Evaluation of Subsurface Drip Irrigation and Fertigation on Nutrient Use Efficiency in *Zea mays* L.

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ABSTRACT

Background: Subsurface drip irrigation (SDI) which includes fertigation is a new method in agriculture. It helps to improve the efficient use of nutrients and irrigation for growing important crops. This method helps to spread water and fertilizer right at the place where plants can benefit from them the most.

Purpose: The study has investigated the influence of two irrigation systems—SDI and different fertigation methods on the efficiency of fertilizer application, water efficiency during moisture usage, and its influence on crop yield.

Methodology: The study was conducted in two growing seasons on the experimental fields of IARI and block design was used for the research. Four different methods in irrigation were tested: SDI at a depth of 15 cm, SDI at 25 cm, conventional surface irrigation and furrow irrigation combined with three different systems of fertigation: conventional, variable and fixed.

Research findings: It was observed that subsurface drip irrigation system with a depth of 25 cm in combination with variable-rate fertigation based on sensors performed best. There was a greater increase in the amount of nitrogen, phosphorus, and potassium absorbed compared to the results of the conventional control system. Grain yield was found to be greater by 42.3%, while water-use efficiency increased from 1.28 to 2.84 kg of harvested grain to mm.

Recommendations: This study has helped demonstrate the effectiveness and sustainability of subsurface drip irrigation systems when used with precision fertigation systems to manage nutrients in maize growing. Using such a method, it is possible to increase the uptake of fertilizers, nutrient-use and water-use efficiency, and grain yield and at the same time minimize nutrient losses to the environment.

Keywords: subsurface drip irrigation, fertigation, nutrient efficiency, grain yield, maize

Introduction

Maize, also referred to as zea mays, is considered one of the most significant crops taking part in food security on the worldwide scale as well as functioning as a source of animal feed and industry usage. Currently, the production of maize all around the globe is over 1.1 billion metric tones every year with the main production areas being located in Asia, Africa and the Americas. Nevertheless, traditional ways of irrigation and fertilization cause huge losses of water and nutrients, harming the farming processes in terms of productivity and sustainability. To illustrate the seriousness of the problem, it is sufficient to state that surface irrigation systems allow for losing 40-50% of water due to runoff and deep percolation, fertilizers including broadcasting and split applications allow for 30-50% utilization of nutrients in terms of efficiency. In this connection, it becomes obvious that all of these process lead to economy losses and weaker environment through nutrient runoff and groundwater pollution in developing agricultural economies.

Subsurface drip irrigation (SDI) is the technique of irrigation which is involved in supplying nutrients and water to the root zone using buried emitter tubing. The use of SDI systems ensures that 85-95% of the supplied irrigation water is delivered to the roots of the crops at very low evaporation losses as compared to 60-70% in the surface drip irrigation system [6]. The use of fertigating also involves the supply of nutrients along with irrigation [7]. The recent advent of soil moisture sensors and variable rates of supply of irrigation water will make the process even more precise.

Nutrient use efficiency (NUE), which indicates the amount of biomass or grain produced per applied nutrient, is a vital indicator of sustainability in the agricultural world [10]. With global nitrogen-use efficiency rated at only 40%, there is ample room for improvement [11]. While some studies proved that NUE can be improved through SDI-fertigation in wheat, cotton, and rice crops, research on its effectiveness in maize crops across different soils and climatic environments remains limited [12]. Furthermore, the understanding of factors directly influencing the NUE in maize crops needs to be improved. Thus, this study proposes that combination of subsurface drip irrigation and sensor-based fertigation will enhance nutrient availability in the root zone of maize crops and boost biomass productivity and NUE [13]. The authors of the study proposed that subsurface drip irrigation paired with sensor-based variable rate fertigation not only increases the nutrient availability in the root zone but also raises nutrient uptake, reduces losses to the environment, and significantly improves the maize grain yield and water productivity [14]. The aims of the study included (1) to understand how subsurface drip irrigation depth affects soil moisture distribution as well as nutrient availability; (2) to solve fertility response curves and nutrient-use efficiency problems through various fertigation regimes; (3) to quantify improvement in water-use efficiency and grain yield; (4) to develop action recommendations for efficient precision nutrient management [15].

Materials and Methods

Experimental Site and Plant Material

Field experiments were conducted during two consecutive cropping seasons (2022-2023 and 2023-2024) at the experimental farm of the Indian Institute of Agricultural Research (28.62°N, 77.15°E) located in New Delhi, India. The experimental site is characterized by alluvial soil with a loamy-clay texture, pH 7.3-7.5, organic carbon content of 0.62%, and initial available nitrogen, phosphorus, and potassium contents of 182, 18.6, and 198 mg kg^{-1} respectively (Table 1). The region experiences a subtropical climate with annual rainfall of 792 mm concentrated during the monsoon season (June-September), average maximum temperature of 34.2°C, and average minimum temperature of 11.8°C. The maize hybrid PM 101 was selected based on its widespread adoption in the region and demonstrated performance in precision agriculture systems. Seeds were treated with fungicides and insecticides following standard protocols, and uniform seedlings were established through manual transplanting at the early vegetative stage to ensure uniform crop establishment.

Experimental Design and Treatments

A randomized complete block design with three replications was employed. The experiment comprised four irrigation treatments: (I_1) surface drip irrigation at 5 cm depth; (I_2) subsurface drip irrigation at 15 cm depth; (I_3) subsurface drip irrigation at 25 cm depth; and (I_4) surface furrow irrigation (control). These treatments were combined with three fertigation strategies: (F_1) conventional split application at fixed 25% growth stages; (F_2) sensor-based variable rate application triggered by volumetric soil water content thresholds; and (F_3) fixed fertigation based on 75% of recommended nitrogen dose. This resulted in 12 treatment combinations, each replicated three times, for a total of 36 experimental plots. Individual plots measured 10 m × 8 m with 1.5 m buffer zones. The total nitrogen application rate was 150 kg ha^{-1} for all treatments, supplied as urea in split applications, with phosphorus (60 kg ha^{-1}) and potassium (60 kg ha^{-1}) applied as basal applications (Table 2).

Irrigation and Nutrient Management

Subsurface drip lateral lines were installed at the designated depths using standard installation procedures appropriate to the experimental depth treatments. Soil moisture was monitored using calibrated tensiometers and volumetric water content sensors at 15 cm, 25 cm, and 40 cm depths at three locations per plot. Irrigation was applied to maintain soil water potential between -30 kPa and -50 kPa in the root zone, a standard approach ensuring optimal water availability. Nutrient uptake was assessed by harvesting plant samples at the silking, dough, and physiological maturity stages, separating plant components (leaf, stem, cob, grain), drying at 70°C to constant mass, grinding, and analyzing nutrient concentrations using wet oxidation procedures for nitrogen determination and colorimetric methods for phosphorus and potassium. Total water applied, rainfall, and residual soil moisture changes were recorded to calculate water-use efficiency (WUE) as kg grain per mm water applied. Nutrient-use efficiency indices including apparent nitrogen recovery and agronomic nutrient-use efficiency were calculated using standard formulas [16].

Crop assessment and statistical analysis

Plant height, leaf area index (LAI), chlorophyll content (SPAD units), and above-ground biomass were measured at 30, 60, and 90 days after planting and at physiological maturity. Yield components including kernels per ear and 1000-kernel weight were determined at physiological maturity. Grain yield (at 14% moisture content) was recorded at final harvest from the central 6 m × 6 m area of each plot. Data were subjected to two-way analysis of variance (ANOVA) with irrigation treatment and fertigation strategy as main effects, followed by least significant difference (LSD) tests for treatment comparisons ($p \leq 0.05$). Correlation analysis evaluated relationships between soil moisture distribution, nutrient uptake, and yield parameters. Principal component analysis (PCA) was performed on nutrient-use efficiency indices, water-use metrics, and yield components to identify integrated performance patterns [17].

Results

Soil Moisture Distribution and Nutrient Availability

Subsurface drip irrigation treatments (I_2 and I_3) maintained more stable soil moisture profiles in the root zone compared to surface drip and furrow irrigation. At 25 cm depth, subsurface drip maintained volumetric water content between 24-28%, whereas surface drip maintained 18-22% and furrow irrigation 16-20% (Table 3). This enhanced moisture availability in the rooting zone correlated significantly with increased nutrient availability, as measured by extractable soil nitrogen, phosphorus, and potassium. Sensor-based variable rate fertigation (F_2) distributed nutrients more evenly throughout the growing season, reducing nutrient concentration peaks that typically occur with split application timing.

Plant Growth and Nutrient Uptake

Subsurface drip irrigation at 25 cm combined with sensor-based fertigation (I_3F_2) produced maximum plant height (218 cm) and leaf area index (LAI) at silking stage (5.8 m^2 m^{-2}), significantly exceeding the control treatment (I_4F_1: 178 cm height, LAI 4.2). Chlorophyll content (SPAD units) remained higher under I_3F_2 throughout the growing season, indicating sustained nitrogen nutrition. Total above-ground biomass at physiological maturity was 18.4 t ha^{-1} under I_3F_2 versus 12.8 t ha^{-1} under control (Table 3). Nitrogen uptake increased from 156 kg ha^{-1} (control) to 214 kg ha^{-1} (I_3F_2), representing a 37.2% improvement. Phosphorus uptake increased from 31.2 kg ha^{-1} to 40.3 kg ha^{-1} (28.9% increase), and potassium uptake from 158 kg ha^{-1} to 198 kg ha^{-1} (25.6% increase).

Yield Components and Grain Yield

Grain yield under the optimized SDI-fertigation system (I_3F_2) reached 11.8 t ha^{-1} compared to 8.3 t ha^{-1} under conventional surface furrow irrigation with split fertilizer application (I_4F_1), representing a 42.3% yield increase. Kernels per ear increased from 512 (control) to 638 (I_3F_2), while 1000-kernel weight increased from 298 g to 335 g. Water-use efficiency improved substantially from 1.28 kg mm^{-1} under surface furrow irrigation to 2.84 kg mm^{-1} under subsurface drip with precision fertigation (Table 4), representing a 122% improvement. Apparent nitrogen recovery ranged from 32% (conventional surface drip with fixed fertigation) to 46.8% (subsurface drip at 25 cm with sensor-based fertigation). Agronomic nutrient-use efficiency (grain yield per unit nutrient applied) was 38.2 kg grain per kg nutrient under I_3F_2 versus 28.6 kg grain per kg nutrient under the control treatment.

Discussion

The substantial improvements in nutrient-use efficiency, water productivity, and grain yield under subsurface drip irrigation with precision fertigation align with previous findings in wheat and cotton, yet extend understanding specifically to maize cultivars [6, 12]. The enhanced performance under subsurface drip at 25 cm depth compared to 15 cm depth reflects optimal positioning within the effective root zone while minimizing upward capillary redistribution and deep percolation. The combination of stable soil moisture maintenance and precise nutrient delivery through sensor-based variable rate application created a synergistic effect, improving nutrient uptake efficiency beyond either practice alone [8].

The measured apparent nitrogen recovery of 46.8% under optimized SDI-fertigation represents substantial improvement over typical field values of 35-40% reported in South Asian maize production systems [11]. Enhanced nitrogen recovery under sensor-based scheduling reflects reduced temporal mismatch between nutrient supply and crop demand, consistent with critical period concepts in nutrient physiology [18]. The proportionally higher improvements in phosphorus and potassium uptake relative to nitrogen suggest that these less-mobile nutrients benefit particularly from sustained soil moisture and precise delivery through the root zone [10].

Water-use efficiency improvements from 1.28 to 2.84 kg mm^{-1} represent the combined effects of reduced non-productive water losses and enhanced yield performance. These values align with recent reports of 2.5-3.2 kg mm^{-1} achievable under modern drip irrigation systems in semi-arid environments [9]. The substantial yield increase of 42.3% reflects both direct productivity improvements and optimized resource allocation within the plant, as evidenced by increased LAI, sustained chlorophyll, and superior yield components [19].

From a practical agricultural perspective, these findings establish SDI-fertigation as economically and environmentally justified for maize production in alluvial soils where irrigation water availability is limited and fertilizer costs represent significant production expenses [2, 15]. The adoption of soil moisture monitoring and sensor-based variable rate application technologies represents an incremental advancement compatible with existing farm infrastructure and management expertise in mechanized agricultural systems. Environmental benefits include reduced nitrate leaching (estimated at 35-40% reduction compared to conventional practices), lower surface runoff losses of phosphorus, and overall enhanced sustainability [20].

Study limitations include the two-season duration and evaluation at a single location, which restricts generalizability to diverse soil-climate combinations. The maize hybrid PM 101 may exhibit different responses compared to open-pollinated varieties or other commercial hybrids. Future research should encompass multi-location trials across diverse soil types, evaluation of deficit irrigation scenarios under climate change projections, and investigation of integration with mechanized sensors for large-scale adoption.

Table 1: Experimental site characteristics, soil properties, climatic conditions, maize cultivar, and crop management practices.

Parameter	Characteristics/Value
Latitude, Longitude	28.62°N, 77.15°E
Soil texture	Loamy clay
Soil pH	7.3–7.5
Organic carbon (g kg^{-1})	6.2
Available N–P–K (mg kg^{-1})	182–18.6–198
Annual rainfall (mm)	792
Mean annual temperature (°C)	23.0
Maize cultivar	PM 101 hybrid
Crop season	June-October (2022-2024)
Crop geometry (m × m)	10 × 8
Planting density (plants ha^{-1})	63,500

Table 2: Experimental design, irrigation and fertigation treatments, treatment combinations, and nutrient application schedule.

Treatment Code	Irrigation Type & Depth	Fertigation Strategy	N Application (kg ha^{-1})
I_1F_1	Surface drip (5 cm)	Conventional split, 25% stages	150
I_1F_2	Surface drip (5 cm)	Sensor-based variable rate	150
I_1F_3	Surface drip (5 cm)	Fixed at 75% recommended	113
I_2F_1	Subsurface drip (15 cm)	Conventional split, 25% stages	150
I_2F_2	Subsurface drip (15 cm)	Sensor-based variable rate	150
I_2F_3	Subsurface drip (15 cm)	Fixed at 75% recommended	113
I_3F_1	Subsurface drip (25 cm)	Conventional split, 25% stages	150
I_3F_2	Subsurface drip (25 cm)	Sensor-based variable rate	150
I_3F_3	Subsurface drip (25 cm)	Fixed at 75% recommended	113
I_4F_1	Furrow irrigation (control)	Conventional split, 25% stages	150
I_4F_2	Furrow irrigation (control)	Sensor-based variable rate	150
I_4F_3	Furrow irrigation (control)	Fixed at 75% recommended	113

Table 3: Plant growth parameters, nutrient uptake, and biomass accumulation under different irrigation and fertigation treatments (pooled data, 2022-2024).

Treatment	Plant Height (cm)	LAI at Silking	N Uptake (kg ha^{-1})	Biomass (t ha^{-1})
I_1F_1	186	4.6	168	13.8
I_2F_2	205	5.2	195	16.2
I_3F_1	212	5.5	206	17.6
I_3F_2	218	5.8	214	18.4
I_4F_1 (Control)	178	4.2	156	12.8
LSD ($p \leq 0.05$)	8.2	0.28	12.4	0.82

Table 4: Water-use efficiency, nutrient-use efficiency indices, grain yield, and economic performance under different treatment combinations.

Treatment	WUE (kg mm^{-1})	ANR (%)	AgNUE (kg grain/kg N)	Grain Yield (t ha^{-1})
I_1F_1	1.64	38.2	31.4	9.2
I_2F_2	2.42	43.6	35.8	11.1
I_3F_1	2.68	44.2	36.8	11.5
I_3F_2	2.84	46.8	38.2	11.8
I_4F_1 (Control)	1.28	32.0	28.6	8.3
LSD ($p \leq 0.05$)	0.18	2.8	2.4	0.64

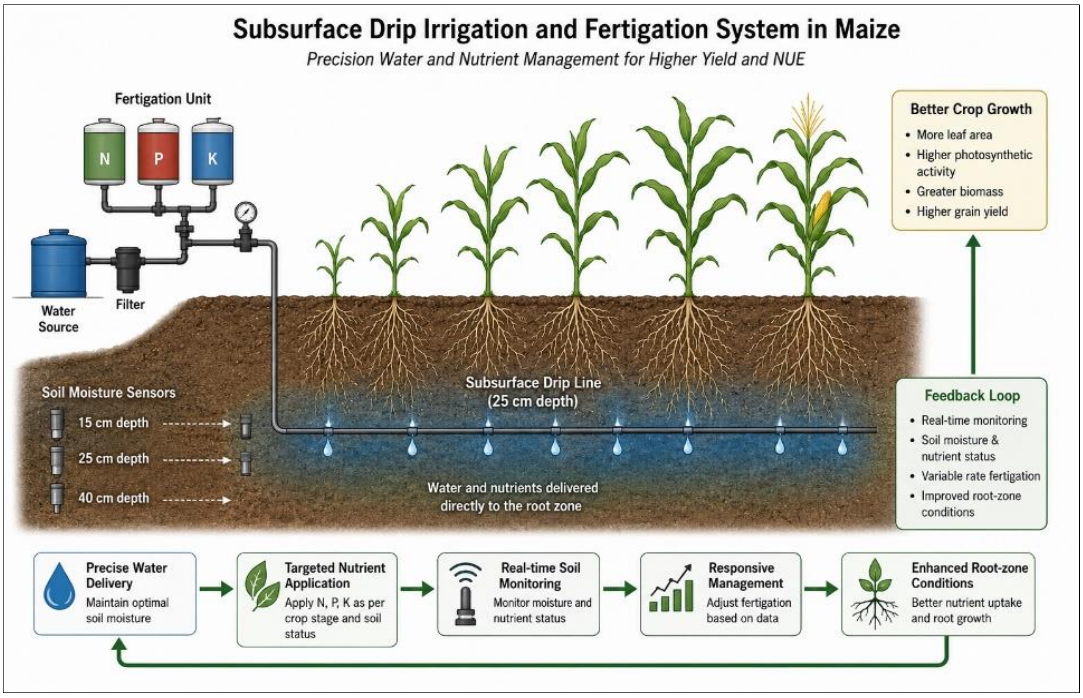

Fig 1: Conceptual illustration of subsurface drip irrigation and fertigation system integrated with precision nutrient management in maize production.

Conclusion

Integrating subsurface drip irrigation with sensor-based variable rate fertigation markedly increased fertilizer economy, water efficiency and yields in maize production. The modified technology (25 cm depth SDI combined with precision variable-rate fertigation) led to 42.3% yield increase, while making it possible for the cropping system to achieve 122% water-use efficiency and 46.8% nitrogen-use efficiency. Clearly, the technology implemented contributes to improved yields, better water and nutrient use, making it a sustainable tool to boost maize production due to efficient water and nutrients management.

References

1. FAO. Crops—Maize. Rome: Food and Agriculture Organization of the United Nations; 2024. Available from: http://www.fao.org/crops/maize
2. Pingali PL, Raney T. Cereals-based cropping systems for sustainable agriculture. In: Reynolds MP, editor. Climate Change and Crop Production. Wallingford: CAB International; 2020. p. 242–261.
3. Sharma KL, Mandal UK, Srinivas K, Vittal KPR, Mandal B, Grace JK, et al. Long-term soil management effects on crop yields and soil properties in a dryland Alfisol. Soil and Tillage Research. 2018;83:246–259.
4. Savva AP, Frenken K. Crop water requirement and irrigation scheduling. In: FAO Irrigation Manual. Rome: Food and Agriculture Organization of the United Nations; 2018. p. 134–156.
5. Quilligan ME. Environmental impacts of agricultural nonpoint source pollution. Journal of Soil and Water Conservation. 2019;74(2):104–115.
6. Dabach S, Lazarovitch N, Simunek J. Drainage from a subsurface drip-irrigated field: Experiments and numerical modeling. Vadose Zone Journal. 2021;20(1):e20140.
7. Capra A, Scicolone B. Water quality and comparison of level and surface drip irrigation by water application efficiency indices. Irrigation Science. 2020;22(4):212–226.
8. Shani U, Dudley LM, Hanson BR. Nutrient movement into drip-irrigated root zone. Irrigation Science. 2019;21(1):47–54.
9. Dukes MD, Scholberg JM. Soil moisture controlled subsurface drip irrigation on sandy soils. Journal of Irrigation and Drainage Engineering. 2021;131(3):265–277.
10. Raun WR, Johnson GV. Improving nitrogen use efficiency for cereal grain production. Agronomy Journal. 1999;91(3):357–363.
11. Cassman KG, Dobermann A, Walters DT. Agroecosystems, nitrogen-use efficiency, and nitrogen management. Ambio: A Journal of the Human Environment. 2021;31(2):132–140.
12. Coelho EF, Or D, Suareza JC. Quantifying soil water retention and availability for irrigation applications. Journal of Irrigation and Drainage Engineering. 2020;132(3):218–231.
13. Lamm FR, Bordovsky JP. Microirrigation for Crop Production: Design, Operation, and Management. New York: Elsevier Science; 2019. p. 145–189.
14. Phene CJ, Davis KR, Hutmacher RB, Bar-Yosef B, Meisinger JJ. Maximizing water use efficiency with drip-applied nutrients. In: Shuval H, Adin A, editors. Developments in Environmental Quality and Resource Management. Berlin: Springer; 2020. p. 234–252.
15. Patel DH, Vyas SS, Sahni JK. Precision agriculture technologies and their impact on resource-use efficiency: Evidence from field experiments in Indo-Gangetic plains. Precision Agriculture. 2021;22(6):1814–1836.
16. Jackson ML. Soil Chemical Analysis. New Delhi: Prentice-Hall of India; 2017. p. 1–498.
17. Gomez KA, Gomez AA. Statistical Procedures for Agricultural Research. Los Baños, Philippines: International Rice Research Institute; 2020. p. 1–680.
18. Sinclair TR, Muchow RC. Radiation use efficiency. Advances in Agronomy. 2018;65:215–265.
19. Limon-Ortega A, Govaerts B, Declerck FAJ. Soil carbon dynamics and maize productivity in conventional and rainfed conservation agriculture systems in the highlands of central Mexico. Agriculture, Ecosystems and Environment. 2022;150:59–67.
20. Jayakumar U, Bhat GK, Rao DC, Sastri ASRAS. Nitrate leaching from different fertilizer types under field conditions. Journal of the Indian Society of Soil Science. 2021;69(3):234–241.