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RESEARCH ARTICLE

A linear programming-based approach for optimizing drip irrigation systems and crop productivity

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Abstract

Sustainable agriculture requires the integration of advanced technologies to enhance productivity and resource efficiency. This study aimed to optimize an automated drip irrigation system. Using linear programming, optimal values for key crop attributes were determined based on different irrigation systems and water quality treatments. Attributes such as plant height, number of leaves, number of branches, number of fruits and yield in respective of irrigation system, water quality and days after transplanting. The results revealed that all the independent attributes affected the plant height, number of leaves, number of fruits, number of branches and yield. The optimum values of plant height, number of leaves, number of branches, number of fruits and optimum yield were higher for the wireless-based drip irrigation system (IS2) with treated fruit processing wastewater (WQ2) than for the wire-based irrigation system. Based on the substantially increased net return in the wireless irrigation system model, it is the better-suited model under the given conditions. Hence, the combination of treated fruit processing wastewater with a wireless-based system is recommended.

Keywords: attributes; drip irrigation; linear programming; optimization; water quality

Introduction

Water availability for irrigated agriculture has become a primary global concern. According to the United Nations, nearly 3.4 billion people are projected to live in water-scarce regions by 2025, with India among the most affected (1). In India, 80 % of the total water use is in the agricultural sector (2, 3). It accounts for approximately 90 % of the 761 billion kiloliters of annual freshwater withdrawals in the country (4, 5). The sustainability of agricultural production depends on the conservation, appropriate use and management of scarce water resources, especially in arid and semiarid areas where users compete over limited water resources (6). Irrigation is required for the production of food and cash crops (7, 8).

Since the balance between water demand and water availability has reached critical levels in many regions of the world and increased demand for water and food production is likely in the future, a sustainable approach to water resource management in agriculture is essential (9-11). Sustainable water management refers to practices that improve crop yield and minimize non-beneficial water losses (12). Due to insufficient surface water sources, 39 m ha of total cultivated land is irrigated by per cent of the total irrigated area, which usually depends on groundwater utilization. India has the most extensive groundwater-based irrigation system in the world, followed by China and the USA, which cover 19 million ha and 17 million ha, respectively (13). Over the next 20 years, 60 % of groundwater sources may be in a severe state of deterioration (14). The excessive demand for groundwater leads to abnormally rapid resource depletion, which has a detrimental effect on water availability (15, 16).

To address these challenges, micro-irrigation technology is rapidly expanding globally for precise water utilization in irrigation, particularly in areas with limited water availability in developed countries. Countries such as the USA, Israel and parts of Europe have successfully adopted these systems to improve crop productivity while reducing input usage (17-19). Micro-irrigation can enhance crop productivity and reduce input consumption, among other benefits to the production process. Drip irrigation can achieve water use efficiency as high as 90 % compared to conventional methods, with the added benefits of improved yield and reduced nutrient loss (20-22). By 2025, global water scarcity is estimated to affect nearly 3.4 billion people and agriculture uses about 70 % of the world's freshwater (23, 24).

In India, despite its potential, the adoption of automated drip irrigation remains limited due to small and fragmented landholdings, as well as high initial investment costs. Furthermore, traditional wired systems face challenges such as maintenance issues, vulnerability to environmental degradation and high installation complexity-especially across large or uneven terrains. In contrast, wireless systems offer greater flexibility and scalability, but their economic and agronomic performance under varying water quality conditions remains underexplored (25-29).

Automated drip irrigation is of 2 types: wired-based and wireless systems. The wired-based system requires regular maintenance for adequate operation. There are interim installations that must be expanded or adjusted to the drip line as plants evolve. This system has a limited lifespan after installation due to the degradation of plastic components in a hot, dry climate, particularly when exposed to ultraviolet light (30, 31). Conventional composition based on isolated wired resolutions presents many complications in measuring and control systems, especially over large geographical areas (32). Currently, numerous drip irrigation systems utilize a successive field automation mechanism, which is hindered by wiring complications, high costs and time-consuming processes, making it challenging to implement in a repetitive manner (33, 34).

In a well-designed automated drip irrigation system, there is no water loss by evaporation, deep percolation or runoff (35, 36). Irrigation scheduling can also be managed preciously to fit crop demands, holding the commitment of boosted yield as well as quality. In India, small and fragmented land holdings, along with the high initial cost of automated drip irrigation systems, made such systems uneconomical for small or medium-sized farms. By considering multiple agronomic attributes-such as plant height, leaf number, branching, fruit count and yield-under varying system configurations and water qualities, the research aims to identify the most effective irrigation strategy for maximizing crop performance and resource use efficiency.

Materials and Methods

Experimental site

A field experiment was conducted to optimize the Automated Drip Irrigation System (ADIS). To achieve this objective, a tomato crop was transplanted during the Zaid season, between the Kharif and Rabi seasons of 2015-2016, at the research farm of JISL Jalgaon and irrigated using both wired and wireless drip irrigation systems. The optimization process involved evaluating the system based on weather and biometric attributes, including plant height, the number of leaves and the number of fruits per plant. Using these parameters, the optimum attribute values were determined through regression analysis.

The best system was identified based on environmental attributes. To enhance cost efficiency in overall system design, an indigenous control circuitry was implemented, incorporating various pressure levels and emitter discharges. Additionally, the optimization of both systems was further verified by considering biometric attributes. For optimizing ADIS (both wired and wireless), both dependent and independent parameters were analyzed. The details of the experiment are provided below.

Experimental layout of automated drip irrigation system

Two different irrigation sources were applied, including fresh water and treated fruit waste water, for growing a tomato crop through wired and wireless ADIS, respectively, with 5 replications each (Fig. 1). Dependent and independent parameters are listed in Table 1 and the detailed specification of layout of experiment is shown in Fig.1 and Table 2. The experimental field size of 1000 m^2 was selected. Field was divided into 20 plots, having 9 × 4 m size of each plot. The factorial randomized block design was selected for the study.

Table 1. Dependent and independent parameters

Treatments	Levels detail	Observed parameters
Irrigation system	IS$_1$-Wired irrigation system and IS$_2$-Wireless irrigation system	Crop characteristics Temperature Soil moisture
Water quality	WQ$_1$-Ground water (GW) and WQ$_2$-Treated fruit processing waste water (TFPWW)	Humidity Soil temperature Evaporation

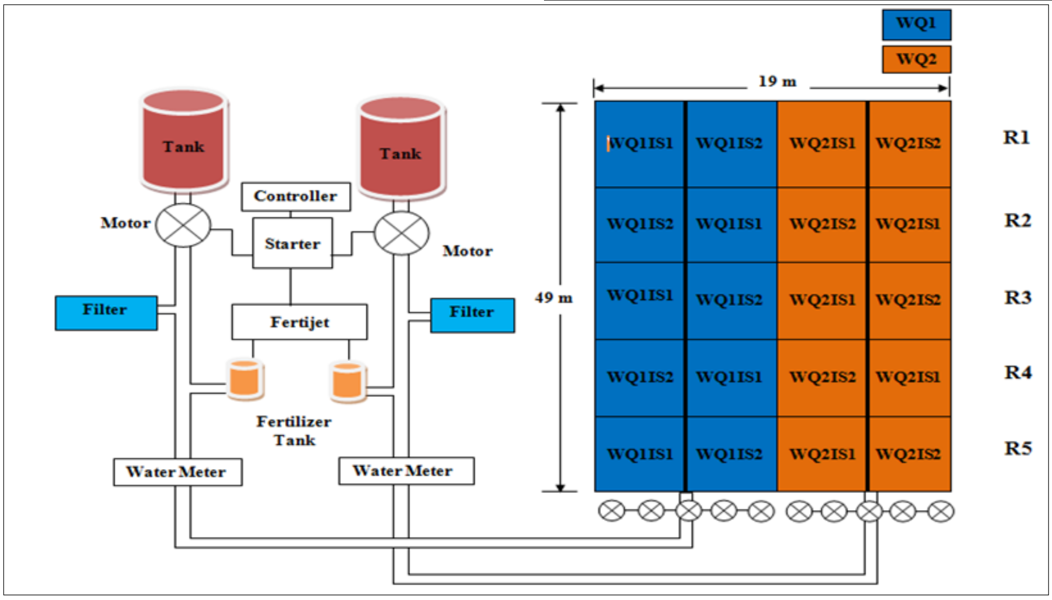

Fig. 1. Schematic layout of automated drip irrigation system.

Table 2. Specifications of experimental layout

Particular	Details
Design of layout	Factorial randomized block design
Number of experimental plots	20
Plot dimensions	9m x 4m
Experimental plot area	1000 m^2
Tank capacity	5000 L
Filter type	Sand and disc filter
Pump	2.5 HP
Number of replications	5

Optimization

Linear programming was performed in this study to optimize the dependent and independent parameters for both irrigation systems. This method is based on the principle that the selected parameters must be given equal weight, ensuring that the optimized combination is as close as possible to the ideal irrigation system (Table 3).

For optimization, various parameters under both wired and wireless irrigation systems were identified. The optimum values of various independent attributes were derived from the evaluation results of the irrigation system and linear programming. Following this, a linear programming equation was developed. After performing linear programming, the optimum combination of independent parameters was selected based on their significance and the maximum observed value of the dependent parameter (Equation i).

Table 3. Developed linear programming model for irrigation systems

Irrigation system	IS_1	IS_2	Total	Max.
Net profit	1.04	1.21	2.23	2.25
WQ_1	68717	70926	138309	141206
WQ_2	72490	74657	145583	145583

IS_1=Wired irrigation system; IS_2-Wireless irrigation system; WQ_1=Ground water (GW); WQ_2=Treated fruit processing waste water (TFPWW)

Results and Discussion

A programme was written on spread sheet to optimize the linear programming formulation. For both seasons, the total crop (tomato) water input was predicted to be 286.79 ton/ha over the cropping period. A linear programming model consisting of 3 major components namely, an objective function for maximizing net returns, a set of linear constraints and a set of non-negativity constraints - was developed (i). The model was formulated to allocate water supplies among the different water treatment, in order to maximizing the net profit. The following equation was used as objective function.

$$P= 1.04x+1.21y \qquad \text{(Eqn. 1)}$$

Where,

Pis the profit

x is yield from IS_1 (Wired based irrigation system),

y is yield from IS_2 (Wireless based irrigation system)

The above objective function is formed by knowing the contribution of both irrigation systems towards the net profit. It is the ratio of total income generated from yield of different irrigation system (Equation 2).

Contribution of irrigation system =

Profit generated by irrigation system (Rs) / yield obtained from irrigation system (kg) (Eqn. 2.)

For IS_1 (Wired based irrigation system) = 144995/139643=1.04 Rs kg^{-1}

For IS_2 (Wireless based irrigation system) = 178138/147147 = 1.21 Rs kg^{-1}

Based on the substantially increased net return in the wireless irrigation system model, it is clearly the better-suited model under the given conditions.

Yield constraint

The constraints state that the maximum yield generated from both irrigation systems should not exceeds 286790 as it is shown by the equation given below

$$x+y<= 286790 \qquad \text{(Eqn. 3.)}$$

The objective function is subjected to constraints x+y<= 286790

Water quality constraint

The constraints state that the maximum yield depended upon water quality should be as stated in equations for WQ_1 and WQ_2

For WQ_1

$$68717x+70926y<=141206 \qquad \text{(Eqn 4.)}$$

For WQ_2

$$72490x+74657y<=145583 \qquad \text{(Eqn 5.)}$$

The above objective function is solved in the Excel spreadsheet using Excel Solver and the decision variables obtained for maximizing the net profit (i.e., the objective function) are shown in Table 3.

The LP formulation considered the yield obtained from different water quality and irrigation system as decision variables. Thus, the maximum value of net profit (P) Rs 343509.00 and this occurs when x=0 and y=283892.The maximum profit, as per the model, is obtained when only IS2 is employed. For maximum yield, WQ_2 was selected as the model, using its full capacity, which is not the case for WQ_1. It demonstrates better performance in terms of higher efficiency and lower cost benefits in IS_2 and WQ_2 (wireless system model) compared to IS_1 and WQ_1 (wired system model).

Conclusion

The ADIS system was optimized for both wired and wireless irrigation to enhance cost efficiency and performance. Weather and biometric parameters were analyzed for each system, considering crop production over a one-hectare area. The study's findings demonstrated that the wireless irrigation system outperforms the wired system in ensuring precise and efficient irrigation management. The programming optimisation was based on the objective function for maximising net returns with minimal use of water resources, facilitated by real-time wireless analysis. Additionally, the precise monitoring and judicious use of water resources would ensure substantial cost benefits on an industrial scale compared to sustainable, eco-friendly technology options.

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Authors' contributions

SKP designed the overall structure of the study and provided conceptual input. PKM co-developed the study design and guided its methodological framework. MK contributed to drafting key sections of the manuscript. PY wrote parts of the manuscript and organized the initial content layout. SY arranged the collected data and organized it for analysis. VY participated in manuscript preparation and ensured consistency in formatting. DM edited the manuscript for language, coherence and clarity. AY assisted in data arrangement and contributed to data validation. PR helped refine the manuscript and contributed to technical content development. All authors reviewed and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: The authors have no conflicts of interest to declare.

Ethical issues: None

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