages (12th leaf stage, silking, and maturity) and yield of maize. The application of nutrients by foliar spraying had a positive effect on both SPAD and NDVI. Both hybrids (FAO350 and FAO510) had a higher grain yield percentage (9% and 5.4%) compared to control. However, hybrid FAO350 had higher grain yield (21.345 t ha^{-1}) than FAO510.

Kandil et al. (2023) designed a split-plot experiment that investigated the effect of maize biofortification when grown under irrigation applied at 15 days, 20 days and 25 days respectively. The foliar treatments included silver nanoparticles (AgNPs), Zn + AgNPs, silicon (Si), Si + Zn, zinc (Zn), Si + AgNPs, and Si + Zn + AgNPs) during 2020-2021 growing season. Both grain yield and quality were impated by irrigation at an interval of 15 days while foliar application of Zn, Si and AgNPs minimised water stress due to extended irrigation intervals thus improving grain yield, physiological plant growth, as well as yield components (Awad et al., 2021; Idrees et al., 2024). 100-kernel weight (KW) alongside other parameters were positively improved at 15-days irrigation interval combined with foliar application of AgNPs + Zn, apart from proline content. Irrigation at 25-day interval alongside foliar application of Si

+ AgNPs + Zn yielded the highest protein and proline content however negatively impacted the harvest index (Gao et al., 2004). The overall best combination of irrigation and foliar nutrient application was irrigation at 15-day interval combined with foliar application of (Zn + Si + AgNPs), followed by irrigation at 15-days combined with foliar application of (Si + AgNPs). Therefore, a combination of irrigation and application of foliar nutrients such as Si, Zn and AgNPs at the appropriate intervals potentially improves grain yield and quality under water stress conditions.

Potassium (K) as a plant nutrient promotes plant growth, grain yield, and quality parameters mainly under water deficit conditions. Maize grown in semi-arid conditions responded differently to soil and foliar potassium application methods during the 2013-2014 in Pakistan under moisture stress conditions *(Amanullah et al., (2016)*. Foliar potassium (K) and Zn application at 1–3% and 0.1–0.2% rates respectively improved plant physiological growth, increased maize yield and improved grain yield traits *(Wasaya et al., (2012)*. Comparison of spraying time showed that when foliar nutrients (K and Zn) were applied earlier during the vegetative stage had better effect on plant growth and yield than foliar spraying at the reproductive stage *(Amanullah et al., (2016)*. Both fertiliser application methods had better effect compared to the control justifying the impact of fertilisation on maize production and growth improvement.

A study by *Henningsen et al. (2022)* investigated the photosynthetic traits, potassium nutritional status, and physiological growth of potassium deficient maize varieties. Potassium deficient plants were monitored for leaf gaseous exchange, foliage potassium absorption, SPAD, rate of re-translocation, and plant biomass production for 21 days after foliar spraying with potassium. Foliar spraying of potassium had a positive significant effect on assimilation of carbon dioxide, and SPAD as well as enhancement of biomass production. There was also increased concentration of potassium and Se within plant tissues when compared to control an indication that potassium was strongly absorbed by the plants (Wang et al., 2013). Although, potassium spraying improved plant growth during the study period, however, the levels of carbon dioxide assimilation and potassium concentration reduced with days following foliar spraying (*Ma et al., 2021*). Therefore, foliar application of potassium significantly effected physiological plant growth, however, couldn’t offer the long-term restoration of plant functionality amongst potassium deficient maize plants.

Matłok et al. (2021) conducted a study that assessed different plant fertilisation technologies applicable to maize grown under field conditions namely, innovative foliar and soil application nutrient methods. Normalized Difference Vegetation Index (NDVI) as a nutritional status plant growth parameter was assessed to correlate it with the grain yield. The study results showed that the complex fertilisation technologies such as innovative foliar fertilisation applied on maize proved to be most effective and efficient. Treatment recorded a 42.4% higher grain yield compared to that of the control.

2.7 Maize production improvement through precision drip irrigation systems

Ocwa et al. (2024) assessed plant growth traits, chlorophyll fluorescence, photosynthetic system II, electron transportation rate (ETR), crop yield, yield components and grain quality. Precision drip irrigation had a positive significant effect ($p<0.05$) on height of maize plants, chlorophyll fluorescence, SPAD, NDVI, yield components, ΦPSII and ETR, and crop yield. During the 2022 and 2023 study seasons, precision drip irrigation had a yield of 9.5 t ha^{-1} and 2.1 t ha^{-1} respectively marking a 250% and 12.1% yield increase respectively. Precision drip irrigation increased grain starch content, however, both protein content decreased by -2.1 and -0.5% respectively for 2022 and 2023 seasons. Biostimulant application under precision drip irrigation optimised grain yield during the year 2022 which had a higher water stress than 2023.

A study assessing performance of seven hybrids under both drip irrigation and non-irrigated conditions. There was no significance difference for the cob dry matter content (DMC) for both conditions (*Zulfiqar et al., 2017)*. However, correlation studies indicated that when dry matter content increased, there was a decrease in cob moisture content (MC) amongst sweet corn varieties under irrigated and non-irrigated conditions. The study proved that both dry matter content and moisture content are critical yield index factors under irrigation conditions. Hybrid performance showed that; the Dessert R72 maize hybrid had the highest yield of 10.82 t ha^{-1}, high Brix/Abbe effect, the Messenger hybrids had the highest cob moisture content. Both Noa and Honey hybrids had the lowest performance under both irrigation and non-irrigation regimes. Messenger and SF1379 hybrids recorded the highest Brix Abbe and Brix Pal performance of 11.25% and 10.5% respectively under irrigation conditions while Dessert R78 the Messenger hybrids recorded the highest Brix/Abbe and Brix/Atago Pal-1 of 13.5% and 11.8% under non-irrigation conditions (*Illés et al., 2022*).

Széles et al. (2024) noted that precision technologies in agriculture offer real time field observations through specialised equipment regarding crop health, chlorophyll and nitrogen content, and soil moisture content. By the help of Unmanned Aerial Vehicle, maize growth including SPAD, and NDVI were monitored for yield under different water regimes during the 2022 growing year. A statistically positive effect ($p<0.05$) was observed for NDVI between irrigated and non-irrigated conditions while SPAD under non-irrigated conditions was significant ($p< 0.05$) at all growth stages (V6, V8, R1 and R3) recording percentage increase of 14.7 % (V6 and V8), 13.9 % (R1) and 30.6 % (R3) among all treatments. Both NDVI and SPAD increased with growth stages but reduced at later growth stages nearing physiological maturity. Irrigation had a positive effect ($p<0.05$) the overall grain yield by 37.2% compared to rainfed treatment. A study conducted at Látókép Experimental Station of Plant Production on FAO370, FAO390, FAO370 and FAO350–400 assessed the water supplementation effect maize yield and grain quality during the 2019 growing year. Irrigation increased maize yield among all the hybrids studied compared to control treatments (*Virág et al., 2020*).

Ehret-Berczi et al. (2022) made a cost benefit and profitability analysis of growing sweet corn in Hungary amidst increased drought effects. The study noted that irrigation so far covers a total of approximately 144 thousand ha. Irrigation has presented an opportunity to expand agricultural cultivation to different parts of the country. Irrigated area of sweet corn expected at approximately 33.6 thousand ha whereby 9.8 thousand ha have been installed with irrigation systems while 23.8 thousand ha require extensive irrigation infrastructural establishment to meet the required irrigation demand. The study concluded that the cost of producing corn under non-irrigated conditions ranged between 1.2-1.9 thousand EUR ha^{-1} compared to 1.5-2.78 thousand EUR ha^{-1} under irrigation conditions. Therefore, irrigation should be able to increase grain yield to meet the cost requirement and increase farmers' profit margin.

Drip fertigation a growing agricultural technology that aims at increasing grain yield while conserving water and fertiliser in the field. *Du et al. (2024)* conducted a 4-year experiment assessing maize phenology, plant biomass, rate of photosynthesis, grain filling, and grain yield. Drip fertigation improved phenology, plant biomass accumulation, grain filling, and translocation thus positively increasing ($p<0.05$) maize grain yield (*Hussain et al., 2020*). Drip fertigation had a significant impact ($p<0.05$) on leaf chlorophyll content which directly translated into better photosynthetic rates, and increased leaf area index (*Popova & Kercheva, 2004)*. Drip fertigation increased plant biomass by 29.5% and 23.1% at and after silking stage compared with other treatments. There were prolonged days of grain filling under drip fertigation which significantly led to an increase of grain weight of 100 kernels, and grain yield (*Simkó et al., 2020*). Overall, when drip fertigation was compared with other treatments, both grain yield and plant biomass had a percentage increase of 34.3% and 26.8%. The results justify the impact of drip fertigation on maize.

Liu et al. (2023) conducted a 7-year experiment between 2015-2021 evaluating performance of drip irrigation and conventional border irrigation method on physiological growth of maize, water use efficiency (WUE) and technology profitability. Drip irrigation had better results on height of maize, leaf area index, grain yield, water use efficiency and was highly economical compared to conventional border irrigation method. Drip irrigation recorded a percentage increase of dry matter translocation (27.44%), and dry matter transfer efficiency (13.97%) compared to border irrigation method. Drip irrigation increased yield, WUE and irrigation water use efficiency (IWUE) by 14.39%, 53.77% and 57.89% with an economic benefit and net return of 756.58 (22.88%) and 1998.87 (60.90%) USD hm^{-1}compared to border irrigation. Conclusively, this study demonstrated how growth, yield, water use efficiency and economic returns of maize were realised because of drip irrigation.

Analysis of soil moisture content, growth of maize, crop coefficients, water consumption, and crop yield was done on maize under drip irrigation on plastic mulch. Increased volume of irrigation water increased soil moisture content (2.86% to 8.71%), water consumption (24.56% to 47.41%) and the crop coefficient (3.43% to 35%). Irrigation had a significant effect on maize plant height (+26.38%), irrigation water use efficiency (22.89%), ear height (+35.01%), ear length (+26.13%), and grain yield (23.24%). The increased soil moisture eventually reduced the soil temperature and maize bald tip length by 4.67%, and 42% respectively. This provides a theoretical foundation aimed at optimisation of production benefits through limited water supply to maize (*Bian et al., 2024*).

Guo et al. (2022) conducted a 2-year experimental study comparing performance of drip and flood irrigation methods coupled with different nitrogen application doses in China. Drip fertigation method enhanced the soil water content, maintained nitrogen content with the soil layers compared with flood fertigation. This led to an increased leaf area index, improved rate of plant growth, and high accumulation of dry matter (DM) under drip fertigation. Drip fertigation reduced the amount of nitrogen fertiliser applied by 20% compared to flood fertigation. Maximum grain yield of 10.4 Mg ha^{-1} was achieved at a fertiliser dose of 375 kg N ha^{-1} under drip fertigation compared to higher nitrogen fertiliser dose of 450 kg N ha^{-1} under flood fertigation. Therefore, drip fertiliser application economically improved grain yield and maize growth with reduced amount of water consumption and nitrogen fertiliser doses.

3. MATERIALS AND METHODS

3.1 Experimental research site

The study was conducted at Látókép Experimental Station of Plant Production, Farm and Regional Research Institute of Debrecen, Institutes for Agricultural Research and Educational Farm, University of Debrecen located 15 km from Debrecen, Eastern Hungary (47°56′N, 21°45′E, 111 m). The three years of study 2023-2025 recorded fluctuating temperature and precipitation data. The highest temperatures were 22.52 ^{o}C (July 2023), 24.23^{o}C (July 2024), 22.193 ^{o}C (June 2025) and lowest temperatures were 9.32 ^{o}C (April 2023), 13.62 ^{o}C (April 2024) and 10.2 ^{o}C (October 2025) respectively. For precipitation, the 2023 growing season had the highest total precipitation level for the period between April to October of 376.2 mm compared to 364.4 mm and 241.7 mm for 2024 and 2025 seasons respectively. Precipitation was highest during the months of August 2023 (85.8 mm), May 2024 (76.2 mm) and July 2025 (86 mm) while the lowest monthly precipitation was 333.3 mm (May 2023), 28.6 mm (July 2024) and 3 mm (October 2025) respectively (Figure 7).

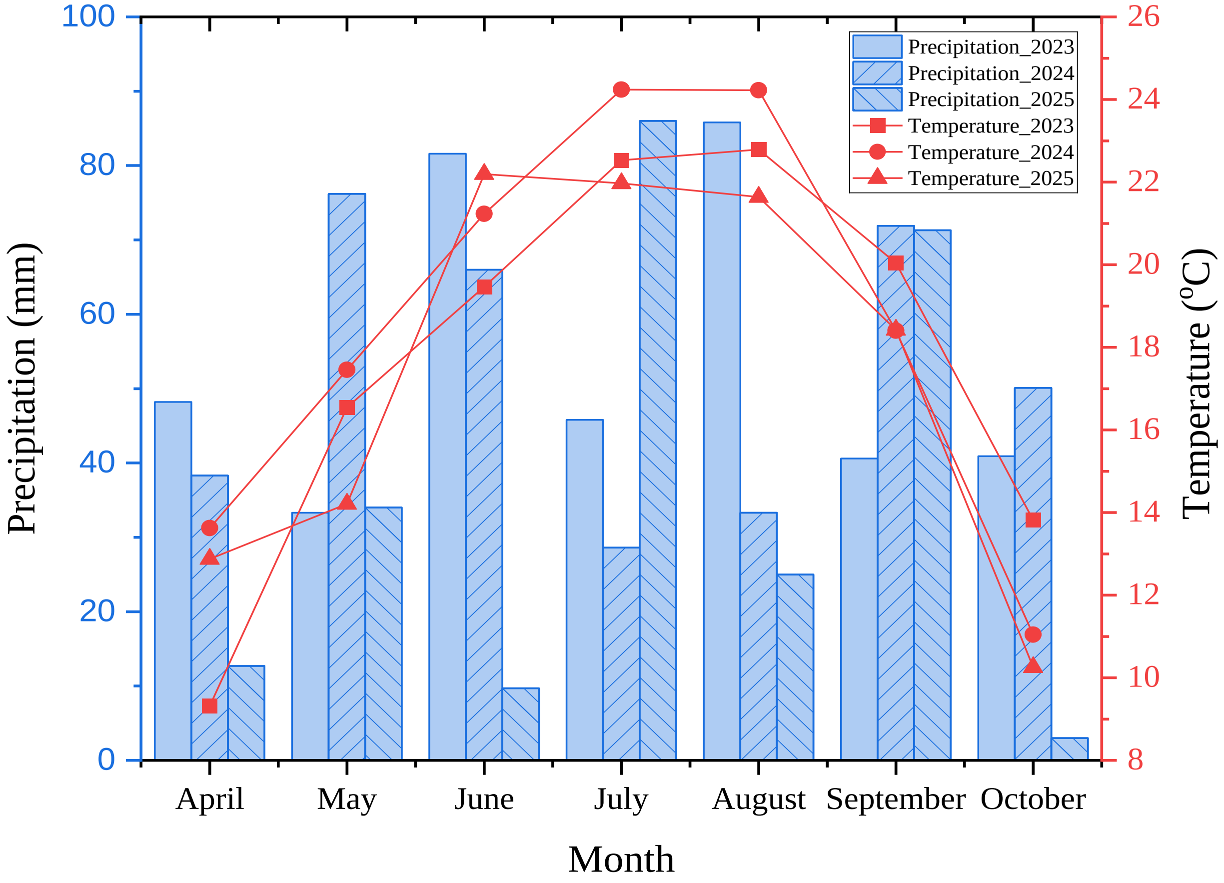


Figure 7 Monthly temperature (average) and total monthly precipitation for the study seasons (Látókép experimental farm, Debrecen, 2023-2025)

3.2 Experiment design

The experiment was laid as a randomized split-plot with three replications during the three growing seasons (2023-2025). On 14th June 2023, 06th June 2024 and 6th June 2025 respectively installation of drip irrigation lines on the surface of the soil near maize plants was done in every row. The precision drip irrigation was accurately managed using a meteorological station-controlled Hydrawise application, supplying exactly 3 liters per hour. Drip irrigation systems were removed on 22nd September 2023, 16th September 2024 and 26th September 2025 respectively. Foliar fertiliser treatment composition and application rates followed the manufacturer's recommendations as shown below. Foliar application was done when plant leaves were well-developed to absorb nutrients. Foliar application of nutrients was done on 3rd June 2023, 29th May 2024, and 4th June 2025 at V6 stage when leaves had well-developed to efficiently absorb foliar nutrients.

3.3 Treatments

This study was performed to evaluate performance of three maize hybrids under foliar fertilization in three replications for three years (2023–2025) under irrigated conditions. The selection of three maize hybrids namely FAO420, FAO430 and FAO490 was based on yield potential, maturity period, stability across different growing environments. Foliar fertilizer treatment was composed of four different products consisting of different nutrients (Table 3). Foliar fertiliser application was done using a Kertitox FSZM 800, made by FarmGep company in Debrecen with a capacity of 800 liters and 18 m spacing width.

3.4 Sowing and management practices

Sowing was done on 20th April 2023, 11th April 2024, and 23rd April 2025 respectively using the Gaspardo MTR 4 pneumatic precision seed drill made in Campodarsego, Italy. One maize seed per hole was the sowing rate at a sowing depth of 5 cm spaced at 76 x 18 cm. Therefore, each hectare accommodated a total of 84.100 plants as total plant density. Proper management and agronomic practices were implemented during the seasons like weed management. Row cultivation was done on 21st May 2023, 13th May 2024 and 19th May 2025 respectively. Additional nutrient fertilisation was done whereby the fertiliser was applied together with irrigation water (fertigation), on 10th July 2023, Megasol orange (25 kg fertiliser) NPK 3-5-40 (0,875 kg N, 1,25 kg P_2O_5, 10 kg K_2O); 20th June 2024, Megasol orange (50 kg fertiliser) NPK

3-5-40 (1,75 kg N, 2,5 kg P_2O_5, 20 kg K_2O) and 31st July 2025, Megasol orange (50 kg fertiliser) NPK 3-5-40 (1,75 kg N, 2,5 kg P_2O_5, 20 kg K_2O).

Table 3 Foliar fertiliser treatment composition

Product 1: 3l/ha	Composition	g/L
	Nitrogen	132
	P_2O_5	1.2
	K_2O	36
	Ca	0.96
	Co	0.0324
	Cu	1.56
	Mg	4.8
	Zn	1.8
	Fe	3.6
	Mn	2.4
	Mo	0.12
	B	2.4
	S	4.8
Product 2: 1l/ha	Composition	g/L
	Zn^{2+}	120
	SO_4^{2-}	59,4
Product 3: 1l/ha	Composition	g/L
	$S_2O_3^{2-}$	330
	SO_3	825
	NH_4^+	165
Product 4: 1l/ha	Composition	g/L
	Mg^{2+}	64.9
	MgO	106.4
	NH_4^+	73.8

3.5 Data collection

Field measurements on physiological growth traits were done at 12-leaf stage (V12), tasselling stage (VT), and silking-physiological maturity (R1-R6) from ten plants selected randomly from each replication. Yield, grain quality parameters and yield components data were collected after harvesting of grains from the field.

3.6 Assessment of Physiological growth traits

The physiological growth parameters studied were Soil Plant Analysis Development (SPAD), plant height, Normalised Difference Vegetation Index (NDVI), Leaf Area Index (LAI).

Measurements were conducted from the field using the SPAD-502 Plus Chlorophyll Meter (Konica Minolta Inc., Tokyo, Japan) to measure the relative chlorophyll from a 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 0–99. A meter ruler was used to measure plant height in centimetres (cm). GreenSeeker hand-held crop sensor (Trimble Inc., Sunnyvale, CA, USA) was employed to measure NDVI. SS1 SunScan Canopy Analysis System (Delta-T Devices Ltd., Cambridge, UK) was used for measuring LAI. Fifteen measurements were collected from the field and average was calculated.

3.7 Assessment of yield and yield traits

Collection of data was done on the following parameters: yield per hectare (t ha^{-1}), cob weight (g), row number, cob number, cob length (cm), cob diameter (mm), grain number per row, 1000 grain weight of kernels (g), and seed weight (g). Harvesting from the field was conducted when the black layer appeared in the grains on 28th September 2023, 19th September 2024 and 10th October 2025 respectively. A random selection of ten (10) maize ears from each replication was done. A Haldrup lt-35 laboratory thresher (HALDRUP GmbH, Ilshofen, Germany) was used to thresh the selected maize ears. An electronic weighing balance was employed to measure cob weight (g), a VSC-201 Vibrating Seed Counter (PLC Tuning Ltd, Hungary) was used to measure the weight of 1000 seeds (g) and the number of seeds per cob, a meter ruler was used to measure the cob length (cm), digital Vanier calliper for measuring the cob diameter (mm), manual counting and recording was done to determine the rows per cob, seed weight per cob and weight of 1000-seeds were determined. Grain yield (GY) in t ha^{-1} was calculated based on a moisture content of 14.5%.

3.8 Grain quality assessment

Grain quality measurements namely oil content (%), protein content (%), moisture content (%), and starch content (%) was done using Perten DA7250 NIR infrared grain analyser. The samples were scanned across the near-infrared wavelength range (approximately 570-1100 nm) collecting up to 30 spectra per sample at 5 nm intervals. This ensured high spectral resolution and analytical precision.

3.9 Statistical data analysis

Data analysis utilized the ANOVA method employing Genstat 64-bit Release 18.2 software. Treatment mean differences were assessed using Tukey test at 5% probability level. Analysis of Variance (ANOVA) was employed to analyse hybrid performance under different water regimes, foliar fertilisation and control. Pearson correlations were employed to examine the relationship between physiological parameters, grain yield and yield parameters. OriginPro Graphing and Analysis Software (version 2024) was used to prepare figures for the study.

4. RESULTS

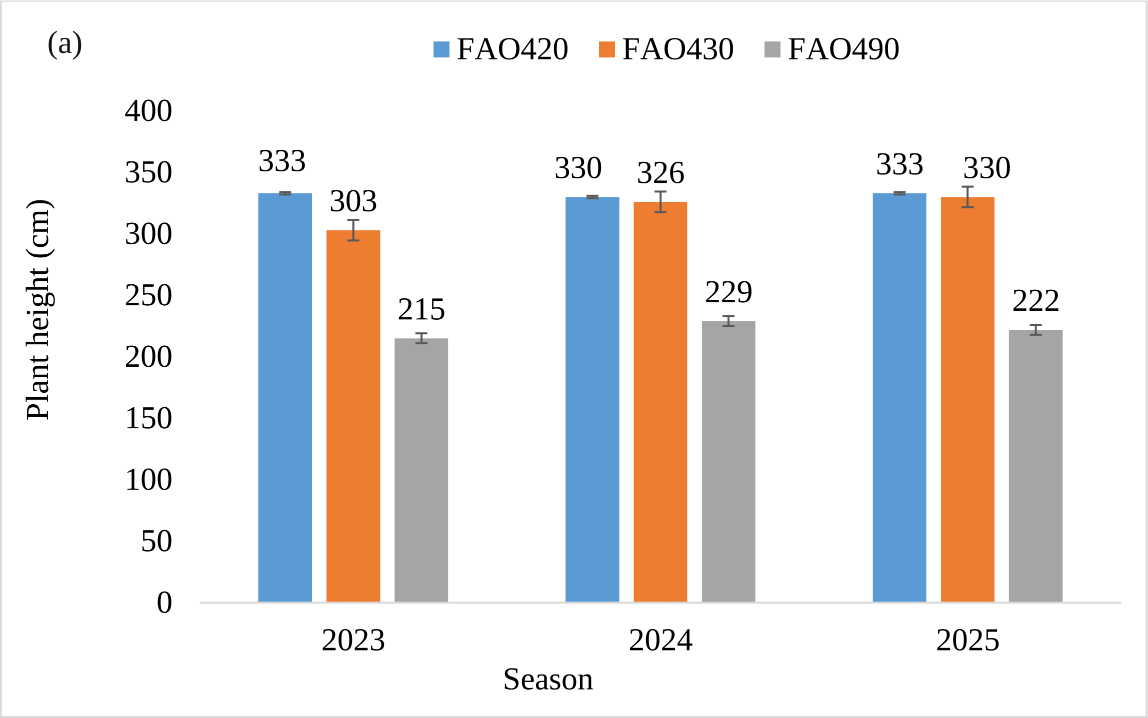
4.1 Results of 2023, 2024 and 2025 experiments

4.1.1 Physiological and growth response to foliar fertilisation and precision drip irrigation

Plant height

In 2023 growing season, average plant height didn’t differ significantly among hybrids FAO420 (334 cm), FAO430 (323 cm) and FAO490 (333 cm) recording a minor difference of 1.4%. Foliar fertilisation didn’t improve plant height; control plant height (338 cm) was higher than foliar treatment (325 cm) thus a 3.9% difference. Precision drip irrigation significantly influenced plant height ($p<0.001$). Plant height was high under precision drip irrigation conditions (338 cm) compared to non-irrigated conditions (325 cm) hence a 4.0% difference. The precision drip irrigation x foliar fertilisation interaction positively influenced ($p=0.047$) plant height. Highest plant height was (347 cm) for precision drip irrigated foliar treatments compared to non-irrigated foliar treatments (321 cm). Other interactions such as the Hybrid × precision drip irrigation and hybrid x foliar fertilisation had no significance effect on plant height ($p>0.05$). In 2024 growing season, plant height was significantly different ($p=0.036$) among hybrids FAO420 (303 cm), FAO430 (323 cm), FAO490 (330 cm) hence the mean plant height differences of 9.2%, 6.5%. Foliar fertilisation had no significance differences on plant height however foliar treated plants (320 cm) were taller than control (314 cm) thus a 2.1% height difference. Precision drip irrigation significantly improved plant height ($p<0.001$), irrigated plants had mean plant height of 328 cm compared to non-irrigated plots (306 cm), a 7.3% height difference. Irrigation x foliar fertilisation interaction had no significance effect on plant height. During 2025 growing season, plant height significantly improved due to foliar fertilisation ($p<0.001$) and the hybrid x foliar fertilisation interaction. Average plant height of hybrids didn’t differ significantly FAO430 (329 cm), FAO490 (322 cm) and FAO420 (315 cm). The mean height under precision drip irrigation (328 cm) was higher than that under non-irrigated conditions (317 cm). Foliar fertilisation treatment improved plant height of maize plants (342 cm) compared to control (302 cm). The precision drip irrigation x foliar fertilisation interaction showed that foliar fertilisation treatment improved plant height (348 cm and 336 cm) compared to control (306 cm and 297 cm) under irrigated and non-irrigated conditions respectively (Figure 8). Across the three-year period, foliar fertilisation and irrigation showed contrasting effects on plant height while irrigation consistently increased plant height by 3.5%

to 7.3% compared to non-irrigated conditions. Combination of irrigation and foliar fertilisation improved plant height by approximately 10–14% compared to control (Figure 9).



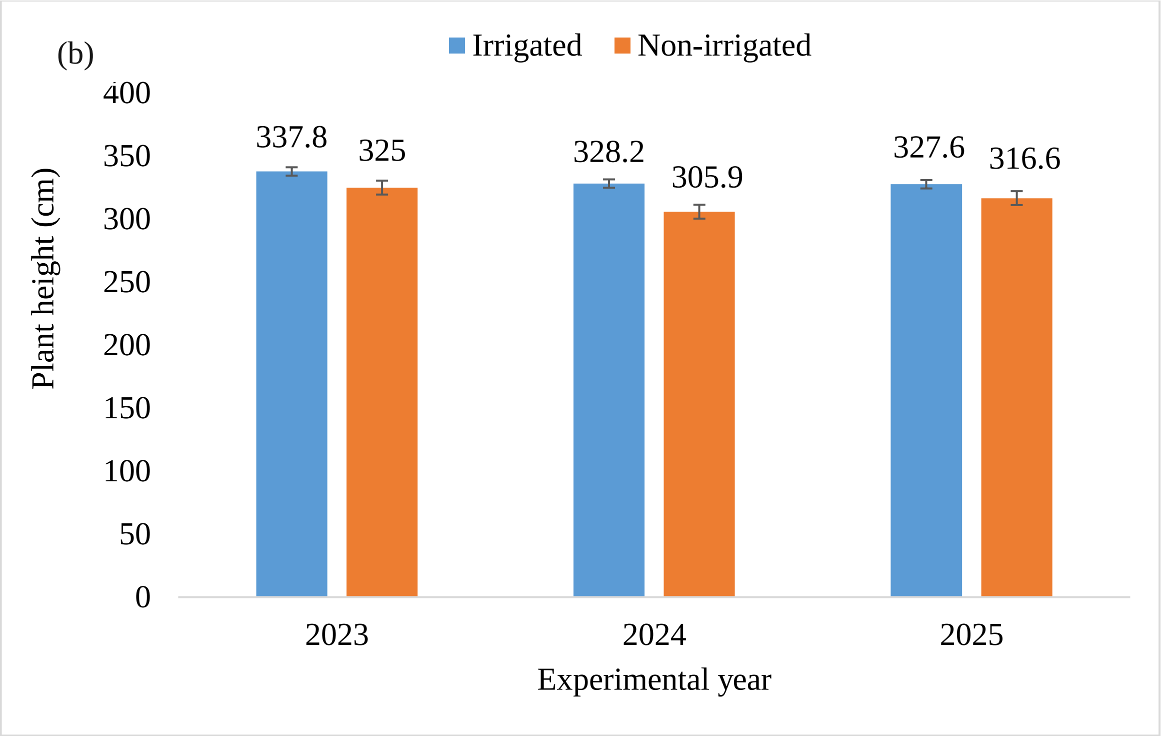
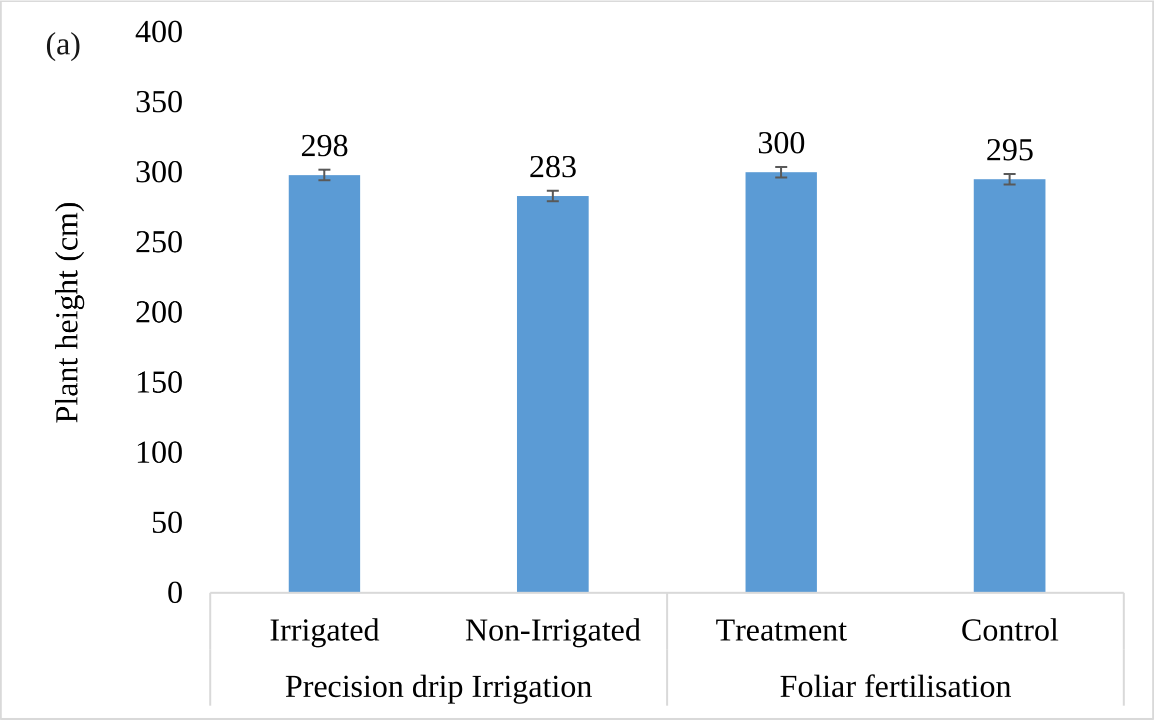


Figure 8 showing (a) plant height of different hybrids and (b) seasonal irrigation effect across the three growing seasons (2023-2025).



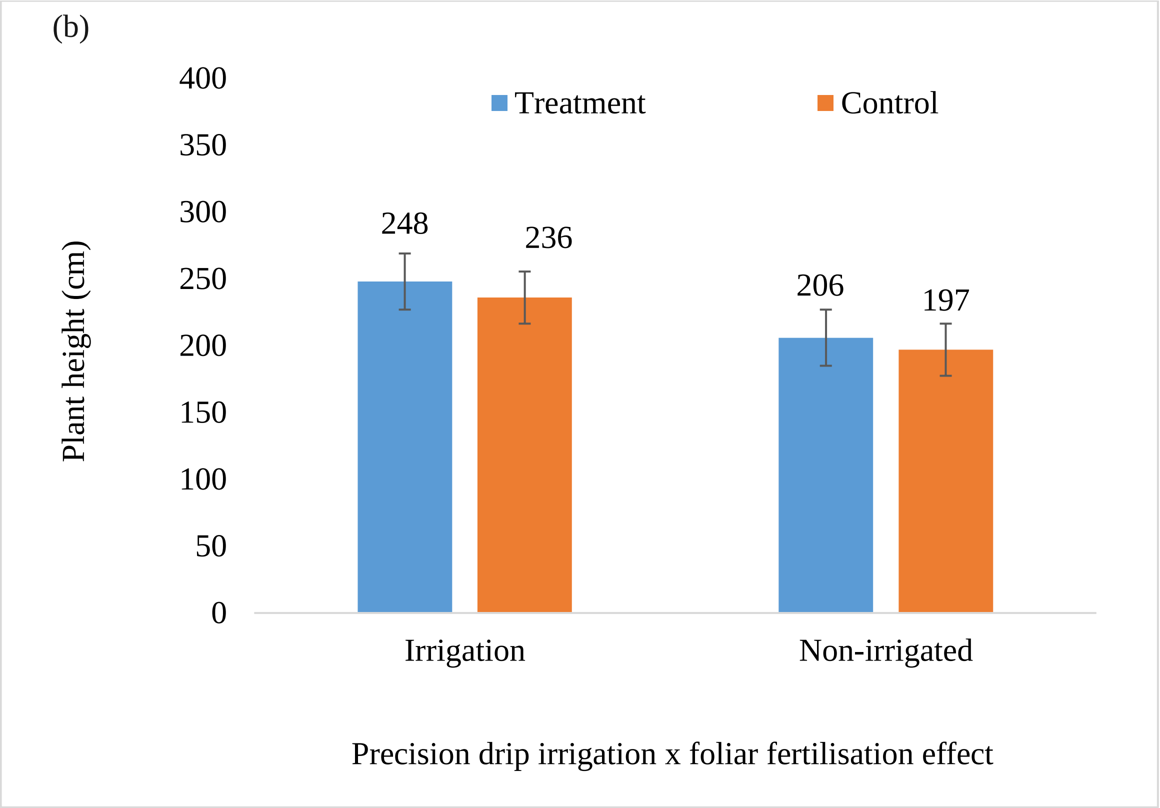


Figure 9 showing (a) overall effect of precision drip irrigation and foliar fertilisation on plant height, (b) precision drip irrigation x foliar fertilisation interaction effect on plant height across the experimental period.

Leaf Area Index (LAI)

In 2023 experimental season, LAI was significantly different ($p<0.001$) among hybrids FAO420 (4.35), FAO430 (6.22), and FAO490 (6.59) respectively. Foliar fertilisation had no significant effect on LAI with the control (6.03) better than foliar treatment (5.86). The interaction between hybrid × foliar fertilisation was slightly significant ($p=0.051$). Control plots for FAO420, and FAO430 had better LAI values compared to treatment, while FAO490 responded differently with treatment (6.385) higher than control (6.797). Precision drip irrigation significantly influenced ($p=0.025$) LAI, precision drip irrigated plots (6.12) had better average LAI value than non-irrigated plots (5.78). The interaction between hybrid × irrigation had a positive significant effect ($p=0.002$). FAO490 had a significance difference between LAI value under precision drip irrigation x foliar fertilisation (7.27) compared to non-irrigated conditions (5.92). In 2024 growing season, the mean LAI values of hybrids were significant different ($P < 0.001$) FAO420 (4.72), FAO430 (6.45), and FAO490 (6.83) respectively. Foliar fertilisation didn’t have a significant effect on LAI, control plots (6.12) had a slightly higher LAI value than foliar treatment (5.91). Precision drip irrigation had a significant effect ($p=0.025$) on LAI, irrigated conditions produced high LAI (6.3) than control (5.81). Hybrid × irrigation interaction ($p=0.002$) had a positive effect on LAI. Precision drip irrigation x foliar fertilisation had average LAI (7.39) compared to treatment under non-irrigated conditions (5.88). Therefore, precision drip irrigation greatly influenced LAI during the 2024 experimental year. During the 2025 experimental year, LAI significantly improved due to irrigation ($p=0.0017$), foliar fertilisation ($p<.001$), hybrid x irrigation ($p=0.001$), irrigation x foliar fertilisation ($p=0.002$) while hybrid, hybrid x irrigation, hybrid x irrigation x foliar fertilisation interaction was non-significant. The average mean LAI between hybrids was FAO490 (6.012), FAO430 (5.898) and FAO420 (5.865). Maize under precision drip irrigation had higher LAI (6.231) compared to non-irrigated conditions (5.618), similarly foliar treatment significantly influenced LAI (6.403) than control (5.447). The interaction between irrigation x foliar fertilisation improved LAI whereby treatments (6.887 and 5.920) performed better than control (5.576 and 5.317) under irrigated and non-irrigated conditions respectively (Figure 10). Across the three-year period, both irrigation and foliar fertilisation influenced LAI. Irrigation consistently increased LAI by approximately 5.9% to 10.9% compared to non-irrigated conditions. Foliar fertilisation combined with irrigation improved LAI by approximately 20–23% compared to control.

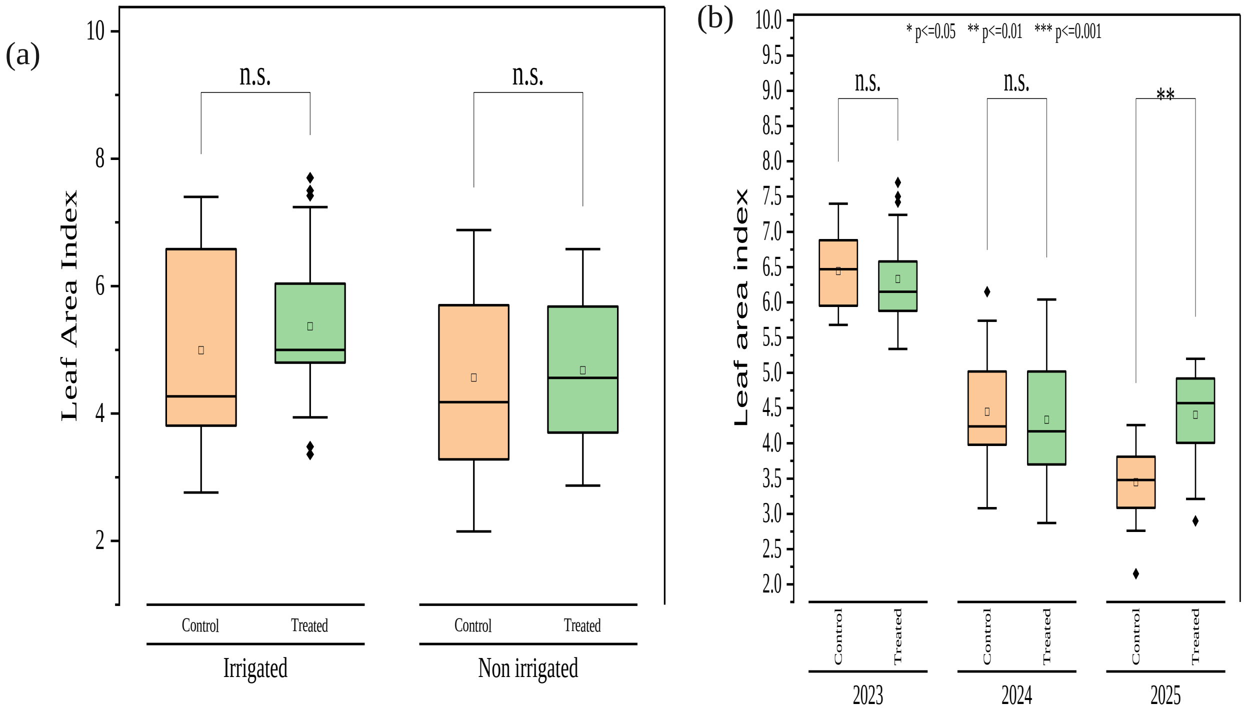


Figure 10 Leaf Area Index (LAI); (a) interaction effect of precision drip irrigation x foliar fertilisation and (b) effect of foliar fertilisation on LAI; ns shows non-significance difference and ** indicate significance differences by Tukey test at $p<0.05$ during the 2023, 2024 and 2025 growing seasons.

Normalised Difference Vegetation Index (NDVI)

In 2023 experimental season, NDVI didn’t differ significantly among hybrids FAO490 (0.689), FAO420 (0.708) and FAO430 (0.746). Precision drip irrigation had a positive effect ($p=0.020$) on NDVI, irrigated plots had a mean NDVI value of 0.736 compared to non-irrigated plots (0.675). Foliar fertilisation treatment slightly improved ($p=0.055$) NDVI, foliar treatment (0.718) high NDVI value than control (0.693). The hybrid × irrigation, hybrid × foliar fertilisation, foliar fertilisation × irrigation, and hybrid × foliar fertilisation × irrigation interactions had no significant effect on NDVI. Therefore, irrigation significantly influenced NDVI, as well marginal influence due to foliar fertilisation in 2023. In 2024 experimental season, significant hybrid differences ($p=0.027$) on NDVI were noted as FAO420 (0.69), FAO430 (0.750), and FAO490 (0.763). Although foliar fertilisation didn’t have a significant effect on NDVI, foliar treatment recorded a higher NDVI value (0.746) than control (0.723). Precision drip irrigation was non-significant ($p>0.25$), however irrigated plots had better NDVI value (0.744) than control (0.713). Hybrid × foliar fertilisation, hybrid × irrigation, foliar fertilisation × irrigation, hybrid × foliar fertilisation × irrigation had no significant effect on

NDVI. Only hybrid differences highly influenced NDVI while both foliar fertilisation and irrigation recorded negligible effects in 2024. During the 2025 experimental season, the mean NDVI values of hybrids were FAO490 (0.7368), FAO430 (0.7137) and FAO420 (0.7037). Foliar fertilisation positively influenced ($p<.001$) NDVI, foliar treatment had a better NDVI (0.7358) than control (0.7003). Precision drip irrigation conditions improved NDVI (0.7327) compared to non-irrigated conditions (0.7034). The irrigation x foliar fertilisation interaction showed that foliar fertilisation treatment improved NDVI (0.7461 and 0.7256) compared to control (0.7192 and 0.6813) under irrigated and non-irrigated conditions respectively (Figure 11). Across the three experimental years, both foliar fertilisation and irrigation consistently improved NDVI compared to the controls. Foliar fertilisation increased NDVI by approximately 2–5% compared to the control, while irrigation improved NDVI by about 3–9% relative to non-irrigated conditions, indicating a generally stronger effect of irrigation.

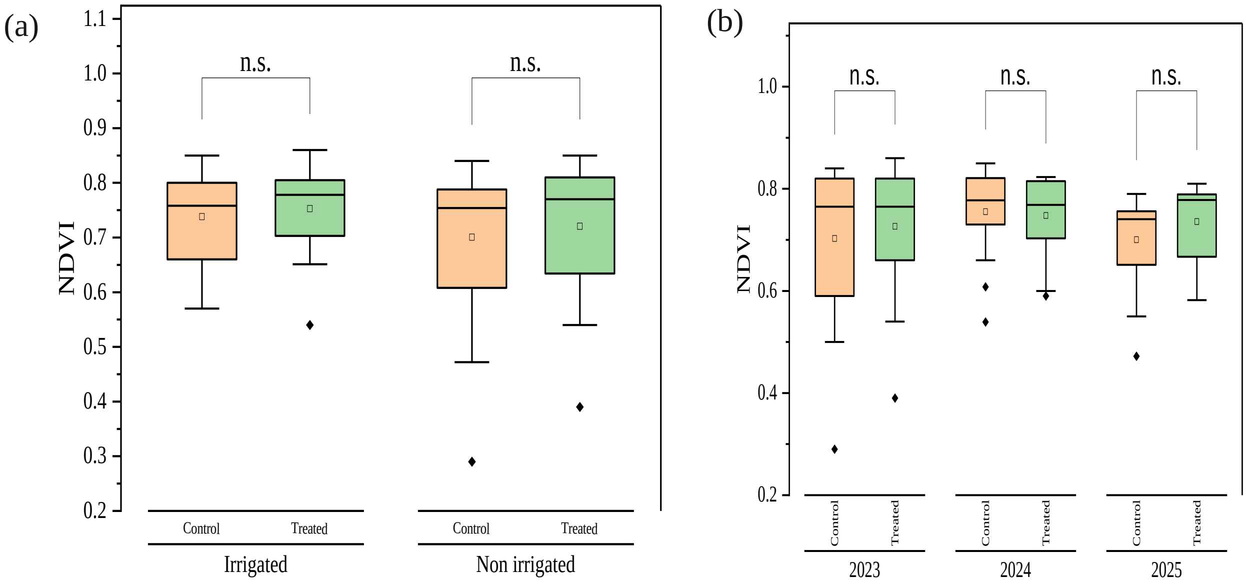


Figure 11 NDVI; (a) interaction effect of precision drip irrigation x foliar fertilisation and (b) effect of foliar fertilisation on NDVI; ns indicates non-significance differences by Tukey test at $p<0.05$ during the 2023, 2024 and 2025 growing seasons.

SPAD

In 2023 experimental season, SPAD didn't differ significantly among hybrids, FAO430 (56.55), FAO420 (51.3) and FAO490 (50.63). Precision drip irrigation significantly ($p=0.002$) influenced SPAD, irrigated plots (55.58) had a high SPAD value than non-irrigated plots (50.84). Foliar fertilisation had no significant effect on SPAD, foliar treatment had slightly high SPAD value (53.72) compared to control (52.7). All the interaction namely hybrid × foliar fertilisation, hybrid × irrigation, foliar fertilisation× irrigation, hybrid × foliar fertilisation × irrigation had no statistical significance on SPAD. Therefore, irrigation was the major factor that influenced SPAD while both hybrid and foliar fertilisation had negligible effects in 2023. In 2024 experimental season, the SPAD value of different hybrids was FAO430 (58.56), FAO420 (52.5) and FAO490 (51.63). Precision drip irrigation had a positive effect (P = 0.002) on SPAD. Higher SPAD values (56.82) under irrigated plots compared to non-irrigated plots (51.79), thus a 9.71% difference. Though foliar fertilisation had no significant effect, a 3.62% difference was recorded between treated (55.81) and control (53.86). During the 2025 growing season, hybrid, irrigation and all interaction effects were non-significant. The mean hybrid SPAD values were FAO430 (49.05), FAO490 (47.90) and FAO420 (47.32). Foliar fertilisation significantly (p<.001) improved SPAD, foliar treatment had a high SPAD value (52.43) than control (43.75). Precision drip irrigation conditions improved SPAD (49.36) compared to non-irrigated conditions (46.82). The irrigation x foliar fertilisation interaction showed that foliar fertilisation treatment improved SPAD (54.14 and 50.72) compared to control (44.58 and 42.93) under irrigated and non-irrigated conditions respectively (Figure 12). Across the 3-year experimental period, foliar fertilisation increased SPAD by approximately 2–20% compared to the control, while irrigation improved SPAD by 5–10% compared to non-irrigated conditions, indicating a stronger and more variable effect of foliar fertilisation treatment.

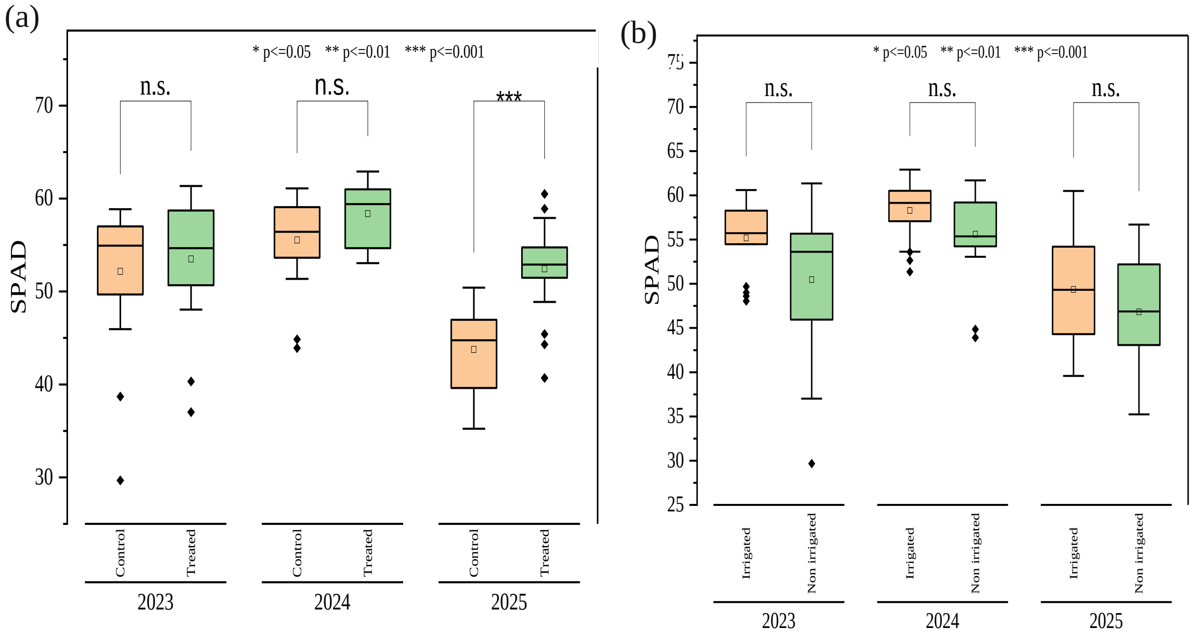


Figure 12 SPAD; (a) effect of foliar fertilisation and (b) effect of precision drip irrigation on SPAD; ns indicates non-significance differences and *** indicates significance difference by Tukey test at p<0.05 during the 2023, 2024 and 2025 growing seasons.

4.1.2 Yield components of maize hybrids under foliar fertilisation and precision drip irrigation

Cob diameter

In 2023 growing season, cob diameter (mm) of hybrids varied significantly (p=0.003), ranging from FAO430 (52.80 mm), FAO420 (47.93 mm) and FAO490 (49.63 mm) respectively. Precision drip irrigation (p=0.031), precision drip irrigation x foliar fertilisation interaction (p<0.001), hybrid × foliar fertilisation × precision drip irrigation interaction (p=0.009) significantly influenced cob diameter. Foliar fertilisation had no significant effect on cob diameter. Precision drip irrigation produced cobs of higher diameter (50.62 mm) than non-irrigated conditions (49.60 mm). Similarly, foliar treatment though non-significant, produced slightly larger cobs (50.58 mm) than control (49.64 mm). Foliar fertilisation under non-irrigated conditions had better cob diameter (50.97 mm) than control (48.23 mm). Therefore, foliar fertilisation was more effective under non-irrigated conditions than precision drip irrigation. In the 2024 growing season, cob diameter among hybrids was significant (p=0.030), FAO430 (51.12 mm), FAO490 (49.51 mm) and FAO420 (46.45 mm) respectively. Foliar fertilisation, precision drip irrigation and all their interactions had no statistical significance on cob diameter. Precision drip irrigation had positive effect as cob diameter was high for non-irrigated cobs (48.57 mm) than irrigated cobs (48.18 mm) though the difference is insignificant. Foliar fertilisation treatment had higher cob diameter (48.82 mm) than control (47.93 mm). Foliar fertilisation × precision drip irrigation interaction showed improved performance whereby foliar fertilisation under non-irrigated conditions increased cob diameter by 1.86% and 0.81% under irrigated conditions. During the 2025 growing season, cob diameter was positively influenced (p<0.001) by hybrid, precision drip irrigation and foliar fertilisation. The interaction between precision drip irrigation and foliar fertilisation had no significant effect on cob diameter. FAO430 recorded the largest cob diameter (49.54 mm), 10.8% and 1.5% larger than FAO420 and FAO490 respectively. The cob diameter for precision irrigated cobs was 7.1% (49.32 mm) larger than non-irrigated conditions (46.06 mm). Cob diameter due to foliar fertilisation treatment (48.36 mm) slightly increased by 2.9% compared to control (47.02 mm). Although, precision drip irrigation and foliar fertilisation had no statistical significance, cob diameter increased by 1.8% and 4.0% under irrigation under non-irrigated conditions respectively due to foliar fertilisation treatment (Figure 13). Overall, across the three-year period, both foliar fertilisation and irrigation consistently improved cob diameter compared to their control. Foliar fertilisation treatment improved cob diameter by 1–4%, especially under non-irrigated conditions, and irrigation enhanced cob diameter by approximately 1–7% compared to non-irrigation indicating a stronger irrigation effect.

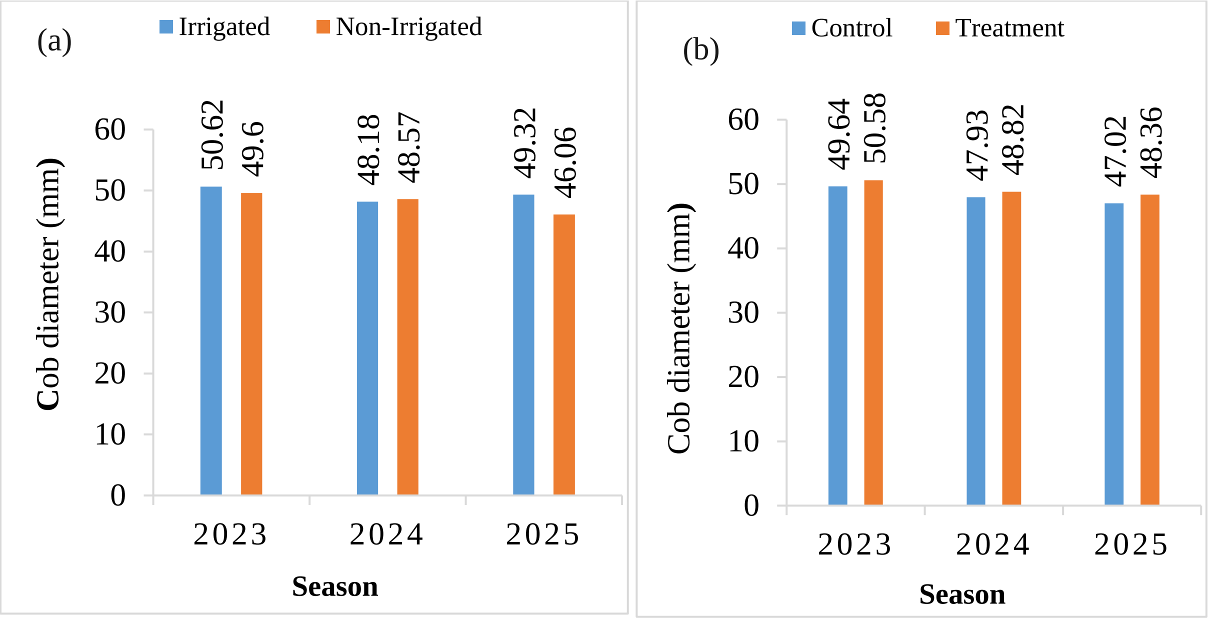


Figure 13 Cob diameter (mm); (a) effect of precision drip irrigation and (b) effect of foliar fertilisation on cob diameter during the 2023, 2024 and 2025 growing seasons.

Cob length

The mean cob length of hybrids was FAO420 (18.83 cm), FAO430 (18.37 cm) and FAO490 (19.17 cm) respectively during the 2023 growing season. Precision drip irrigation significantly influenced ($p<0.001$) cob length. Foliar fertilisation and all interactions showed no statistical significance on cob length. Foliar fertilisation though non-significant but treated cobs were longer (19.30 cm) than control (18.75 cm). The significance of irrigation produced longer cobs (19.74 cm) compared to non-irrigated cobs (18.31 cm) thus a strong irrigation effect. Although, all interaction effects were non-significant, the foliar fertilisation × irrigation effect was observed on increased length of cobs, under non-irrigated conditions, a 9.32% length difference was recorded between treatment (18.91 cm) and control (17.91 cm) while a 6.31% cob length difference was noted between treatment (19.89 cm) than control (19.58 cm), however treatment under precision drip irrigation was significantly high than treatment under non-irrigation. In 2024 growing season, cob length of hybrids was significantly different ($p=0.007$), FAO490 (19.17 cm), FAO420 (17.33 cm) and FAO430 (16.63 cm) respectively. Hybrid × Irrigation interaction significantly influenced ($p=0.012$) cob length. Cob length wasn't significantly influenced by both foliar fertilisation and irrigation. Non-foliar treated cobs were slightly longer (17.54 cm) compared to treated cobs (17.26 cm) though effect was non-significant. Similarly, cobs under non-irrigated conditions were slightly longer (17.58 cm) than those from irrigated plots (17.22 cm). The effect of foliar fertilisation × irrigation interaction was slightly high for foliar treatment under precision drip irrigation (17.43 cm) compared to control (17.00 cm). During the 2025 growing season, both precision drip irrigation and precision drip irrigation x foliar fertilisation positively influenced ($p<0.001$) on cob length. Hybrid, and foliar fertilisation had no significant effect on cob length. Precision drip irrigation increased cob length by 5.1% with cob length of 18.4 cm and 17.5 cm for irrigated and non-irrigated conditions respectively. Precision drip irrigation x foliar fertilisation interaction statistically increased length of cobs by 7.9% and 4.5% under irrigation under non-irrigated conditions respectively due to foliar fertilisation treatment (Figure 14). Overall, across the three-year period, both foliar fertilisation and irrigation improved cob length compared to the control. Foliar fertilisation treatment increased cob length by 1–9% especially under non-irrigated conditions, while irrigation enhanced cob length by approximately 3–9%, indicating a stronger and more consistent irrigation effect (Figure 15).

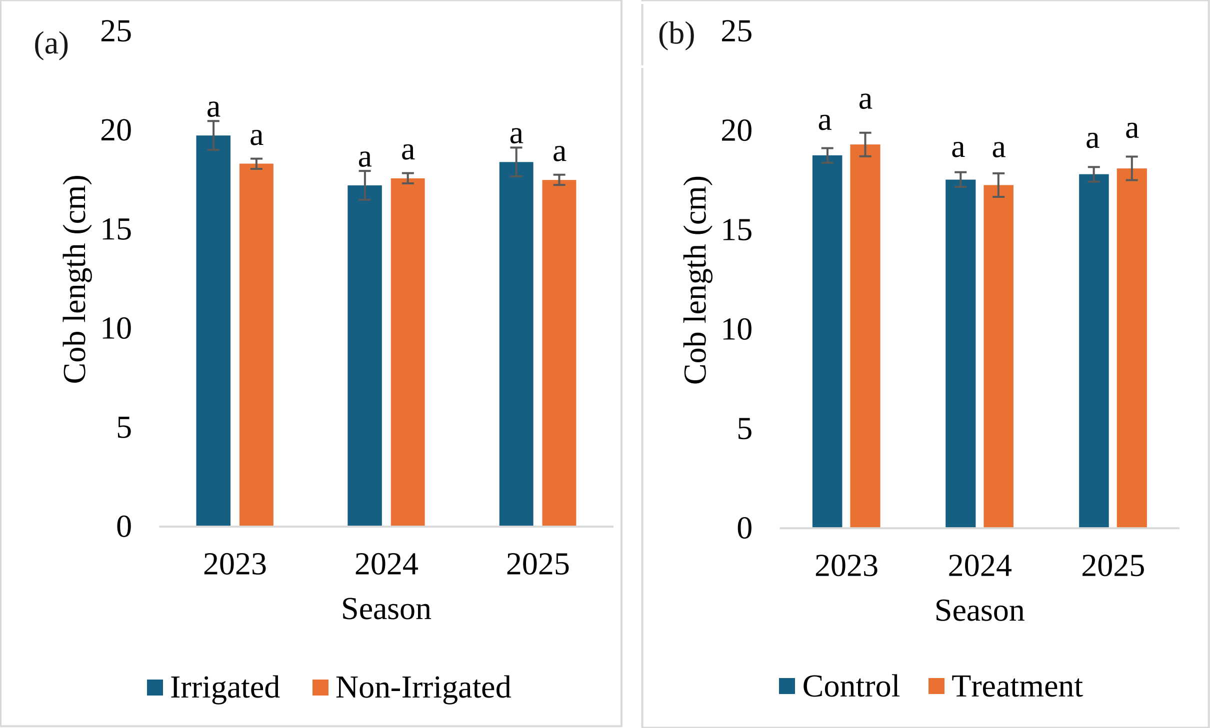
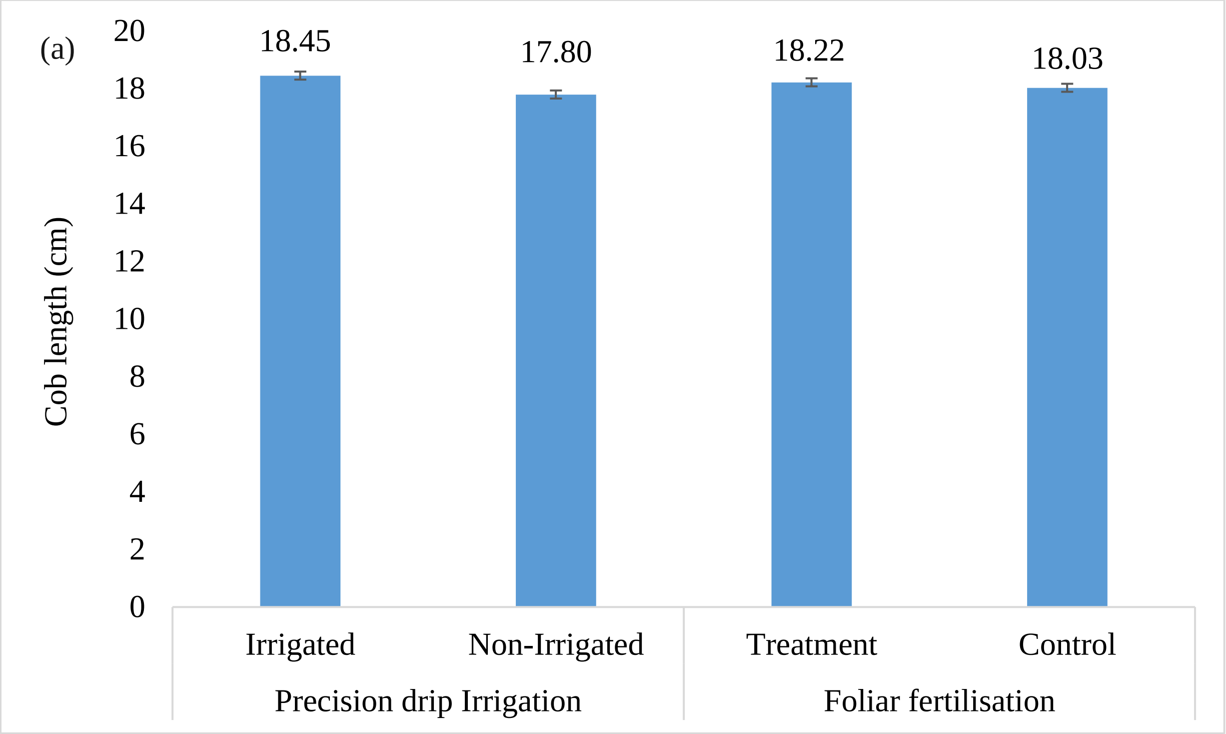


Figure 14 Cob length (cm); (a) effect of precision drip irrigation and (b) effect of foliar fertilisation on cob length; a, b letters indicate significance difference by Tukey test at $p<0.05$ during the 2023, 2024 and 2025 growing seasons.



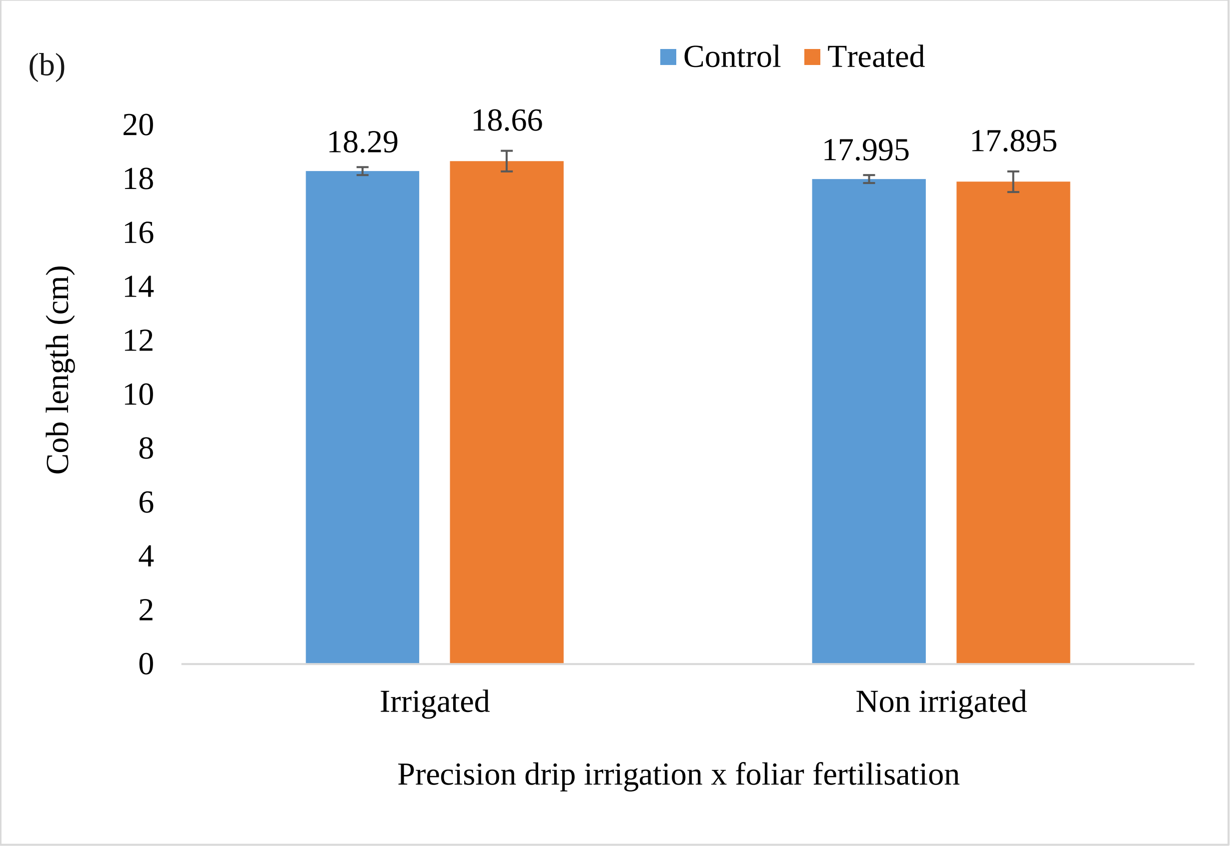


Figure 15 showing the overall effect of (a) precision drip irrigation and foliar fertilisation; and (b) precision drip irrigation x foliar fertilisation on cob length.

Cob weight

In 2023 growing season, cob weight of hybrids was FAO430 (315.2 g), FAO420 (226.7 g) and FAO490 (274.0 g). Foliar fertilisation × precision drip irrigation interaction had a positive significant effect (p=0.019) on cob weight. There were no significant effects noted for foliar fertilisation, irrigation, foliar fertilisation × irrigation interaction, hybrid × foliar fertilisation × irrigation interaction on cob weight. Foliar fertilisation treatment weighed slightly heavier (284.5 g) than the control (266.0 g), though the difference was non-significant (p=0.463). Precision drip irrigation didn't significant influence cob weight (p=0.550), cobs under precision drip irrigation conditions (280.3 g) weighed slightly heavier than cobs from non-irrigated conditions (270.3 g). Contrasting results showed that the effect of foliar fertilisation was high (22.08%) under non-irrigation conditions compared to irrigated conditions (10.93%). In 2024 growing season, cob weight of hybrids was significantly different (p=0.009), FAO490 (262.1 g), FAO430 (235 g) and FAO420 (203.8 g) respectively. Cobs from control weighed heavier that treatment for both irrigation and foliar fertilisation. Foliar fertilisation × precision drip irrigation interaction had a significant (p=0.036) effect on cob weight. A nuanced pattern was observed whereby foliar treatment under irrigated conditions produced heavier cobs (230.3 g) than control (211.1 g), while foliar treatment under non-irrigated conditions produced lighter cobs (210.8 g) compared to control (240.6 g). Therefore, foliar fertilisation proved more beneficial under irrigation conditions than non-irrigated conditions. During the 2025 growing season, cob weight was positively influenced (p<0.001) precision drip irrigation and foliar fertilisation. Precision drip irrigation increased cob weight by 34.7% with a weight of 254.0 g and 188.5 g for irrigated and non-irrigated conditions respectively. Cob weight due to foliar fertilisation treatment (233.8 g) increased by 12.0% compared to control (208.7 g). Precision drip irrigation x foliar fertilisation interaction had no statistical significance, cob weight increased by 11.7% and 12.5% under irrigation under non-irrigated conditions respectively due to foliar fertilisation treatment (Figure 16). Overall, across the three-year period, both foliar fertilisation and irrigation generally increased cob weight compared to the control. Foliar fertilisation treatment improved cob weight by 3–12% especially under non-irrigated conditions, while precision drip irrigation enhanced cob weight by 4–35% showing a stronger and consistent irrigation effect (Figure 17).

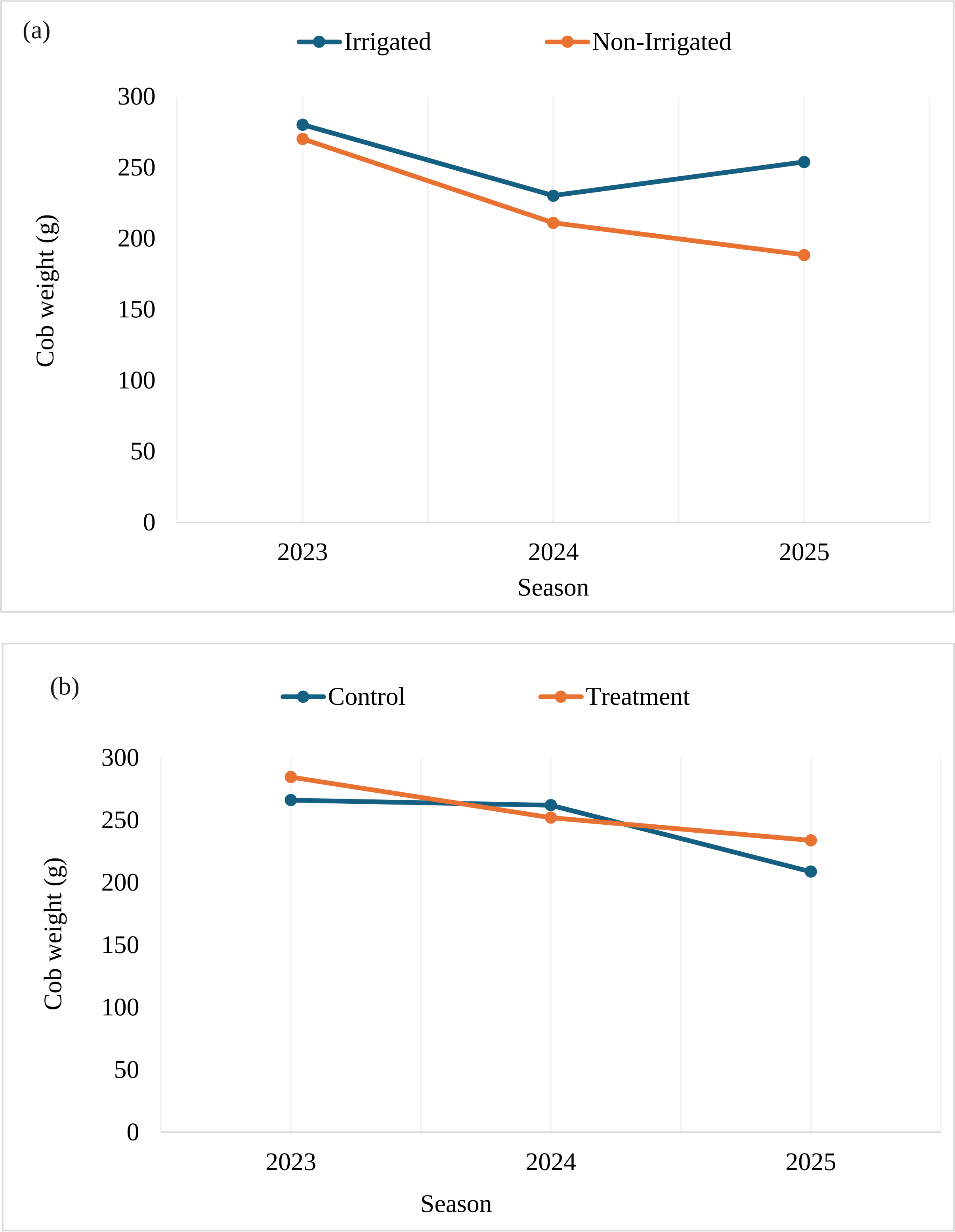
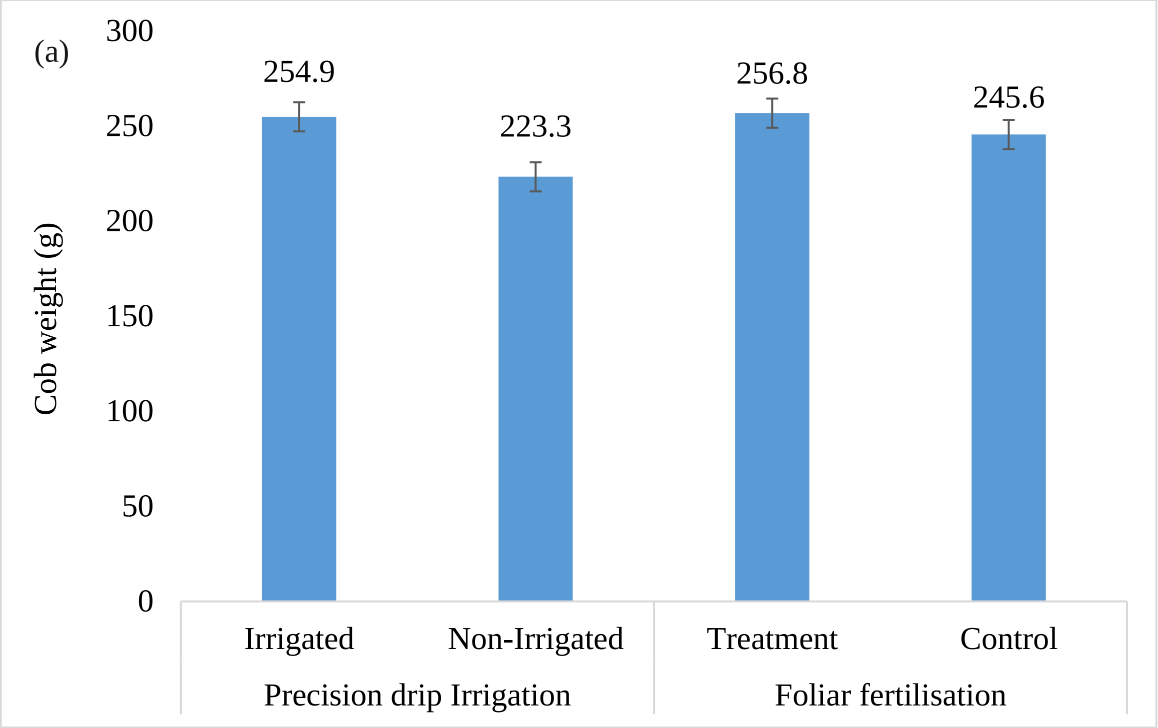


Figure 16 showing seasonal effect of (a) precision drip irrigation and (b) foliar fertilisation on cob weight during the 2023, 2024 and 2025 growing seasons.



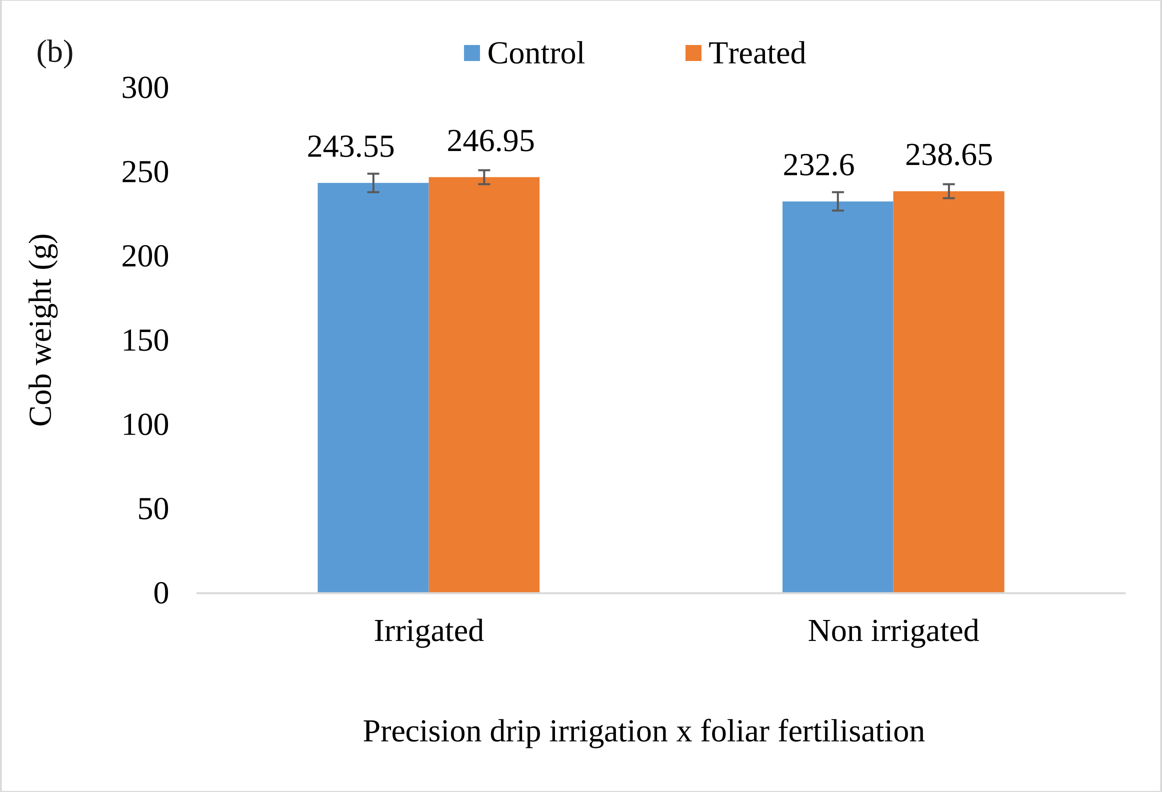


Figure 17 showing the (a) overall effect of precision drip irrigation and foliar fertilisation; interaction effect between precision drip irrigation and foliar fertilisation on cob weight.

Number of rows per cob

In 2023 growing season, the number of rows per cob for the hybrids ranged from FAO420 (16.50), FAO430 (16.33) and FAO490 (16.00) respectively. All treatments and their possible interaction had no significant effect on number of rows per cob. Slight differences were noted among foliar fertilisation whereby treatment had (16.42) rows compared to control (16.08). Foliar fertilisation × irrigation interaction achieved marginal increase between control (3.16%) and treatment (1.04%). Thus, foliar fertilisation was slightly more effective for non-irrigated conditions than irrigated conditions in 2023. In the 2024 growing season, foliar fertilisation (p=0.012), irrigation (p=0.028), and foliar fertilisation × irrigation interaction (p=0.028) significantly influenced the number of rows per cob. Among hybrids, FAO430 (13.08) had the highest rows per cob, FAO420 (12.75), and the lowest FAO490 (11.75). Independently, foliar fertilisation and irrigation increased the number of rows per cob, under foliar treatment was 13.42, compared to control (12.00). Foliar fertilisation × precision drip irrigation interaction showed that foliar fertilisation treatment under non-irrigated conditions had higher row number (14.83) than foliar treatment under irrigated conditions (12.00). This interaction reveals a complex relationship that foliar treatment was effective under inadequate moisture levels. During the 2025 growing season, number of rows per cob was positively influenced (p<0.001) by hybrid. Precision drip irrigation and foliar fertilisation had no significant effect on number of rows per cob. FAO420 recorded the highest number of rows (17.70) recording 8.6% and 7.0% larger than FAO430 and FAO490 respectively. The number of rows per cob increased by 1.8% and 4.6% due to precision drip irrigation and foliar fertilisation respectively. Similar trend was observed in terms number of rows per cob. Overall, across the three-year period, both foliar fertilisation and precision drip irrigation slightly increased the number of rows per cob by 1–5% and 2% respectively compared to the control indicating a modest effect of both treatments.

1000 grain weight of kernels

In 2023 growing season, a significant effect (p<0.001) of hybrid on 1000 grain weight of kernels showed that FAO430 (536.0 g), FAO490 (477.8 g), and FAO420 (433.6 g). Foliar fertilisation had no positive effect on 1000 grain weight of kernels. Treatment produced slightly higher average seed weight (497.8 g) than the control (481.6 g), thus a 3.4% difference. Precision drip irrigation had a significant effect (p<0.001) on 1000 grain weight of kernels. Non-irrigated plants had higher average seed weight (524.7 g), compared to irrigated conditions (454.8 g). Hybrid × precision drip irrigation interaction significantly (p=0.015) influenced 1000 grain weight of kernels. FAO430 and FAO490 performed well under non-irrigated conditions having a 22.5% and 19.8% increased 1000 grain weight of kernels respectively. Foliar fertilisation × precision drip irrigation interaction had a significant effect ($p=0.006$) on 1000-seed weight. Foliar fertilisation was more effective under non-irrigated conditions whereby a 26% weight difference compared to the control. Therefore, foliar fertilisation was more effective under moisture stress conditions as it mitigated the negative impact of drought on seed filling. In 2024 growing season, FAO490 had the highest mean 1000 grain weight of kernels (477.4 g), compared to FAO430 (459.7 g) and Hybrid 420 (428.4 g). Hybrid x foliar fertilisation x precision drip irrigation ($p<0.001$) had a significant effect on the 1000 grain weight of kernels while foliar fertilisation and irrigation effects were non-significant ($p>0.05$) the 1000 grain weight of kernels. Foliar fertilisation treatment had a marginal higher (450.3 g) 1000 grain weight of kernels than the control (449.6 g). The significant interaction effect of hybrid × foliar fertilisation × irrigation indicates a combined effect of different factors on the 1000 grain weight of kernels. FAO490 when exposed to foliar fertilisation, produced a higher 1000 grain weight of kernels of 485.6 g under non-irrigated conditions than under irrigated conditions (463.2 g). During the 2025 growing season, 1000 grain weight of kernels significantly improved ($p<0.001$) due to precision drip irrigation and foliar fertilisation. The 1000 grain weight of kernels increased by 15.9% and 18.7% due to precision drip irrigation and foliar fertilisation respectively. Although, precision drip irrigation x foliar fertilisation had no statistical significance on 1000 grain weight of kernels, an increase of 16.7% and 21.2% under irrigation under non-irrigated conditions respectively due to foliar fertilisation treatment was noted. Application of drip fertigation after silking stage increased the biomass of plants by 29.5% and 23.1% compared to treatments (Figure 18). Overall, across the three-year period, foliar fertilisation increased 1000 grain weight of kernels by 3–21% under non-irrigated conditions compared to the control while irrigation improved 1000 grain weight by 16% indicating that both treatments positively influenced kernel weight.

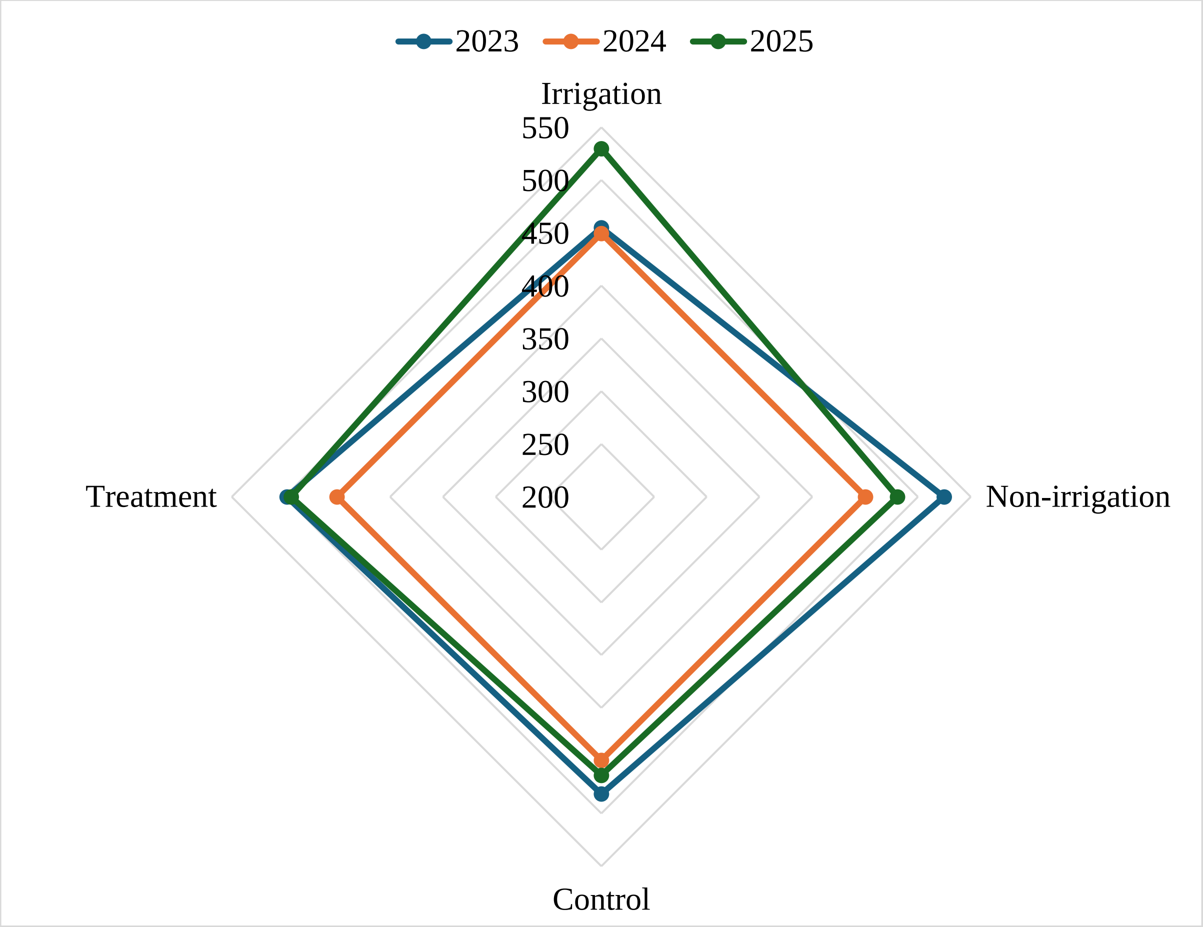


Figure 18 Radar chart of 1000 grain weight of kernels for control and treatment under precision drip irrigation and non-irrigated (NI) conditions during the three growing seasons (2023-2025).

Grain weight

In 2023 growing season, FAO430 hybrid had the highest mean grain weight (240.1 g), compared to FAO490 (226.4 g), and FAO420 (216.3 g), 11% difference between the highest and lowest-performing hybrids. Foliar fertilisation effect was non-significant, foliar treatment had a higher average mean grain weight (236.6 g) compared to control (223.7 g), thus a 5.8% difference. Precision drip irrigation had a significant effect ($p = 0.012$) on grain weight whereby irrigation (241.8 g) had a 10.7% weight difference compared to non-irrigation (218.5 g). Therefore, water supplementation influenced grain development and kernel filling. A positive ($p=0.014$) foliar fertilisation x precision drip irrigation effect, foliar treatment effectively improved grain weight under non-irrigated conditions from 200.6 g to 236.4 g compared to irrigated conditions where no effect was observed. An implication that foliar fertilisation effectively mitigated negative effects moisture stress and improved grain weight. Hybrid x foliar fertilisation x precision drip irrigation had a positive statistical effect ($p=0.030$) on grain weight. FAO420 had a substantial grain weight improvement of 33% due to foliar fertilisation under non-irrigated conditions (241.6 g) compared to control (181.6 g). In 2024 growing season, grain weight of hybrids was significantly different ($p=0.009$), FAO490 had the highest grain weight (235.1 g), compared to FAO430 (208.2 g) and FAO420 (173.8 g). Foliar fertilisation, precision drip irrigation, and all the interaction effects were non-significant ($p>0.05$). Foliar fertilisation treatment had marginal grain weight of (198.2 g) than the control (197.3 g). Similarly, irrigation had a minor influence of 2.2% on grain weight compared to non-irrigated conditions. Hybrid x foliar fertilisation x precision drip irrigation interaction though non-significant showed differential hybrid performances such as FAO420 and FAO430 when exposed to foliar treatment exhibited a 10.7% and 3.6% increase in grain weight (175.8 g) compared to control (171.8 g) under non-irrigated conditions. While under irrigated conditions, FAO490 and FAO430 had a 7.5% and 4.9% higher grain weight due to foliar treatment compared to control. The 2024 findings demonstrated how corn genotype was a major determinant of grain weight. During the 2025 growing season, seed weight was positively influenced ($p<0.001$) by both precision drip irrigation and foliar fertilisation. The seed weight increased by 36.3% and 10.6% due to precision drip irrigation and foliar fertilisation respectively. Although, precision drip irrigation x foliar fertilisation had no statistical significance on seed weight, an increase of 9.3% and 12.4% under irrigation under non-irrigated conditions respectively due to foliar fertilisation treatment was noted (Figure 19). Overall, across the three-year period, foliar fertilisation increased grain weight by 3–33% under non-irrigated conditions compared to the control while irrigation improved grain weight by approximately 2–36%, indicating that both treatments enhanced grain development.

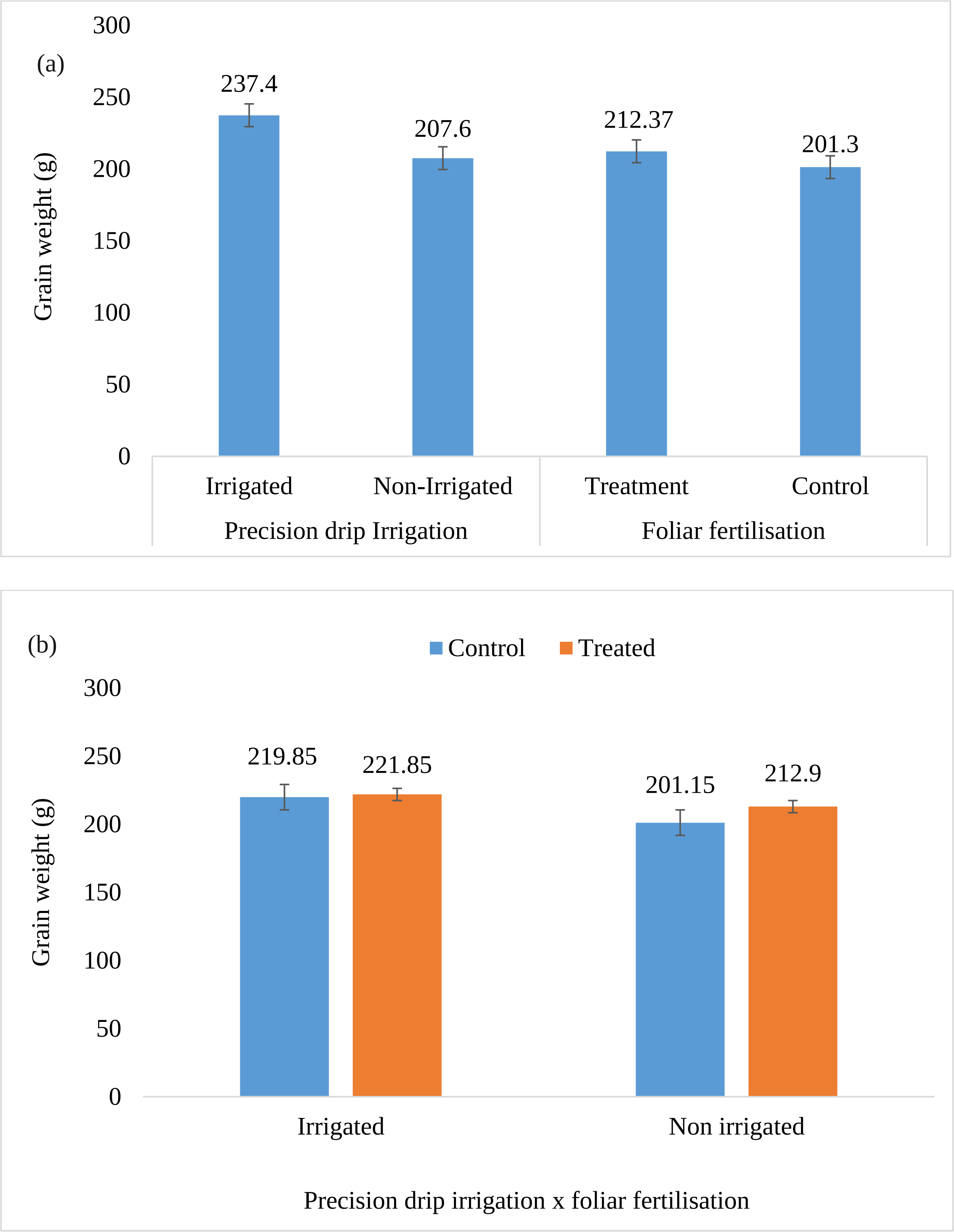


Figure 19 showing effect of (a) precision drip irrigation and foliar fertilisation; (b) the interaction effect of precision drip irrigation x foliar fertilisation on grain weight.

Number of grains per row

In 2023 growing season, precision drip irrigation significantly influenced (p=0.022) the number of grains per row. FAO490 hybrid had the highest mean number of grains per row of 38.17 compared to FAO420 (36.67) and FAO430 (36.25). Foliar fertilisation, and all their interactions had no significant effect (p>0.05) on number of grains per row. Foliar fertilisation though non-significant, treatment had more grains per row (38.00) than the control (37.17). Precision drip irrigation increased the number of grains per row (38.75) compared to non-irrigated conditions (36.42), justification of the impact of adequate soil moisture in grain development of corn. Foliar fertilisation × precision drip irrigation had no positive effect on the number of grains per row. Foliar treatment had more grains per row (37.67) compared to control (35.17) under non-irrigated conditions.   In 2024 growing season, the average grain number per row was FAO490 (38.92), FAO420 (35.25), and FAO430 (32.08). Foliar fertilisation × precision drip irrigation (p=0.029), and hybrid × irrigation (p=0.014) had a significant effect on number of grains per row. Foliar fertilisation and precision drip irrigation effects were non-significant. Precision drip irrigation (36.21) had more grains per row than non-irrigated conditions (34.62). Hybrid × precision drip irrigation positive interaction (p = 0.014) showed how hybrids responded when exposed to irrigation. The foliar fertilisation × irrigation has a statistically positive interaction (p=0.029). During the 2025 growing season, seed number per cob was positively influenced (p<0.001) by precision drip irrigation. The seed number per cob increased by 18.9% due to precision drip irrigation with 488.8 to 411.0 seeds under irrigation and non-irrigated conditions. Overall, across the three-year period, foliar fertilisation slightly increased the number of grains per row by 2–7% under non-irrigated conditions compared to the control, while irrigation consistently enhanced grain number by approximately 6–19%.

4.1.3 Grain quality response to foliar fertilisation and precision drip irrigation

Moisture content (%)

In 2023 growing season, hybrids had different moisture content; FAO430 (16.084%), FAO490 (15.390%) and FAO420 (14.170%). Hybrid x foliar fertilisation interaction was significant (p<.001). Precision drip irrigation, foliar fertilisation and all other interactions were non-significant. Foliar fertilisation treatment had a 15.226% moisture content slightly higher than the control (15.204%). A low moisture content of 15.106% was noted under precision drip irrigation conditions compared to that under non-irrigated conditions (15.323%). Precision drip irrigation x foliar fertilisation was non-significant, however foliar fertilisation treatment recorded high moisture content of 15.110% and 15.341%higher than the control (15.102% and 15.306%) under both irrigated and non-irrigated conditions respectively. In the 2024 growing season, precision drip irrigation, hybrid x precision drip irrigation and precision drip irrigation x foliar fertilisation significantly influenced grain moisture content. Moisture content of hybrids was FAO490 (12.763%), FAO430 (12.753%), FAO420 (11.863%) respectively. The moisture content under precision drip irrigation (12.721%) was slightly high than under non-irrigated conditions (12.198%). Foliar fertilisation treatment had a 12.550% moisture content slightly high than control (12.369%). Precision drip irrigation x foliar fertilisation showed that foliar treatment had high moisture content under non-irrigated conditions (12.557%) over control (11.839%) while control had a high moisture content (12.899%) over treatment (12.543%) under irrigated conditions. During the 2025 growing season, hybrid and irrigation showed significance differences (p<0.001) while foliar fertilisation was non-significant. FAO490 had the highest moisture content (16.79%) compared to FAO430 (15.76%) and FAO420 (14.61%). This represented a 14.9% difference between FAO490 and the lowest hybrid FAO420. Precision drip irrigation achieved a 13.9% moisture content difference between irrigation (16.74%) and non-irrigated conditions (14.70%). Precision drip irrigation x foliar fertilisation interaction had no significant effect on moisture concentration showing that foliar application effects were consistent across both irrigation and non-irrigated conditions (Table 4, Figure 20). Overall, across the three-year period, foliar fertilisation treatment slightly high grain moisture content by about 1–3% under non-irrigated conditions compared to the control while irrigation generally had a stronger effect, increasing moisture content by approximately 3–14% relative to non-irrigated conditions.

Oil content (%)

In 2023 growing season, oil content of grain was significantly affected by the interaction between hybrid and foliar fertilisation (p=0.007). Hybrid, precision drip irrigation, foliar fertilisation and all other interactions were non-significant. Oil content of hybrids was FAO430 (3.638%), FAO490 (3.667%) and FAO420 (3.692%) respectively. Although, both precision drip irrigation and foliar fertilisation were non-significant, grains under precision drip irrigation conditions had a slightly higher oil content (3.698%) than non-irrigated conditions (3.633%). Similarly, foliar fertilisation treatment had a 3.706% oil content slightly higher than 3.626% moisture content for control. The hybrid x foliar fertilisation interaction showed significant positive results for both FAO430 and FAO490 whereby treatment had a higher oil content (3.713% and 3.940%) compared to 3.563% and 3.395% for control respectively. Precision drip irrigation x foliar fertilisation was non-significant, however foliar fertilisation treatment (3.741% and 3.670%) was high compared to control (3.656% and 3.597%) under both irrigated and non-irrigated conditions respectively. In the 2024 growing season, grain oil content was marginally influenced foliar fertilisation. Precision drip irrigation and all interactions were non-significant. Oil content of hybrids was significantly different FAO420 (3.576%), FAO430 (3.468%), and FAO490 (3.300%) respectively. Grains from precision drip irrigated plots had a lower oil content (3.385%) than under non-irrigated conditions (3.511%). Similarly, control had a higher oil content (3.552%) than foliar fertilisation treatment (3.344%). The hybrid x precision drip irrigation interaction produced mixed results whereby FAO430 had higher oil% (3.632%) under irrigated condition over non-irrigated conditions (3.305%) while both FAO490 and FAO420 performed better under non-irrigated conditions (3.483% and 3.745%) compared to irrigated conditions (3.117% and 3.407%) respectively. Precision drip irrigation x foliar fertilisation was non-significant, foliar fertilisation treatment (3.311% and 3.377%) was low compared to control (3.459% and 3.646%) under both irrigated and non-irrigated conditions respectively. During the 2025 growing season, hybrid showed significance differences ($p<0.001$) while irrigation and foliar fertilisation were non-significant. FAO430 had the highest oil content (3.50%) compared to FAO420 (3.40%) and FAO490 (3.04%). This represented a 15.1% difference between the highest and the lowest hybrid. Precision drip irrigation had no positive effect on oil content, under non-irrigated conditions, a 4.2% oil content was noted compared to 3.24% under irrigated conditions. Foliar fertilisation though non-significant had a 3.0% effect on oil content (%) whereby treatment (3.36%) had better oil content than control (3.26%). Precision drip irrigation x foliar fertilisation interaction had no significant effect on oil concentration showing that foliar application effects were consistent across both irrigation and non-irrigated conditions (Table 4, Figure 20). Overall, across the three-year period, foliar fertilisation slightly increased grain oil content by about 1–3% compared to the control, while irrigation had variable effects ranging from –4% to +2%, indicating that hybrid genotype was a stronger determinant of oil content than either treatment.

Protein content

In 2023 growing season, protein content of grain was significantly affected by the hybrid (p=0.003). precision drip irrigation, foliar fertilisation and all interactions had no significant effect on protein%. FAO430 had the highest protein content (6.992%) compared to FAO420 (6.211%), and FAO490 (5.706%). Although, precision drip irrigation was non-significant, protein content was high under irrigated conditions (6.345%) compared to non-irrigated conditions (6.261%). Similarly, foliar fertilisation treatment had a 6.361% protein content slightly higher than 6.245% for control. Precision drip irrigation x foliar fertilisation was non-significant, however foliar fertilisation treatment had higher protein% (6.397% and 6.324%) than to control (6.293% and 6.197%) under both irrigated and non-irrigated conditions respectively. In 2024 growing season, protein content of grain was significantly affected by the hybrid (P=0.024), precision drip irrigation x foliar fertilisation (p=0.017) and hybrid x precision drip irrigation x foliar fertilisation (P=0.009). FAO430 had the highest protein content (7.7173%) compared to FAO420 (6.853%), and FAO490 (6.200%). Precision drip irrigation was non-significant; protein content was high under non-irrigated conditions (6.857%) compared to irrigated conditions (6.627%). Foliar fertilisation treatment had slightly high protein content (6.361%) than control (6.245%). The hybrid x precision drip irrigation showed that all hybrids (FAO420, FAO430, FAO490) had better protein content under non-irrigated conditions (7.052%, 7.310%, 6.210%) compared to precision drip irrigation conditions (6.653%, 7.037%, 6.190%) respectively. Foliar fertilisation treatment had a high protein content (6.808%) compared to control (6.446%) under precision drip irrigation conditions while control performed better than treatment under non-irrigated conditions. During the 2025 growing season, hybrid and foliar fertilisation showed significance differences (p<0.001) while irrigation was non-significant. FAO430 had the highest protein content (6.16%) compared to FAO420 (5.77%) and FAO490 (5.59%). This represented a 10.2% difference between the highest and the lowest hybrid. Precision drip irrigation had no positive effect on protein content, under non-irrigated conditions, a 5.90% protein content was noted compared to 5.78% under irrigated conditions. Foliar fertilisation showed a positive effect on protein content with a 7.9%

protein content improvement whereby treatment (6.06%) had better protein content than control (5.62%). Precision drip irrigation x foliar fertilisation interaction had no significant effect on protein concentration showing that foliar application effects were consistent across both irrigation and non-irrigated conditions (Table 4, Figure 20). Overall, across the three-year period, foliar fertilisation slightly increased grain protein content by about 2–8% under irrigated conditions compared to the control while precision drip irrigation had inconsistent effects, indicating that hybrid genotype and foliar treatment were more influential on protein content than water supplementation.

Starch content

Grain starch content was significantly different among hybrids (p=0.001), hybrid x foliar fertilisation interaction had a significant effect (p=0.006) on starch%. Precision drip irrigation, foliar fertilisation and all other interactions had no significant effect on starch%. FAO420 had the highest starch content (65.012%) compared to FAO490 (63.737%), and FAO430 (62.973%). Precision drip irrigation was non-significant; starch content was high under non-irrigated conditions (64.044%) compared to irrigated conditions (63.771%). Similarly, foliar fertilisation treatment had a lower starch content (63.786%) than control (64.029%). Hybrid x foliar fertilisation interaction had no significant effect, FAO420 treatment had a high starch content (65.230%) than control (64.793%) while all other hybrids (FAO430 and FAO490) had a negative trend whereby control performed better than treatment. Precision drip irrigation x foliar fertilisation was non-significant, control (64.148% and 63.910%) performed better than foliar fertilisation treatment (63.940% and 63.631%) under both irrigated and non-irrigated conditions respectively. In 2024 growing season, grain starch content was significantly different among hybrids (p=0.041). Precision drip irrigation, foliar fertilisation and all other interactions had no significant effect on starch%. FAO420 had the highest starch content (64.558%) compared to FAO490 (63.767%), and FAO430 (62.767%). Precision drip irrigation was non-significant; starch content was high under non-irrigated conditions (63.989%) compared to irrigated conditions (63.406%). Similarly, foliar fertilisation treatment had a lower starch content (63.611%) than control (63.783%). The hybrid x precision drip irrigation showed FAO420 performed better under irrigated conditions (64.767%) compared to non-irrigated conditions (64.350%), FAO430 and FAO490 had better starch content under non-irrigated conditions (63.733% and 63.883%) compared to irrigated conditions (61.800% and 63.650%) respectively. Hybrid x foliar fertilisation interaction had no significant effect, FAO420 treatment had a high starch content (65.230%) than control (64.793%) while both FAO430 and

FAO490 had a negative trend whereby control performed better than treatment. Precision drip irrigation x foliar fertilisation was non-significant, foliar fertilisation treatment had better starch content (63.467%) over control (63.344%) under irrigated conditions while control (64.222%) performed better than treatment (63.756%) under non-irrigated conditions. During the 2025 growing season, hybrids had different starch concentration, similarly foliar fertilisation and precision drip irrigation significantly influenced ($p<0.001$) starch content. FAO420 had the highest starch concentration (62.98%) compared to FAO430 (61.25%) and FAO490 (60.75%). This represented a 3.7% difference between the highest and the lowest hybrid. Under non-irrigated conditions, a 62.48% starch content was noted compared to 60.84% under irrigated conditions. Foliar fertilisation showed a positive effect on starch content with a 1.6% starch concentration improvement whereby treatment (62.14%) had better starch content than control (61.18%). Precision drip irrigation x foliar fertilisation interaction had no significant effect on starch concentration showing that foliar application effects were consistent across both irrigation and non-irrigated conditions (Table 4, Figure 20). Overall, across the three-year period, foliar fertilisation slightly increased grain starch content by about 1–2% compared to the control, while irrigation had inconsistent effects, genotype was the main determinant of starch concentration.

Table 4 showing moisture (%), oil (%), protein (%) and starch (%) due to precision irrigation and foliar fertilisation application (* indicates significance difference)

	Precision Drip Irrigation											
	2023				**2024**				**2025**			
	moisture (%)	Oil (%)	Protein (%)	Starch (%)	moisture (%)	Oil (%)	Protein (%)	Starch (%)	moisture (%)	Oil (%)	Protein (%)	Starch (%)
Irrigated	15.106	3.69	6.34	64.04	17.74*	3.38	6.62	63.4	16.74*	3.2	5.78	60.84
Non-Irrigated	15.323	3.63	6.21	63.77	12.19	3.51	6.85	63.98	14.7	4.2	5.9	62.48
	Foliar fertilisation											
Control	15.204	3.62	6.36	64.02	12.369	3.55	6.24	63.78	15.92	3.2	6.06	61.16
Treatment	15.226	3.7	6.24	63.77	12.55	3.34	6.36	63.61	15.52	3.3	7.9*	62.14

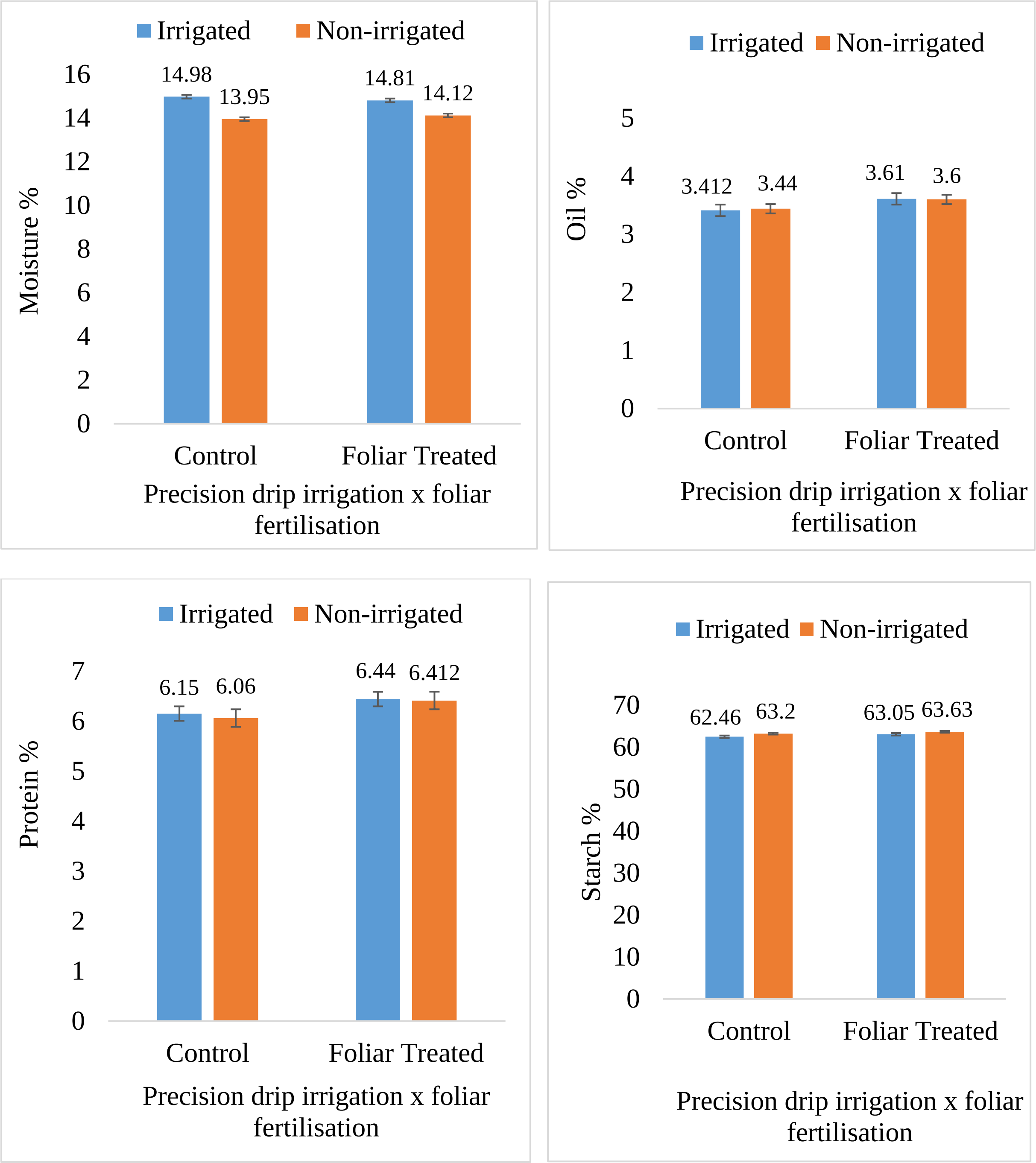


Figure 20 showing effect of precision drip irrigation x foliar fertilisation on grain quality parameters; a) moisture %; b) oil %; c) protein %) and d) starch %

4.1.4 Yield response to foliar fertiliser application and precision drip irrigation

During the 2023 growing season, hybrid and foliar fertilisation positively influenced ($p<0.001$) grain yield while irrigation had no significant effect. Hybrid yield performance was FAO420 (14.01 t ha^{-1}), FAO430 (17.79 t ha^{-1}) and FAO490 (17.46 t ha^{-1}). FAO490 had 27.0% and 24.6% higher yields than FAO420 and FAO430 respectively (Figure 22a). Although, precision drip irrigation had no significant influence on grain yield, however, yield due to irrigated conditions (16.53 t ha^{-1}) was higher (1.4%) than non-irrigated conditions (16.30 t ha^{-1}). Foliar fertilisation positively influenced grain yield. Foliar treatment had a 4.2% yield increased grain yield (16.76 t ha^{-1}) than control (16.08 t ha^{-1}). The hybrid × foliar fertilisation interaction was significant ($p<0.001$), FAO420 had a 16.5% grain yield increase due to foliar fertilisation treatment (15.07 t ha^{-1}) than control (12.94 t ha^{-1}) compared to FAO430 and FAO490 with minimal differences. The precision drip irrigation × foliar fertilisation interaction was non-significant, foliar fertilisation optimised grain yield by 4.7% and 3.8% under precision irrigation and non-irrigated conditions respectively. Grain yield was 16.15 t ha^{-1} (treatment) and 16.91 t ha^{-1} (control) for irrigated conditions while 16.00 to 16.61 t ha^{-1} under non-irrigated conditions. During the 2024 growing season, hybrid, foliar fertilisation, and irrigation positively influenced ($p<0.001$) grain yield. Hybrid yield performance was FAO420 (16.47 t ha^{-1}), FAO430 (16.34 t ha^{-1}) and FAO490 (18.03 t ha^{-1}). FAO490 had 9.5% and 10.3% higher yields than FAO420 and FAO430 respectively. Contrary to 2023 growing season, precision drip irrigation had a strong positive significant influence ($p<0.001$) on grain yield, yield due to irrigated conditions (19.67 t ha^{-1}) was significantly higher (38.3%) than non-irrigated conditions (14.22 t ha^{-1}). Foliar fertilisation treatment significantly improved grain yield by 5.7%, grain yield for treatment was (17.42 t ha^{-1}) than control (16.48 t ha^{-1}). The hybrid × foliar fertilisation interaction was significant ($p<0.001$), FAO490 achieved the highest grain yield due to foliar fertilisation treatment (21.31 t ha^{-1}) while under non-irrigated conditions, grain yield ranged between 13.94 – 14.75 t ha^{-1} for all hybrids. The irrigation × foliar fertilisation interaction was non-significant; grain yield improved from 19.31 to 20.03 t ha^{-1} (3.7%) and 13.64 to 14.80 t ha^{-1} (8.5%) due to foliar fertilisation under precision drip irrigation and non-irrigated conditions respectively. During the 2025 growing season, hybrid, foliar fertilisation, irrigation and hybrid x irrigation interaction positively influenced ($p<0.001$) grain yield. Hybrid yield performance was FAO420 (15.99 t ha^{-1}), FAO430 (18.64 t ha^{-1}) and FAO490 (19.98 t ha^{-1}). FAO490 had 16.6% and 25.0% higher yields than FAO420 and FAO430 respectively. Similarly to 2024 growing season, precision drip irrigation had a strong positive significant influence ($p<0.001$) on grain yield,

yield due to irrigated conditions (19.78 t ha^{-1}) was significantly higher (18.9%) than non-irrigated conditions (16.63 t ha^{-1}). Foliar fertilisation treatment significantly improved grain yield by 18.7%, grain yield for treatment was (19.76 t ha^{-1}) than control (16.65 t ha^{-1}). The hybrid × irrigation interaction was significant ($p<0.001$), whereby FAO430 and FAO490 responded highly to precision drip irrigation than FAO420. Precision drip irrigation × foliar fertilisation interaction had a positive effect on grain yield, foliar fertilisation application under precision drip irrigated conditions increased grain yield by 13.0% whereby treatment yielded 20.99 t ha^{-1} compared to control 18.57 t ha^{-1} while under non-irrigated conditions, an increase of 25.9%, was observed between treatment 18.53 t ha^{-1} and control 14.72 t ha^{-1}. There was a positive significant hybrid × irrigation × foliar fertilisation interaction ($p<0.001$) whereby FAO420 responded strongly to foliar fertilisation under non-irrigated conditions while FAO430 and FAO490 achieved greatest grain yield due to foliar fertilisation under precision drip irrigation conditions (Figure 22). Across the 3-year experimental period, foliar fertilisation and precision drip irrigation increased grain yield by approximately 4.2–18.7% and 1.4–38.3% respectively compared to control indicating a consistent positive effect on productivity. Overall, precision drip irrigation (18.7 t ha^{-1}) and foliar fertilisation (18.0 t ha$^{-1)}$ significantly improved grain yield compared to non-irrigated conditions (15.7 t ha^{-1}) and control (16.4 t ha^{-1}) respectively (Figure 21). The combination of foliar fertilisation and irrigation resulted in the highest productivity, whereas the lowest yields were consistently observed under control and non-irrigated conditions.

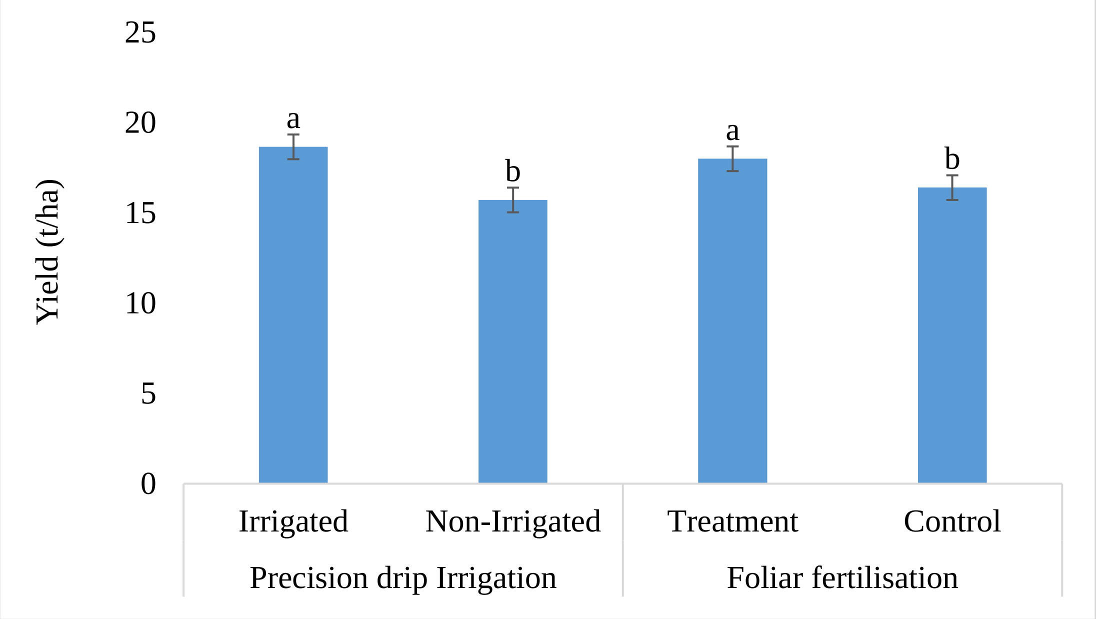


Figure 21 showing grain yield as affected by precision drip irrigation and foliar fertilisation across the experimental period.

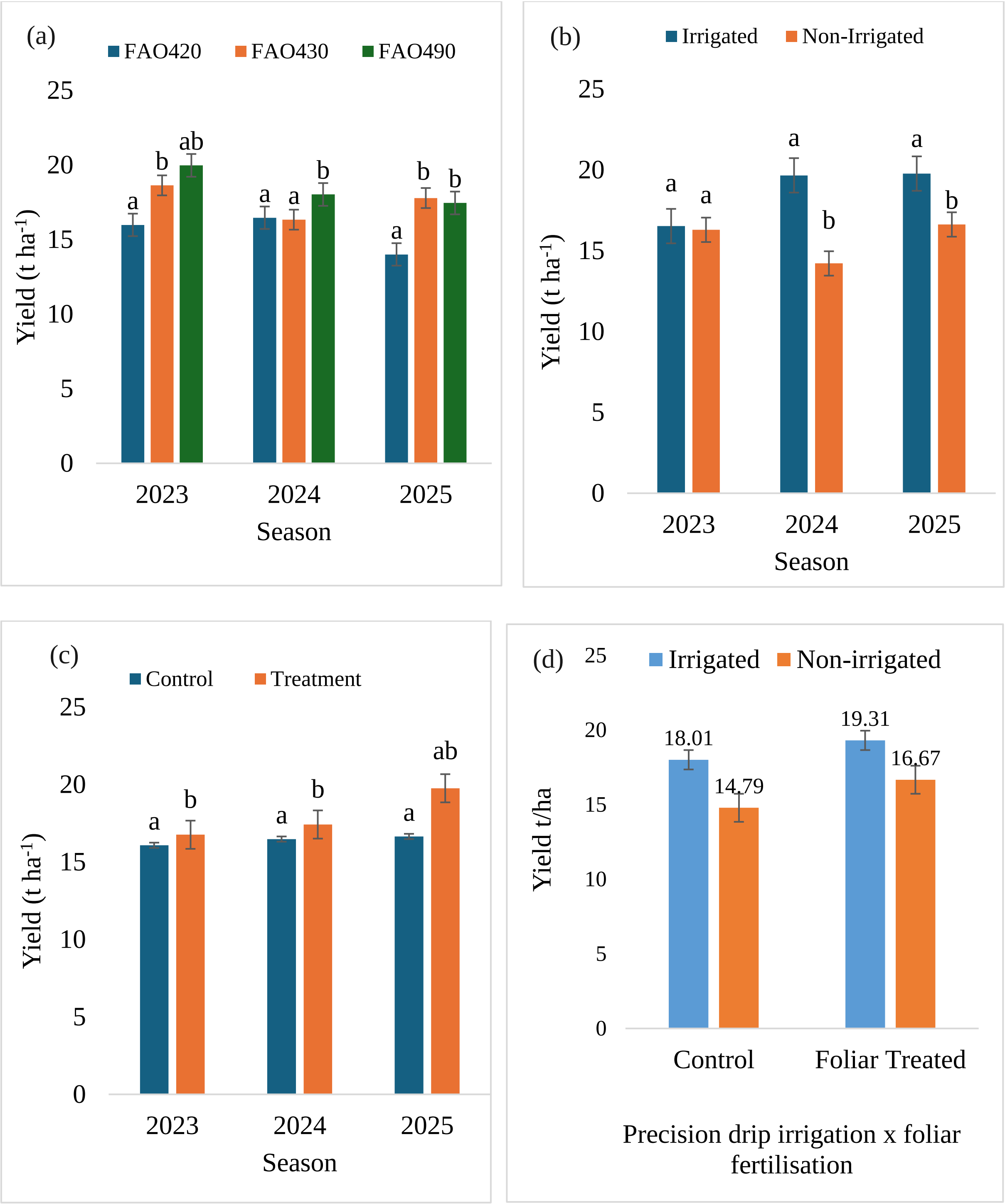


Figure 22 grain yield (t ha^{-1}); (a) hybrid yield performance; (b) effect due to precision drip irrigation and (c) effect of foliar fertilisation on grain yield; (d) precision drip irrigation x foliar fertilisation; a, b and ab letters indicate significance difference by Tukey test at $p<0.05$ during the 2023, 2024 and 2025 growing seasons.

4.2 The relationship between physiological growth, yield parameters and grain yield

4.2.1 The relationship between physiological growth parameters and grain yield

The analysis of correlation between different physiological parameters namely plant height, NDVI, SPAD and LAI and overall grain yield across the experimental period has established significant relationships. Plant height, SPAD, and LAI have exhibited a positive linear correlation with grain yield, while NDVI showed a weak linear relationship with yield (Table 5, Figure 23). The correlation coefficient (r) of plant height, SPAD, LAI, NDVI have been noted as (0.5636, 0.514, 0.552, and 0.183) respectively (Table 5, Figure 23). The results indicate that taller plants produced higher grain yield than short plants. Similarly, plants with high canopy development and improved leaf area, high concentration of chlorophyll positively improved grain yield. The weak relationship between NDVI and grain yield shows that although it's a proxy for crop vigor, its contribution to yield was non-significant compared to LAI, SPAD, and plant height.

Table 5 Relationship between physiological growth parameters and grain yield

Trait	Correlation Coefficient (r)	P-value	Simple description
Plant Height	0.5636	<0.001	Strong linear relationship
NDVI	0.1832	0.2848	Weak linear relationship
SPAD	0.5141	0.0013	Strong linear relationship
Leaf Area Index	0.5523	<0.001	Strong linear relationship

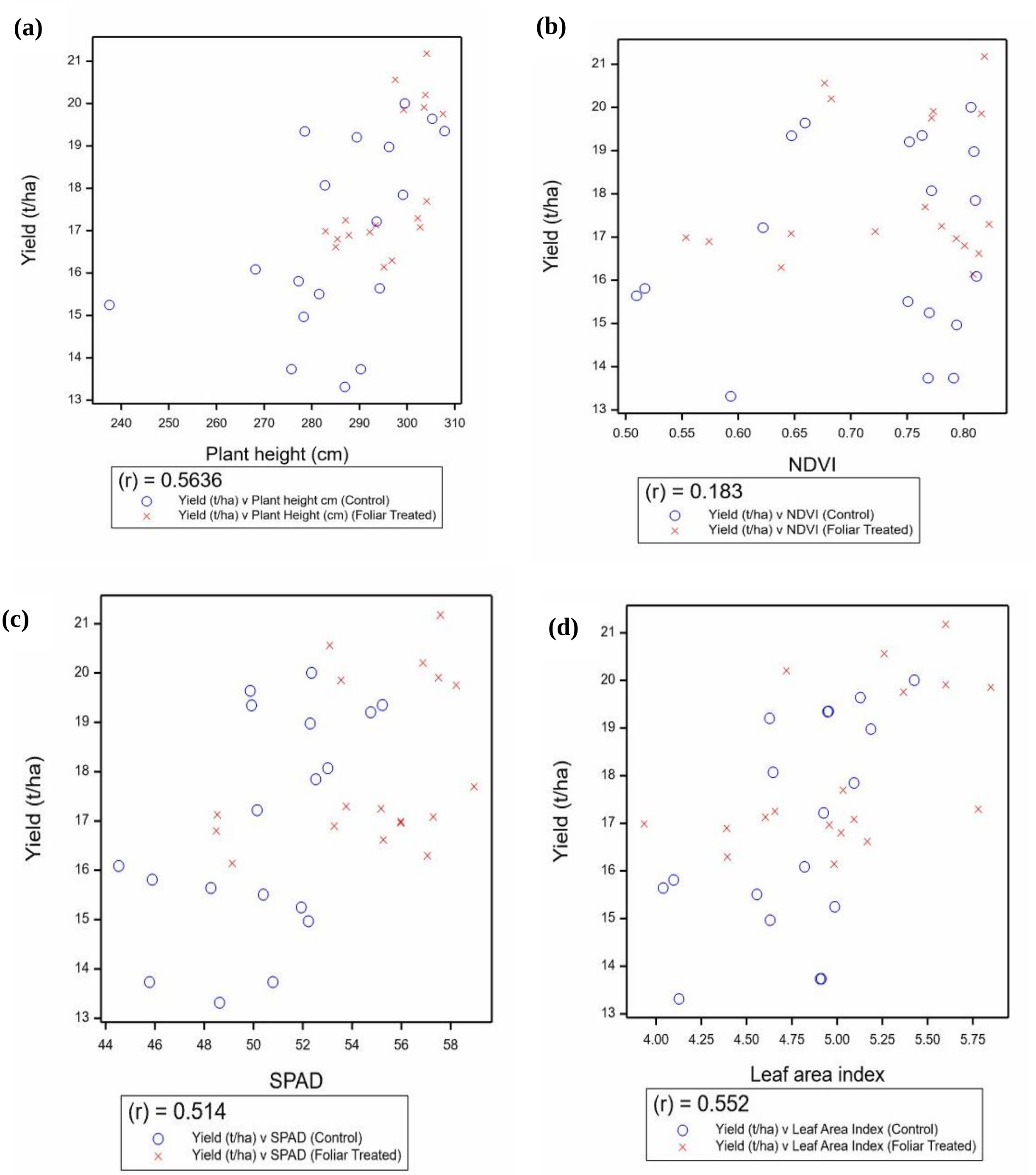


Figure 23 Correlation analysis of physiological growth traits and grain yield; a) plant height vs grain yield under foliar fertilisation, b) NDVI vs grain yield under foliar fertilisation c) SPAD vs grain yield under foliar fertilisation, d) LAI vs grain yield under foliar fertilisation.

4.2.2 The relationship between yield components and grain yield

Correlation analysis established significant positive linear relationship between all yield components studied and grain yield (t ha^{-1}). Cob length (cm), cob diameter (mm), cob weight (g), the number of grains per cob, grain weight (g), number of grains per row, and 1000 grain weight of kernels had a significant effect on grain yield with correlation coefficient (r) of 0.464, 0.644, 0.713, 0.649, 0.743, 0.444, and 0.471 respectively (Table 6, Figure 24). This indicated that longer, thicker, and heavier cobs with high kernel number and seed mass had better grain yield. Therefore, improvement of yield traits directly translates into higher yield performance of maize. The results showed that grain yield was strongly influenced by cob weight, seed weight, cob diameter, and number of grains per cob, while cob length, seeds per row, and thousand seed weight played secondary but significant roles. Suggesting that maize yield improvement wasn't only controlled by physiological parameters but also sink strength and grain filling efficiency. The results agree with recent studies indicating that parameters such as the 1000-grain weight, cob diameter, and cob weight positively correlated with grain yield.

Table 6 Relationship between yield parameters and grain yield

Trait	Correlation Coefficient (r)	P-value	Description
Cob length	0.4639	0.0044	Moderate linear relationship
Cob diameter	0.6438	<0.001	Strong linear relationship
Cob weight	0.7130	<0.001	Strong linear relationship
Seed weight	0.7428	<0.001	Strong linear relationship
Number of grains per cob	0.6489	<0.001	Strong linear relationship
Number of seeds per row	0.4435	0.0067	Moderate linear relationship
1000 grain weight of kernels	0.4714	0.0037	Moderate linear relationship

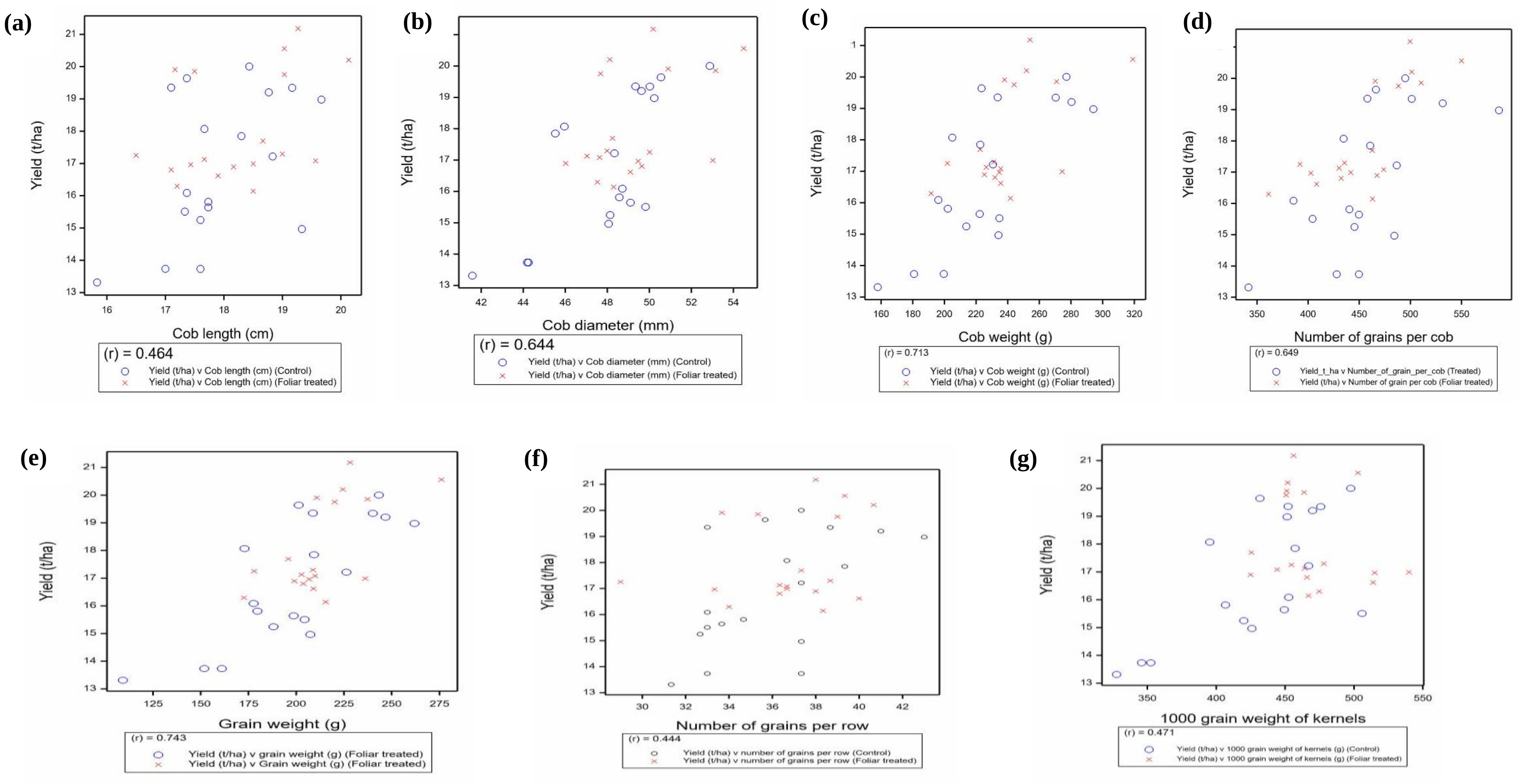


Figure 24 Correlation analysis of yield components and grain yield; a) cob length vs grain yield under foliar fertilisation, b) cob diameter vs grain yield under foliar fertilisation, c) cob weight vs grain yield under foliar fertilisation, d) Number of grains per cob vs grain yield under foliar fertilisation, e) Grain weight vs grain yield under foliar fertilisation f) Number of grains per row vs grain yield and g) 1000 grain weight of kernels vs grain yield under foliar fertilisation.

5. DISCUSSION

5.1 Physiological and growth response to foliar fertilisation and precision drip irrigation

Our findings corroborate with recent findings that maximum irrigation improved optimum plant height (*Nawaz et al., 2024*). A study conducted by *Liu et al., (2023)* noted that plant height improved due to precision drip irrigation. Plant height improved by 13.8% and 10.8% due to application of medium irrigation at the different growth stages (*Gu et al., 2021*). *Nik-Khah et al. (2024)* reported that foliar micronutrient application ($MnSO_4$, $FeSO_4$, and $ZnSO_4$) significantly improved plant height. Due to foliar application of zinc and iron, plant height was higher for treatment (280 cm) than control (196 - 222 cm) according to *Khalafi et al., (2021).* Foliar application of biostimulants such as Elusine indica extracts had a significant effect on plant height under drought stress (*Han et al., 2024). Zhu et al. (2025)* noted no significance fferences on plant height due to the interaction between irrigation, fertiliser application, and year. Through foliar application of zinc at the rate of 100 mg Zn l^{-1} maize plant height was influenced (*Oliveira et al., 2022; Biswal et al., 2024*). *Al-Ghazal et al. (2023)* reported that foliar application of seaweed extracts positively influenced plant height of maize during different seasons.

Recent studies have noted the positive impact of irrigation on LAI (*Nawaz et al., 2024*), which agrees with our findings that precision irrigation significantly improved LAI across different years. Similarly, *Liu et al. (2023)* reported a 22.2% LAI difference under drip irrigation over conventional border irrigation. Amount of irrigation was also observed to affect LAI whereby medium irrigation rate had 22.6% and 16.7% LAI difference over both lower and high irrigation rates according to *Gu et al., (2021).* A study by *Zhu et al., (2025)* noted that LAI consistently improved across the study period due to application of irrigation and micronutrients such as nitrogen. The interaction effect of fertiliser application and irrigation significantly improved LAI (*Yan et al., 2021*), yielded a higher LAI of 4.8 (*Chinasho et al., 2023).* Through foliar application of zinc and Ortho Silicic Acid (OSA) biofertilizer at the rate of 100 mg Zn l^{-1} and 0.25% respectively influenced LAI of maize (*Oliveira et al., 2022; Biswal et al., 2024*).

Our findings agree with *Tamás et al. (2023)* that irrigation positively influenced NDVI. Similarly, *Balaout et al. (2022)* reported that foliar fertiliser application improved NDVI by 8% and 25% respectively. Nitrogen fertilisation had a positive effect on NDVI throughout the vegetative period according to *Tamás et al., (2023).* Foliar application of biostimulants improved NDVI across different physiological growth stages *(Zelenák et al., 2022*). Foliar application of 2% K_2SO_4 effectively enhanced the total chlorophyll (9%) under drought stress conditions as reported by *Oliveira et al., (2022). Ocwa et al. (2024)* noted that both precision drip irrigation, biostimulants and microelements application on maize had a significant effect ($p<0.05$) on NDVI. There was a significance difference ($p<0.05$) for NDVI between irrigated and non-irrigated conditions *(Széles et al., (2024).*

Notably, *Liu et al. (2023)* reported SPAD improvement due to precision drip irrigation. However, irrigation quantity was seen as a key factor that improved SPAD (chlorophyll content) of maize (*Gu et al., 2021*). *Liu et al. (2022)* noted that high and medium irrigation rates improved SPAD compared to lower irrigation rate. During a study on nitrogen fertilisation x water management interaction, a significant effect on SPAD was noted (*Guo et al., 2021*). Foliar fertilisation had a 12% and 4% SPAD improvement at 12-leaf and silking growth stages (*Balaout et al., 2022*). The foliar application of biostimulants positively improved SPAD (62.8) in Ivola maize hybrid according to *Zelenák et al., (2022)*. Foliar application of urea at 0.10‒3.20% concentration at V6, V12, VT and R2 maximized the relative chlorophyll content and photosynthetic capacity of summer maize (*Klofac et al., 2023*). Similarly, ZnEDTA and $ZnSO_4$ applied alongside trehalose influenced chlorophyll content according to (*Matlok et al., 2020*). Ortho Silicic Acid (OSA) biofertiliser applied at 0.25% positively influenced SPAD values of maize (*Biswal et al., 2024*).

5.2 Yield components of maize hybrids under foliar fertilisation and precision drip irrigation

A study by *Yadav et al. (2024)* correlated with our findings that cob diameter values were significantly different among different maize varieties with values varying between 13.85 cm to 15.56 cm respectively. These results highlighted the impact of maize variety on cob diameter therefore important for maize varietal selection to achieve required physiological growth. Maize cob length was influenced by several factors such as environment, genetics, and management practices including fertiliser application and water availability according to *Campos, (2011). Chinasho et al. (2023)* showed that blended fertilizer application produced higher performance in terms of cob length. The length of cob varied significantly ($p<0.05$) among different maize accession lines (*Imam et al., (2024).*

Results by *Tóth et al. (2022)* showed that cob weight improved due to the zinc (Zn) and amino acids foliar application on fodder corn. Also, an increase in superoxide dismutase (SOD) activity among treatments compared to the control indicated increased cob weight (*Tóth et al. 2022).* Similarly, cob weight improved due to precision drip irrigation during 2022 and 2023 seasons (222.19 g and 304.6 g) compared to 57.3 g and 261.9 g under water stress condition (*Ocwa et al., 2024).* Application of different biostimulants under both precision drip irrigation and non-irrigated conditions during the 2022 experimental year recorded cob weight of T1 (237.8 g), T2 (226.0 g), and T3 (230.0 g) compared to 49.8 g, 68.4 g and 63.2 g under water stress *(Ocwa et al., 2024).*

Important to acknowledge that like many other morphological characters, the number of rows per cob is equally an important trait in maize (*Troyer, 2006*). This trait is also largely influenced by environment, genetics, and management practices (*Campos, 2011*). Recent studies supported our findings that no significance differences (p<0.05) were noted among the different maize accession lines with minimal differences (*Imam et al., 2024).* High number of rows per cob influences grain yields (*Brown, 2011),* but excess row numbers per cob leads to a reduction in grain seed sizes and low quality of grains (*Liu, 2019).* Minor cob length variations noted might be attributed to varietal differences as earlier reported by *Kiani et al., (2017).*

A significant increase in 1000 grain weight of kernels due to drip fertigation was recorded by *Du et al., (2024). Ocwa et al. (2024)* during the 2022 and 2023 growing seasons noted that 1000 grain weight of kernels significantly improved due to application of precision drip irrigation with weight values of 363.3 and 534.7 g compared to 268.3 and 505.2 g under non-irrigated conditions. Further noted that biostimulant treatment and its interaction with precision drip irrigation significantly improved 1000 grain weight of kernels in 2023 experimental year. According to *Zelenák et al. (2022),* the application of foliar biostimulants to Ivola and Mv Marfi maize optimised 1000 grain weight of kernels by 22.8% and 6%. Also, *Chinasho et al. (2023)* noted an increase in 1000 grain weight due to foliar application of blended fertilizer application.

Deshpande et al. (2017) studied the application of foliar fertilisers at critical growth stages which improved grain weight. Another study revealed that foliar treatment significantly produced heavier grains (229 g/1000 grains) compared to control (*Amanullah et al., 2014*). Similarly, hybrid difference was noted as a major determinant of grain weight in plants (*Imam et al., 2024). Chinasho et al. (2023)* reported better performance in seed number per cob due to blended fertilizer application. Application of precision drip irrigation positively (p<0.05) improved the grain number per cob. The number of grains per cob due to precision drip irrigation was 538 and 506 grains while cobs under non-irrigated conditions recorded 164 and 468 grains during the 2022 and 2023 growing seasons (*Ocwa et al., 2024).* However, foliar application of biostimulants had no significant effect on the grain number per cob under both precision drip irrigation and non-irrigated conditions respectively *(Ocwa et al. 2024)*. Similarly, hybrid difference was noted as a major determinant of number of seeds per cob *(Imam et al., 2024).*

5.3 Grain quality response to foliar fertilisation and precision drip irrigation

Foliar fertiliser application at critical phenological stages has proved effective towards improvement of maize grain quality. Foliar application of Urea Ammonium Nitrate (UAN) together with waste element S optimised the grain quality status of maize (*Ahmad et al., 2023*; *Tejada et al., 2018).* Foliar micronutrient application boosts quality parameters such as carbohydrate content, oil content, fibre content, protein content, kernel size, mineral content and grain weight (*Deshpande et al., 2017*). Notably, foliar spraying of glutamine on maize enhanced the total carotenoid concentration, oil content, protein content, minerals, fatty acids, and α-tocopherol (*Crista et al., 2024*). *Artyszak et al. (2025)*, compared the effect of silicon-based products on maize yield and quality applied through both foliar and soil. There was significant and beneficial effect on the grain quality parameters such as protein and fat content however a reduction in starch content was recorded. Foliar Ortho Silicic Acid (OSA) application improved dry matter content (11.3%), protein content (1.3%), and ash content (3.3%) however detergent fibre content (2.0%) and percent acid detergent fibre content (2.7%) decreased (*Biswal et al., 2024*). There was a slight increase in starch content due to the foliar fertiliser application (*Duque-Acevedo et al., 2020; Rácz et al., 2021*). *Bojtor et al. (2022)* noted that application of nitrogen fertilizer at the rate of 120 kg ha^{-1} improved the amount of crude protein content. *Rodrigues et al. (2021)* noted that the sugar concentration improved at the grain-filling stage. *Ocwa et al. (2024)* studied the effect of precision drip irrigation and application of biostimulants and microelements on maize. Precision drip irrigation increased grain starch content, however, both protein content decreased by -2.1% and -0.5% respectively for 2022 and 2023 seasons. Biostimulant application under precision drip irrigation optimised grain yield during the year 2022 which had a higher water stress than 2023.

5.4 Yield response to foliar fertiliser application and precision drip irrigation

Recent studies support our findings as foliar fertiliser application increased maize yield. *Buligon et al. (2023)* applied Ortho Silicic Acid (OSA) (0.25%) yielding 53.63 t ha^{-1} and 13.35

t ha^{-1} of both green fodder (GFY) and dry fodder (DFY), thus a 10.6% and 45.3% yield increase over the control. Zinc (ZnI) foliar application increased maize yield from 892 to 2519 kg ha^{-1} (*Rehman et al., 2021; de Souza Júnior et al., 2022*), ZnO application also increased maize yield (17.1%) (*Škarpa et al., 2021*). Similarly, *Cheah et al. (2022)* noted that the effective dose of 100 mg Zn l^{-1} had the highest yield of 7583.4 kg ha^{-1} through foliar fertilisation. Both zinc (Zn) and Iron (Fe) applied through maize leaves improved the yield with the highest yield of 5220.5 kg ha^{-1} and 4885.5 kg ha^{-1} respectively (*Khalafi et al., 2021*). Manganese (Mn ha^{-1}) foliar fertilisation at the vegetative stage increased maize yield by 19% over control (*Stewart et al., 2021*), however, when zinc, iron and boron were applied through foliar fertilisation had no impact on maize grain yield (*Stewart et al., 2021*). Foliar phosphorous fertilisation recorded a 21.4% grain yield increase over the control (*Islam et al., 2024*). Foliar application of SiAl at different doses (0.5 and 1.0 g L^{-1}) increased maize grain yield (*Jalal et al., 2023*). Also, foliar Glutamine (Gln) application on maize hybrid ZD958 at a dose of 1.25 mM increased yield by 20.0% and 38.0% under sufficient and low nitrogen levels respectively (*Crista et al., 2024*). Contrary, high levels (0.84 kg ha^{-1}) of increased zinc application registered a yield decrease by 4.5% attributing this to high toxicity levels (*Islam et al., 2024*). Similarly, water management, foliar biostimulant and micronutrients application optimized grain yield. During the 2022 and 2023 seasons, grain yield improved significantly ($p<0.05$) due to application of precision drip irrigation achieving 13.3 t ha^{-1} and 19.4 t ha^{-1} compared to 3.8 t ha^{-1} and 17.3 t ha^{-1} under non-irrigated conditions. Due to application of biostimulants under precision drip irrigation, grain yield improved by 9.5 t ha^{-1} and 2.1 t ha^{-1} in 2022 and 2023 seasons respectively. However, during 2023 growing season under both irrigated and non-irrigated condition, application of biostimulant and micronutrients application significantly ($p<0.05$) improved grain yield (*Ocwa et al., 2024*).

5.5 The relationship between physiological growth, yield parameters and grain yield

Correlation results demonstrated how both physiological traits and yield parameters can be used as primary predictors of grain yield in maize. *Dixet and Dubey, (1984)* noted that many factors such as genetic factors and environmental fluctuations influenced grain yield. Correlation studies help understand the association between different traits with grain yield (*Dixet and Dubey, 1984; Dwyer et al., 1994*). Our results agreed and as well contradicted recent studies as follows. Plant height had a significant correlation with increased grain yield as reported by (*Dhakal et al., 2017*). Another study showed that number of rows per cob ($r = 0.39$), plant height ($r = 0.53$), number of grains per row ($r = 0.50$), cob diameter ($r = 0.43$) and cob length (r = 0.47) significantly correlated with grain yield (*Dobos et al., 2012; Yadav et al., 2024*). Plant density also had a positive correlation with physiological growth parameters such as yield, plant height, and number of kernels row. Correlation results at the highest plant density showed significant associations between kernel yield, plant height and number of kernels per row. At 100,000 plants ha^{-1}, kernel yield was strongly correlated with 1000-kernel weight, number of kernels per row, and plant height (*Mahmood et al., 2025*). Parameters such as the 1000 grain weight of kernels, and cob diameter positively correlated with grain yield. The strongest direct correlation effect was due to 1000-grain weight while plant height showed the highest indirect positive correlation effect on grain yield (*Valizadeh, & Bahrampour, 2013*). Contrary, there was no significant phenotypic correlation between leaf breadth, number of kernel rows per ear, plant height, number of kernels per row, ear per plant, and ear height with grain yield across different genotypes (*Ghimire et al., 2015*). There was a non-significant negative phenotypic correlation between the number of kernel rows per ear and grain yield (*Ghimire et al., 2015*).

The highest direct correlation effect was due to 1000 grain weight of kernels while plant height showed the highest indirect positive correlation effect on grain yield (*Valizadeh, & Bahrampour, 2013*). Ear diameter, tassel length, ear weight, and ear length positively associated with grain yield (*Barros et al., 2010*). Grain yield was substantially positively associated with ear diameter, thousand kernel weight, days to physiological maturity, tassel length, ear length, and ear weight (*Pariyar et al., 2018*). It has been noted that increased grain yield can be attributed to cob length (*Brown, 2011)*. The strongest linkage between grain yield was due to ear length, ear diameter, thousand kernel weight, number of kernels per row, days to physiological maturity, and ear height (*Raut et al., 2017*). Also, studies by *Thapa et al. (2022)* and *Kandel & Shrestha (2020)* noted a positive correlation between cob attributes and grain yield. Contrary, there was a non-significant association between number of ears per plant and grain yield *(Raut et al., 2017).*

6. CONCLUSIONS

Physiological growth of maize was mainly influenced by precision drip irrigation and foliar fertilisation. Hybrids exhibited differential physiological growth patterns. The hybrid performance differences were more evident under precision drip irrigation conditions. FAO490 demonstrated stability and superiority of physiological growth performance under both precision drip irrigation and precision drip irrigation x foliar fertilisation interaction compared to FAO420 and FAO430. Hybrid specific yield performance was noted whereby some hybrids performed better in irrigated conditions while others under non-irrigated conditions. FAO490 consistently had the highest grain yield than FAO420 and FAO430 respectively across 2023, 2024 and 2025.

Seasonal effects were observed during the growing seasons in response to both precision drip irrigation and foliar treatment. Season conditions such as precipitation and temperature are a major factor affecting effectiveness of foliar fertilisation. Overall, maize growth and yield depended on hybrid > season > precision drip irrigation > foliar fertilisation. However, foliar fertilisation acted as a complementary management tool rather than a primary driver of physiological improvement.

Yield components positively responded to precision drip irrigation and foliar micronutrient application. Precision drip irrigation predominantly influenced yield parameters boosting cob weight, cob diameter, seed weight, cob length, number of seeds per cob, and thousand-seed weight. The interaction of precision drip irrigation x foliar fertilisation substantially improved maize yield parameters through optimisation of sink development and grain filling processes.

The grain quality traits improved due to precision drip irrigation and foliar fertilisation. Moisture% was higher under precision drip irrigation compared to non-irrigated conditions. This can be attributed to increased water availability at grain filling stage which prolonged physiological activity and delayed grain desiccation. However, minimum effect on oil%, protein%, and starch% was observed due to precision drip irrigation and foliar fertilisation. The findings suggested that targeted precision drip irrigation and foliar fertilisation strategies improved nutritional value of grains.

The evaluation of grain yield across the three-year growing period showed strong and consistent results across hybrids due to precision drip irrigation, and foliar fertilisation. Precision drip irrigation and foliar fertilisation treatment significantly influenced ($p<0.001$)

grain yield. Therefore, precision drip irrigation, foliar fertilisation and their interaction are highly recommended practices that improve grain yield.

Correlation analysis established significant positive linear relationship between physiological growth, yield components and grain yield (t ha^{-1}). This indicated that longer, thicker, and heavier cobs with high kernel number and seed mass had better grain yield. Therefore, improvement of physiological growth and yield traits directly translates into higher yield performance of maize.

The study results have demonstrated the effect of precision drip irrigation and foliar nutrient application on maize growth, yield (quantity) and grain quality, establishing correlation between physiological growth, yield components and maize yield. Furthermore, studied the performance of different maize hybrids across different seasonal conditions such as temperature and precipitation. This integrated agronomic management strategy can be adapted to different agro-ecological zones with varying climatic conditions to improve maize production, productivity, yield and grain quality stability.

Future studies should aim at:

- Refining foliar fertilisation application since this study applied micronutrients once, timing of fertiliser application to ascertain the most effective growth stage of application that would improve results, formulation, and nutrient composition so that there is better synchronisation of nutrient supply at critical phenological stages, particularly under water-limited conditions.
- Repeated long-term experiments examining genotype x irrigation x foliar fertilisation x environmental interactions across different soil types and agro-climatic zones to validate the broader applicability of these results.
- Breeding programs should integrate physiological traits into hybrid selection criteria to enhance hybrid responsiveness to precision irrigation and foliar nutrient strategies as this will support the development of climate-resilient and high-yielding maize cultivars.

7. NEW SCIENTIFIC RESULTS

The following are the new scientific results of this study.

1. Physiological growth parameters improved across the three-year period due to foliar fertilisation and irrigation. Plant height, LAI, NDVI and SPAD improved by 3.5%, 5.9%, 3% and 5% under irrigated conditions compared to 7.3%, 10.9%, 9% and 10% under non-irrigated conditions. Foliar fertilisation increased NDVI and SPAD by 2–5% and 2–20% compared to the control. The interaction between precision drip irrigation and foliar fertilisation improved plant height and LAI by 10–14% and 20–23% compared to control.
2. FAO490 consistently performed better than FAO420 and FAO430. Plant height, LAI and NDVI of FAO490 improved by 4-42% under irrigated conditions while NDVI and plant height improved by 6–8% under non-irrigated conditions due to foliar fertilisation across 2023, 2024 and 2025. FAO490 recorded 9-27% and 10-25% higher yield compared to FAO420 and FAO430 across 2023, 2024 and 2025. Precision drip irrigation x foliar fertilisation recorded a 20% higher yield for FAO430 and FAO490 hybrids than under non-irrigated conditions.
3. Foliar fertilisation effectively improved grain weight, 1000 grain weight of kernels, number of rows per cob, cob weight, cob length and cob diameter improved by 3-33%, 3-21%, 1-5%, 3-12%, 1-9% and 1-4% respectively compared to control. Precision drip irrigation improved cob diameter, cob weight and 1000 grain weight of kernels by 7.1%, 34.7% and 17.0% respectively.
4. Foliar fertilisation and precision drip irrigation significantly increased ($p<0.001$) grain yield. Foliar fertilisation enhanced grain by 4.2%, 5.7%, 18.7% compared to control, while precision drip irrigation increased yield by 1.4%, 38.3%, and 18.9% compared to non-irrigated conditions across 2023, 2024 and 2025 growing seasons. Precision drip irrigation × foliar fertilisation interaction increased grain yield by 4.7%, 3.7%, 13.0% under irrigated conditions and 3.8%, 8.5%, 25.9% under non-irrigated conditions respectively. Overall, foliar fertilisation and precision drip irrigation increased grain yield by 4–19% and 1–39% respectively compared to control.
5. Grain quality parameters were influenced by foliar fertilisation and precision drip irrigation. Foliar fertilisation consistently enhanced protein content, oil content, and starch content by 2–8%, 1–3%, and 1–2% compared to the control. Grain moisture content was higher by 3–14% under irrigation compared to non-irrigated conditions,

while moisture content was 1–3% slightly higher due to foliar fertilisation compared to control.

6. Correlation analysis revealed significant relationship between physiological growth, yield components and grain yield. Plant height, SPAD, and LAI, cob length, cob diameter, cob weight, the number of grains per cob, seed weight, seeds per row, and thousand seed weight exhibited a positive linear correlation coefficient (r) of 0.5636, 0.514, 0.552, 0.183, 0.464, 0.644, 0.713, 0.649, 0.743, 0.444, and 0.471 respectively with grain yield. Maize yield wasn’t only controlled by physiological parameters but also sink strength and grain filling efficiency.

8. PRACTICAL UTILIZATION OF RESULTS

Precision drip irrigation and targeted foliar fertilisation together with proper hybrid selection offers a clear strategy to improve maize productivity, resource-use efficiency, and reduce effects of climatic stress.

1. The study findings offer vital insights to improve maize production systems for areas affected by adverse climate changes such as drought. Precision drip irrigation demonstrated consistent results thus enhancing and stabilising both growth and grain yield. Practically adopting precision drip irrigation ensures efficient and adequate timely water supply improving soil moisture needed at critical growth stages such as tasselling, silking, and grain filling. This targeted water supplementation maximised grain yield as well as reduced water losses through evaporation and deep percolation. This renders it suitable precision technology for semi-arid and drought areas.
2. Foliar fertilisation proved a cost-effective complementary precision management strategy alongside precision drip irrigation. The results showed that physiological traits and yield components improved due to foliar fertilisation, this enhanced nutrient-use efficiency of plants where root uptake might have been constrained. Practically farmers apply foliar fertilisation as both a corrective and supplemental management approach to correct any transient nutrient deficiencies observed at key phenological stages other than only relying solely on higher basal fertiliser rates.
3. The findings on genotype-specific responses identified act as a guiding tool for hybrid selection. Farmers can select hybrids for intensive production systems that consistently performed well under different conditions namely irrigated conditions and foliar fertilisation. Conversely, hybrids that performed well under non-irrigated conditions and control (no foliar fertilisation) should be targeted for production in resources and infrastructure constrained regions as this helps farmers match genetic potential of hybrids with available resources and management strategies.
4. Application as an in-season diagnostic tool to farmers, and agronomists. The strong correlations findings between physiological traits, yield components, and overall grain yield offers a practical way by which timely and effective measure of irrigation and foliar fertilisation effects can be monitored using crop growth status thus taking proper and timely management decisions to improve yields.

9. SUMMARY (in English)

This study during the 2023-2025 growing seasons addressing the application of sustainable precision technologies in maize production such as precision drip irrigation and foliar fertilisation due to climatic variabilities. The study evaluated the effect of foliar fertilisation on maize growth and yield under irrigated and non-irrigated conditions. The field experiment was designed as a randomised split–plot design with irrigation. Data was collected on physiological parameters namely plant height, NDVI, LAI, and SPAD; yield components including cob length, cob weight, number of grains per cob, cob diameter, seed weight, and 1000 grain weight of kernels, grain yield (t ha-1) adjusted to 14% moisture, and grain quality traits such as moisture, oil, protein, and starch content. Physiological growth parameters improved across the three-year period due to foliar fertilisation and irrigation. Plant height, LAI, NDVI and SPAD improved by 3.5%, 5.9%, 3% and 5% under irrigated conditions compared to 7.3%, 10.9%, 9% and 10% under non-irrigated conditions. Combination of irrigation and foliar fertilisation improved plant height and LAI by 10–14% and 20–23% compared to control. Foliar fertilisation increased NDVI and SPAD by approximately 2–5% and 2–20% compared to the control. Foliar fertilisation and precision drip irrigation increased grain yield by approximately 4.2–18.7% and 1.4–38.3%. The strong precision drip irrigation × foliar fertilisation interaction was observed in 2025 growing season, the season that had higher precipitation and lower temperatures an indication of foliar nutrient application effectiveness under adequate soil moisture thus substantial yield improvements among hybrids. Correlation analysis demonstrated a strong positive relationship between physiological traits, yield components and grain yield an indication that improved growth and development of maize directly translated into higher yield. This study demonstrates the impact of precision drip irrigation and foliar fertilisation as a practical, resource-efficient pathway that improves maize productivity under variable agro-climatic conditions.

10. SUMMARY (in Hungarian)

A dolgozat témája a 2023–2025-ös tenyészidőszakok alatt tapasztalt éghajlati ingadozásokra vonatkozóan a kukoricatermesztésben alkalmazott fenntartható precíziós technológiák, úgy mint a precíziós csepegtető öntözés és a lombtrágyázás. A dolgozat során értékeltem a lombtrágyázás hatását a kukorica növekedésére és termésére öntözött és nem öntözött körülmények között. A szántóföldi, öntözéses kísérlet randomizált, split-plot elrendezésben valósult meg. Adatgyűjtés történt a fiziológiai paraméterekről, nevezetesen a növénymagasságról, az NDVI-ről, a LAI-ról és a SPAD-ról; a terméskomponensekről, beleértve a csövek hosszát, tömegét, a csövenkénti szemszámot, a csövek átmérőjét, a szemtömeget és az ezerszemtömeget, a 14%-os nedvességtartalomra korrigált szemtermést (t/ha), valamint a szemek minőségi jellemzőit, mint például a nedvesség-, olaj-, fehérje- és keményítőtartalom. A fiziológiai növekedési paraméterek a hároméves időszak alatt javultak a lombtrágyázás és az öntözés hatására. A növénymagasság, a LAI, az NDVI és a SPAD öntözött körülmények között 3,5%-kal, 5,9%-kal, 3%-kal és 5%-kal javult, szemben a nem öntözött körülmények között mért 7,3%-kal, 10,9%-kal, 9%-kal és 10%-kal. Az öntözés és a lombtrágyázás kombinációja a kontrollhoz képest 10–14%-kal, illetve 20–23%-kal javította a növénymagasságot és a LAI-t. A lombtrágyázás a kontrollhoz képest körülbelül 2–5%-kal, illetve 2–20%-kal növelte az NDVI és a SPAD értékét. A lombtrágyázás és a precíziós csepegtető öntözés a szemtermést körülbelül 4,2–18,7%-kal, illetve 1,4–38,3%-kal növelte. A precíziós csepegtető öntözés és a lombtrágyázás közötti erős kölcsönhatás a 2025-ös termesztési időszakban volt megfigyelhető, amely időszakban magasabb csapadékmennyiség és alacsonyabb hőmérséklet volt jellemző, ami a megfelelő talajnedvesség mellett a lombtrágyázás hatékonyságát jelzi, és így a különböző hibridek között jelentős hozamnövekedést eredményezett. A korrelációelemzés erős pozitív kapcsolatot mutatott ki a fiziológiai tulajdonságok, a terméskomponensek és a szemtermés között, ami arra utal, hogy a kukorica jobb növekedése és fejlődése közvetlenül magasabb termést eredményezett. A dolgozat bemutatja a precíziós csepegtető öntözés és a lombtrágyázás hatását, mint egy gyakorlati, erőforrás-hatékony módszert, amely változó agroklimatikus körülmények között javítja a kukorica termőképességét.

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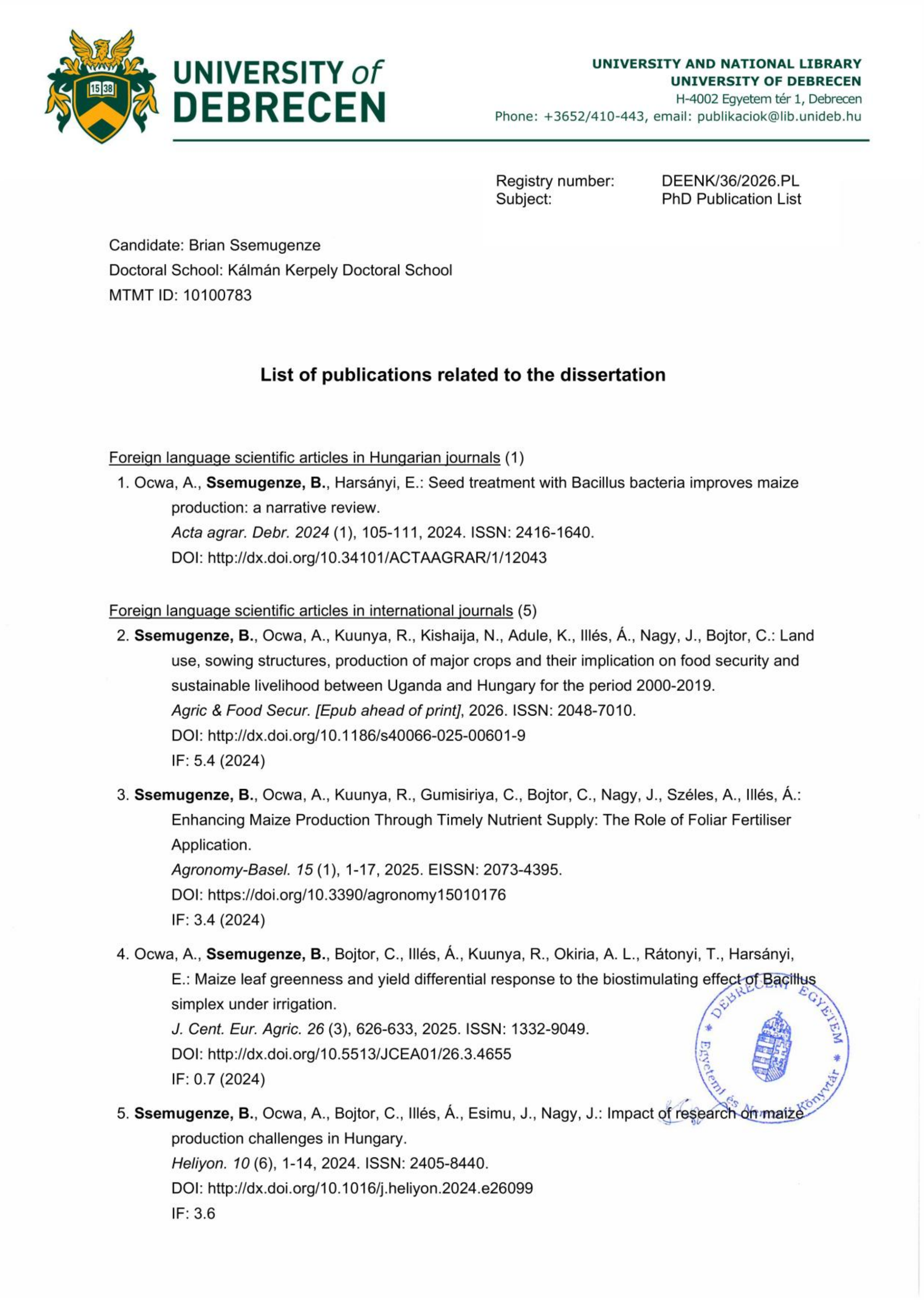
12. PUBLICATION LIST



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Candidate: Brian Ssemugenze
Doctoral School: Kálmán Kerpely Doctoral School
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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.
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2. **Ssemugenze, B.**, Ocwa, A., Kuunya, R., Kishaija, N., Adule, K., Illés, Á., Nagy, J., Bojtor, C.: Land use, sowing structures, production of major crops and their implication on food security and sustainable livelihood between Uganda and Hungary for the period 2000-2019.
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3. **Ssemugenze, B.**, Ocwa, A., Kuunya, R., Gumisiriya, C., Bojtor, C., Nagy, J., Széles, A., Illés, Á.: Enhancing Maize Production Through Timely Nutrient Supply: The Role of Foliar Fertiliser Application.
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In: Scientific Conference of PhD Students of FAFR, FBFS and FHLE SUA in Nitra with international participation - Proceedings of abstracts on occasion of the Science and Technology Week in the Slovak Republic. Ed.: Monika Tóthová, Judita Lidiková, Kristína Candráková, Dominik Holly, Slovak University of Agriculture in Nitra, Slovakia, Nitra, 57, 2023. ISBN: 9788055226606

12. **Ssemugenze, B.**, Ocwa, A., Tóth, B., Nagy, J.: Waste sludge composition and potential use as a fertilizer: a review.
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List of other publications

Foreign language scientific articles in Hungarian journals (2)

13. Akuo, R., Okiria, A. L., **Ssemugenze, B.**, Gumisiriya, C., Kabaale, P. F., Ocwa, A.: Assessment of electrical conductivity and germinability of groundnut genotype seeds.
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Foreign language scientific articles in international journals (2)

15. Kishaija, N., Ocwa, A., Kuunya, R., **Ssemugenze, B.**, Heil, B.: Climate change mitigation and livelihood components under smallholder cofee farming: a bibliographic and systematic review.
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17. Kuunya, R., Ahmed, O. M. M., **Ssemugenze, B.**, Gumisiriya, C., Tamás, A., Ragán, P.: Assessment of Soil Electrical Conductivity and Yield Responses of Maize Hybrids under different Plant Densities.
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19. 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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    In: II. Magyar Agrártudományi Doktoranduszok Szimpóziuma : Absztraktkötet. Szerk.: Hajdú Péter, Doktoranduszok Országos Szövetsége, Budapest, 51, 2024. ISBN: 9786156457431

24. Kuunya, R., Ocwa, A., **Ssemugenze, B.**, Széles, A., Ragán, P.: Management of biodegradable farm waste using black soldier fly larvae.
    An. Uni. Oradea Fasc. Ecotoxi. Zooteh. Tehno. Industr. Alimentara. 23, 5, 2024. ISSN: 1583-4301.

25. Bojtor, C., Nagy, J., Széles, A., Harsányi, E., **Ssemugenze, B.**, Ocwa, A., Illés, Á.: Nitrogen use efficiency of maize in different fertilisation levels based on long-term field experiment.
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26. Kuunya, R., Zagyi, P., **Ssemugenze, B.**, Széles, A., Ocwa, A., Ragán, P.: Relay cropping as a tool for improving the resilience and sustainability of the environment: a bibliographic analysis.
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27. Kuunya, R., Horváth, É., Ocwa, A., **Ssemugenze, B.**, Széles, A., Ragán, P.: Remote sensing technology as a better technique for assessing land degradation.
In: LXV. Georgikon Napok Tudományos Konferencia = 65th Georgikon Days Scientific Conference /szerk. Pőr Csilla, Szabó-Soós Adrienn, Szabó Péter, Magyar Agrár- és Élettudományi Egyetem Georgikon Campus, Keszthely, 27-28, 2024. ISBN: 9786156338105

28. Ocwa, A., Bojtor, C., Illés, Á., **Ssemugenze, B.**, Harsányi, E.: Effect of biostimulant application on the photosynthetic efficiency of maize.
In: Scientific Conference of PhD Students of FAFR, FBFS and FHLE SUA in Nitra with international participation - Proceedings of abstracts on occasion of the Science and Technology Week in the Slovak Republic. Ed.: Monika Tóthová, Judita Lidiková, Kristína Candráková, Dominik Holly, Slovak University of Agriculture in Nitra, Slovakia, Nitra, 52, 2023. ISBN: 9788055226606

29. Ocwa, A., Mohammed, S., **Ssemugenze, B.**, Harsányi, E.: Precision nutrient application technologies in crop production.
In: 20th Wellmann International Scientific Conference : Book of Abstracts. Eds.: Ingrid Gyalai; Szilárd Czóbel, University of Szeged Faculty of Agriculture, Hódmezővásárhely, 37, 2023. ISBN: 9789633069240

Total IF of journals (all publications): 21,6
Total IF of journals (publications related to the dissertation): 16,2

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.

30 January, 2026

13. DECLARATION

STATEMENT

I wrote this thesis in the framework of the University of Debrecen, Kálmán Kerpely Doctoral School for the purpose of obtaining a doctoral degree (Ph.D.) at the University of Debrecen.

Debrecen, 20.........................

....

signature of the candidate

STATEMENT

I hereby certify that the doctoral candidate, Ssemugenze Brian, has carried out his work under my supervision within the framework of the above-mentioned Doctoral School between 2022 – 2026. The candidate has made a decisive contribution to the results of the thesis through his independent creative work, and the thesis is the candidate's independent work. I recommend that the thesis be accepted.

Debrecen, 20...............................

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signature of the supervisor

14. ACKNOWLEDGEMENT

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"Being confident of this, that He who began a good work in you will carry it on to completion until the day of Christ Jesus". (Philippians 1:6)

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