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An IoT-Enabled Decision Support System for Improving Water Use Efficiency and Crop Yield in Citrus Groves

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Abstract – Water management is essential in semi-arid agriculture, where irrigation is a primary use of water. This paper measures an Internet of Things (IoT)-enabled Decision Support System (DSS) in precision irrigation in a citrus grove using a period of nine months. Two similar regions were compared: Field A was traditional farmer estimates, and Field B was the DSS algorithm of real-time soil moisture, temperature, and rain. DSS irrigation used 44,290 L of water (up by 46 percent over 96,569 L in traditional irrigation), yielding 91 kg/tree versus 67 kg/tree, which improved by 35 percent. The result was that Field B experienced 35% more revenue and saved 22.8 million cubic feet of water. Proceeding with DSS into national lemon production estimated the possible savings as more than 645 million liters and annual improvements of over 20,700 tons. The indicative outcome suggests that DSS-based irrigation is efficient regarding sustainable precision agriculture.

Keywords – Decision Support System (DSS), Precision Irrigation, Water Use Efficiency (WUE), IoT Agriculture, Citrus grove Yield, Smart Farming, Resource Optimization.

I. INTRODUCTION

Given the contexts of the dry and semi-arid areas of the world, the regulation of water resources, and consequently the regulation of irrigation, becomes ever more relevant with respect to the growing of fruit crops. Many scholars specifically seek to address the nuances of the growing of fruit crops and the irrigation of such crops, as well as the criteria to be utilized in the determination and regulation of such crops in ways that seek to improve the yield and to reduce any losses. Irrigation is the foremost and should be the primary concern for the fruit growers. Not only is this the foremost and primary concern, but this should also be the fundamental concern to any fruit growers in any water-scarce areas of the world. South Asia, sadly, is also water-scarce [1].

When water is applied more frequently than is needed, it can cause the removal of more nutrients from the soil, cause waterlogging of the soil, increase the incidence of pests and diseases, and can cause an increase in the operational and maintenance costs of the irrigation equipment. Proper timing of irrigation in fruit tree plantations can enhance the efficacy of water usage, reduce the cost of irrigation, and improve tree and fruit productivity. For fruit crops, irrigation is important in increasing and sustaining yield levels and quality of the fruits.

During the transition from hunting and gathering to farming civilizations, the need to improve methods of farming and manage available water resources became a priority. In the past few decades, the use of innovative, integrated, and high-precision technologies in the conventional agricultural system to manage water resources has gained the interest of researchers. Xing and Wang [2] state that the combination of water management and precision farming technologies can improve the productivity of conventional agricultural systems. In addition, it can ensure its productivity and sustainability and address the concerns of global food and water.

In addition to the above, decision support systems (DSS), integrated remote sensing technology, global positioning systems, and other technologies have shown that precision farming is a modern agricultural management and cultivation system that distributes available resources in a targeted way. Loggings of exact measurements help ensure crops and soils are provided with the correct amounts of nutrients and water, which help with optimal development and yield while also enhancing water use efficiency (WUE). It acts as a center for tackling the main pillars of traditional farming.

More than 70% of the rural households' income and over 25% of the economy of the state are provided by the agriculture sector of the country of Pakistan [3]. We lack an application that integrates IT with agriculture to enable farmers to optimize their income. Information Technology is crucial to enhancing performance across several sectors, including banking, airlines, and everyday interactions. The farmers own land, their only resource, and they want to maximize its use. The substantial decline in the agricultural sector due to insect infestations, adverse weather conditions, and, most critically, inadequate on-farm and off-farm management procedures has made it ineffective and unproductive. Consequently, Pakistan has a poor position on the global average yield map.

The objective of the agricultural DSS project is to address these difficulties by enhancing data management via ongoing study of agricultural dynamics. This data-driven DSS facilitates decision-making at several levels, including agricultural policymakers and, most crucially, farmers. Information Systems will provide them with a guidance. In foreign countries where information technology is integrated into agriculture, productivity has significantly improved. The impetus for this endeavor stems from the continual collapse of Pakistan's economy over the last several decades. Improvement is necessary via the integration of technology and the use of IT into agriculture [4].

We assess the usefulness of an IoT-driven DSS to optimize irrigation timing and enhance crop-growing in citrus groves. In particular, our study focusses on comparing the efficiency of water use and yield performance between conventional, farmer-controlled irrigation and DSS-controlled irrigation, which incorporates real-time environmental and soil data.

The rest of the sections in this paper have been organized as follows: Section II provides an account of the study site, irrigation management algorithm, data collection and statistical analysis of the study. Section III describes previous works on traditional irrigation, traditional irrigation system, and ADSS, among others. In Section IV, a critical discussion of results, which include but not limited to total irrigation usage, water consumption efficiency, and cultivation of lemon crop assessment in Pakistan. Lastly, Section V concludes the study highlighting the evolvement of the citrus production industry and its integration of IoT technology.

II. MATERIALS AND METHODS

Experimental Design and Site

Our study was done in an orchard of lemon used commercially in Pakistan during nine months, the period of the major growing season (January to September). The orchard was separated in two experimental plots (called Field A and B) which were under the control of either a traditional farmer-managed irrigation scheme or a sensor-controlled DSS. The plots had a planting density of 70 mature lemon trees per acre and of about 0.5 hectares each.

Experiment Before the experiment, the soil was characterized in detail to identify θ_v (volumetric water content), θ_{fc} (field capacity), θ_{pwp} (permanent wilting point), ρ_b (bulk density), organic carbon content and nutrients. Regular measurements of the meteorological parameters such as rainfall, air temperature, relative humidity, speed of the wind, and solar radiation were taken at the site through a weather station to give the input variables to the DSS model. The orchard pattern and distribution of roots were plotted to achieve specific positioning of sensor and also to create equal monitoring of the field.

Irrigation Management and DSS Algorithm

In Field A, irrigation events were implemented using the visual evaluation and experience of the grower. At the Field B, the DSS algorithm made use of real-time soil and crop data, which was used to calculate irrigation requirements with improved accuracy. An advanced multi-layer soil water potential and root uptake model was used to derive the volume of irrigation that a tree received per unit time $I_r(t)$ at a given time t as in Eq. (1).

$$I_r(t) = \sum_{i=1}^{n} \left[\frac{\theta_{fc,i} - \theta_{v,i}(t)}{1 + e^{-\alpha_i \left(T_s(t) - T_{opt,i} \right)}} + \frac{\kappa_i ET_{c,i}(t) \left(1 - \frac{\theta_{v,i}(t)}{\theta_{fc,i}} \right)^{\beta_i}}{1 + \gamma_i \Delta\theta_i(t)} \right] \tag{1}$$

In this case, n refers to the layer count of soil in the root zone, $\theta_{fc,i}$ refers to layer's field capacity i, $\theta_{v,i}(t)$ is the measured volumetric contents of water in layer i, $T_s(t)$ is the current edaphic temperature, $T_{opt,i}$ is the optimum edaphic temperature where root water can take uptake in layer i, and $\alpha_i, \kappa_i, \beta_i, \gamma_i$. $\Delta\theta_i(t)$ represents the temporal change in ground water content in each layer and it quantifies the short-term redistribution.

A mechanistic water flux model of nonlinear capillary rise, percolation, and root uptake distribution was also included in the DSS, and computed using Eq. (2).

$$\frac{\partial \mathrm{\theta_i}}{\partial \mathrm{t}} = \frac{\partial}{\partial \mathrm{z}} \left[\mathrm{K}(\mathrm{\theta_i}) \left(\frac{\partial \mathrm{\psi_i}}{\partial \mathrm{z}} + 1 \right) \right] - \mathrm{S_i}(\mathrm{\theta_i}, \mathrm{LAI}) - \mathrm{R_i}(\mathrm{t}) \tag{2}$$

where θ_i denote the volumetric water content of soil in layer i at depth z, $K(\theta_i)$ unsaturated hydraulic conductivity, ψ_i soil matric potential, S_i root extraction rate affected by leaf field index (LAI), and $R_i(t)$-redistribution between layers. A nonlinear logistic function was also used to model the root water uptake term to a greater degree of precision when exposed to water-stress, using Eq. (3).

$$S_i(\theta_i, LAI) = S_{\max,i} \cdot \frac{LAI}{LAI_{\max}} \cdot \frac{1}{1+e^{-\lambda_i\left(\theta_i-\theta_{\mathrm{crit},i}\right)}} \tag{3}$$

where $S_{\max,i}$ is the maximum uptake rate of layer i, and $\theta_{\mathrm{crit},i}$ represents the level of water stress, and λ_i is the steepness parameter of the stress response curve.

The DSS issued irrigation before a certain depletion fraction MAD_i in any soil layer, as in Eq. (4).

$$\theta_{v,i}(t) \leq \theta_{fc,i} - MAD_i \cdot \left(\theta_{fc,i} - \theta_{pwp,i}\right) \tag{4}$$

The total irrigation volume per tree was then distributed among soil layers according to root density weighting w_i in Eq. (5).

$$I_r(t) = \sum_{i=1}^{n} w_i \cdot \Delta\theta_i(t) \cdot D_{rz,i} \tag{5}$$

where $D_{rz,i}$ is the depth of soil layer i.

Data Collection and Yield Assessment

Table 1 presents the parameters considered for root and soil zones. The sensor network was used to record soil moisture, temperature, and volumes of irrigation at 30-minute intervals. Water stress was measured by measuring soil moisture levels at 15 cm, 30 cm and 45 cm depth and recording canopy temperature at a 1-hour interval (see **Table 2**). Image-based analysis was done to estimate the LAI by capturing monthly high-resolution images of the trees. Per-tree lemon yield was measured at harvest and total per-acre yield calculated with regard to planting density. Yield per acre was multiplied with market price to estimate revenue.

Table 1. Parameters of Soil and Root Zone

Parameter	Symbol	Unit	Notes
Field capacity	θ_{fc}	$m^3\ m^{-3}$	Pre-trial lab measurement
Permanent wilting point	θ_{pwp}	$m^3\ m^{-3}$	Measured per soil layer
Available water capacity	AWC	$mm\ m^{-1}$	$= \theta_{fc} - \theta_{pwp}$
Root-zone depth	D_{rz}	m	Based on root profile mapping
Bulk density	ρ_b	$kg\ m^{-3}$	On-site measurement
Max leaf field index	$LAI_{\max}$	$m^2\ m^{-2}$	For canopy water extraction term

Table 2. Sensor Configuration and Data Logging

Sensor Type	Depth / Location	Logging Interval	Units
Soil moisture	15 cm, 30 cm, 45 cm	30 min	$m^3\ m^{-3}$
Soil temperature	Root zone	30 min	°C
Canopy temperature	Canopy top	Hourly	°C
Weather station	Field center	Hourly	mm, °C, %, $m\ s^{-1}$

Statistical Analysis

All the measurements were handled using R (v4.3.0). Mean, coefficient of variation, and standard deviation, as descriptive statistics were computed. Generalized linear models were used to test hypothesis testing as they consider non-linear irrigation-yield associations, computed using in Eq. (6)

$$Y = \beta_0 + \beta_1 I_r + \beta_2 \ln(I_r) + \beta_3 I_r^{0.5} + \beta_4 \frac{1}{I_r} + \varepsilon \tag{6}$$

where Y is per-tree yield, I_r is irrigation volume, β_i are coefficients, and ε the error term. Water-use efficiency was evaluated as in Eq. (7).

$$WUE = \frac{Y}{\sum_t I_r(t)} \text{ kg per m}^3 \text{ applied water} \tag{7}$$

Nonlinear mixed-effects models were applied to assess temporal soil moisture dynamics across layers, as in Eq. (8).

$$\theta_i(t) = \theta_{fc,i} - \left(\theta_{fc,i} - \theta_{pwp,i}\right) \cdot \exp\left[-\phi_i \cdot t^{\psi_i}\right] + \eta_i(t) \tag{8}$$

where ϕ_i and ψ_i are shape parameters, and $\eta_i(t)$ represents stochastic soil moisture fluctuations. Model validation was performed via residual analysis, R², and Akaike Information Criterion (AIC).

III. LITERATURE REVIEW

Sanchis-Ibor, Manzano-Juárez, and García-Mollá [5] defines "Traditional Irrigation" as the organizational and technical control of irrigation activities that existed before the implementation of modern approaches (such as drip irrigation and sprinkling) and the dissolution of traditional organizational frameworks (including associations and typical property managements). The authors retain ancient irrigation model as an important part of the cultural legacy of lost agrarian agro-ecosystems of former agro-ecosystems of Europe, and thus, they are cultural heritage and must be recognized as such and preserved at the international and national levels.

Da-Silva-Branco, De Brito, and Seixas [6] describe the systems as still being the "active living landscapes" of Europe, and as such, they continue to offer economic returns by embodying certain sustainably used land practices that are adaptive to the physical and biotic constraints of the environment.

Fernald et al. [7] describe Traditional Irrigation Systems (TIS) as systems that are not merely historical and cultural relics but as living demonstrations of the principles of sustainability as systems that are multifunctional. The scholars argue that TIS contribute to the stewardship of the environment by providing and preserving landscape diversity and by an efficient utilization of water and energy; they economically sustain rural communities by inexpensive production, resource sharing, and ecosystem services; they foster social inclusion and recognize traditional rights and cultural identity; and they provide social coordination, conflict management and strategic governance.

Fig 1. Rivers and Irrigation Network of Pakistan.

Angelakis et al. [8] have described the Karez irrigation system, which employs a groundwater tunnel system that, upon reaching a defined distance, runs the risk of overflowing, thereby discharging the water at the desired point. Karez irrigation, in the greater Pakistan region, is practiced in Balochistan, a region where karez is the most primitive and successful irrigation technique. Kahn [9] has depicted the irrigation system of karez in Pakistan, as shown in **Fig. 1**. The primary stream of the Indus River, at Tarbela, is supplemented by two major tributaries on the left at the Jhelum, in Mangla, and on the right at the Chenab, in Marala, and in and around the Kabul at Nowshera.

The company operates under customary law, administered socially and managed communally. This paper analyzes the major aspects of karez irrigation, such as interval, types and forms of karez, longevity, periods of flowing, volumetric discharge, improvement and distribution of land, and irrigation management. The differences in karez irrigation systems' preservation and management characteristics stemming from various tribes and their cultures within the region of Balochistan are the focal point of this study.

Brunner-Parra et al. [10] initiated an Agricultural Decision Support System (ADSS) aimed to guide farmers in the proper employment of agricultural tractors in the implementation of mechanized soil erosion sensitive fields. The aim of their research is to improve travel routes to reduce damage to soil-sensitive fields caused by large-scale automobiles. Route modifications may decrease vehicle energy use and enhance operational efficiency. Conversely, it is crucial to evaluate the mechanical effects of vehicles on edaphic structure, particularly the potential for edaphic compaction and stresses.

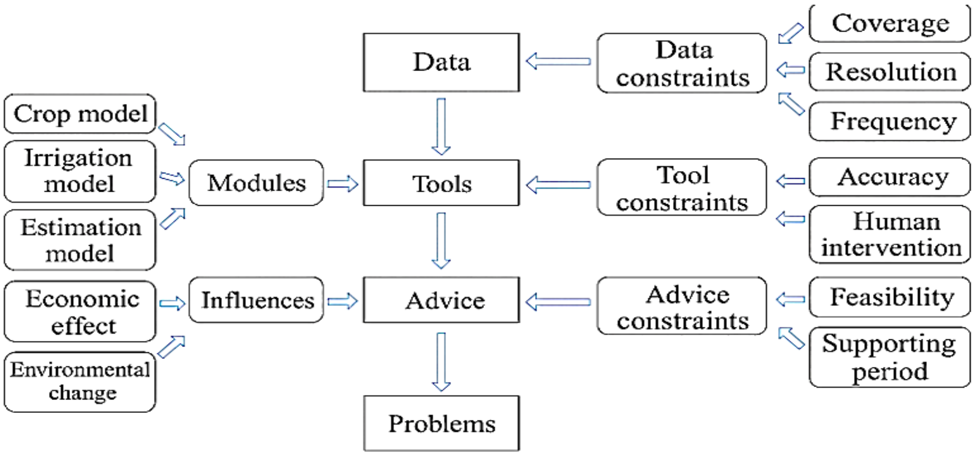

Fig 2. A General Model of ADSSs.

Georgakakos [11] examined their chosen Agricultural Decision Support Systems (ADSSs), which included deployments in: (i) food waste management, (ii) climate change adaptation, (iii) water resource management, and (iv) mission planning. Every ADSS is examined from a methodical perspective by adhering to the basic structure (see **Fig. 2**). In **Fig. 2**, farming data must be gathered first and used as input for the decision-making modules (tools). Guidance on agricultural management is produced based on computer outcomes. Farmers may thereafter choose the best suitable strategy and implement it to address the issues. It is fundamental to consider limits to guarantee the quality of the advice supplied. The decision-making processes of farmers about adoption are affected by several social variables. More creative DSS development techniques use a less technical and analytical orientation, recognizing the significance of social and human perspectives in farmers' decision-making processes. Risquez and Moore [12] emphasized that, in addition to the characteristics of the technology, the congruence between the technology and user ambitions (such as objectives, values, beliefs, personality, culture, and motivation) and capacities (including human, social, natural, physical, and financial) affects the degree of adoption.

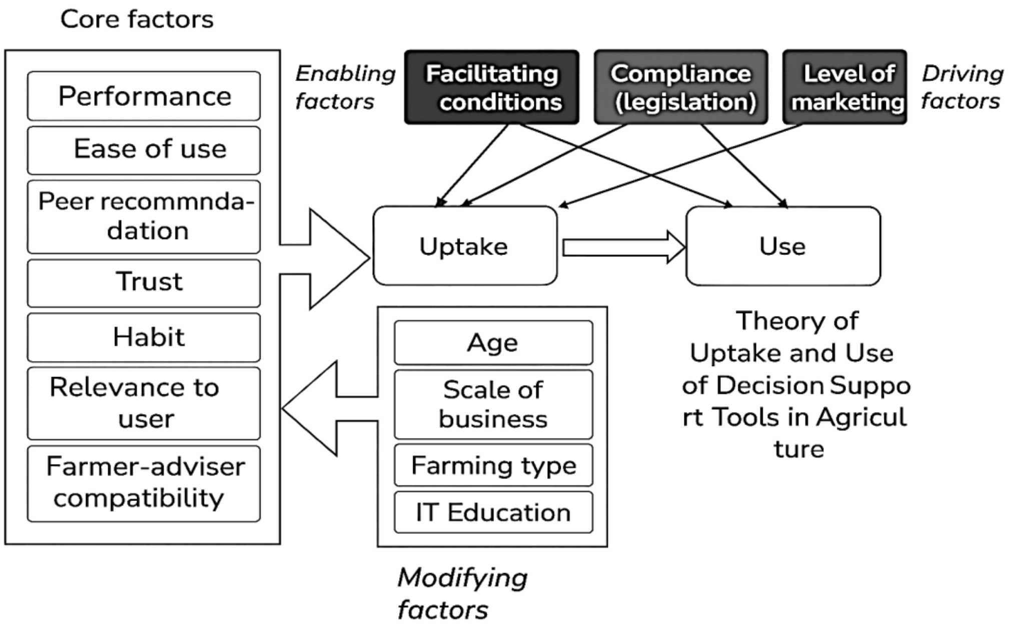

Fig 3. Determinants Affecting the Adoption and Use of ADSS in the UK.

Rose et al. [13] identify 15 determinants affecting the adoption and utilization of various ADSSs in the United Kingdom, based on semi-structured interviews with farmers and advisors. These determinants encompass technology characteristics, end-user attributes, and the compliance environment, including performance, usability, trust, user relevance, marketing intensity, IT literacy, and farmer age (see **Fig. 3**). Comparable variables have been recognized and examined to differing degrees in other publications.

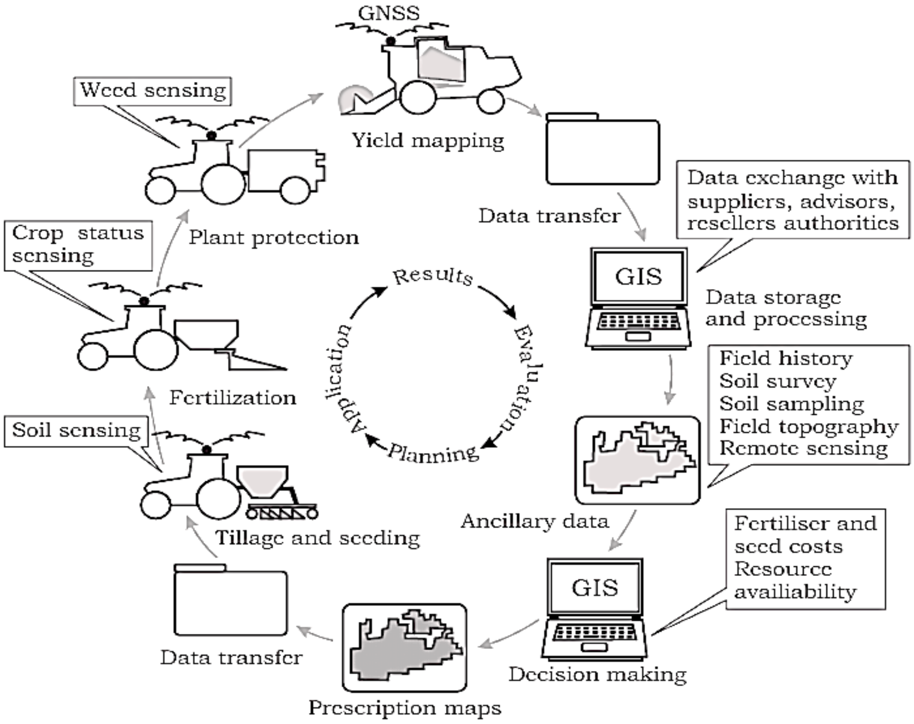

Fig 4. Information Flow in Precision Agriculture for Crop Production.

Precision agriculture has the capability and insight to use natural resources effectively while safeguarding the environment. Four phases exist for the implementation of precision agriculture: (a) characterizing the magnitude and scope of variability in soil and crop characteristics; (b) analyzing the implications and origins of variability; (c) administering variability on both spatial and temporal levels; and (d) assessing the results derived from variability management strategies. **Fig. 4** illustrates the information flow in precision agriculture for crop production.

IV. RESULTS AND DISCUSSION

Throughout the nine-month research of the designated citrus grove, the irrigation volumes implemented according to the farmer's estimations using the conventional technique in Field A and according to the DSS approach in Field B were documented. Irrigation systems' impact on lemon production within the two agricultural zones was appraised at the end of the season.

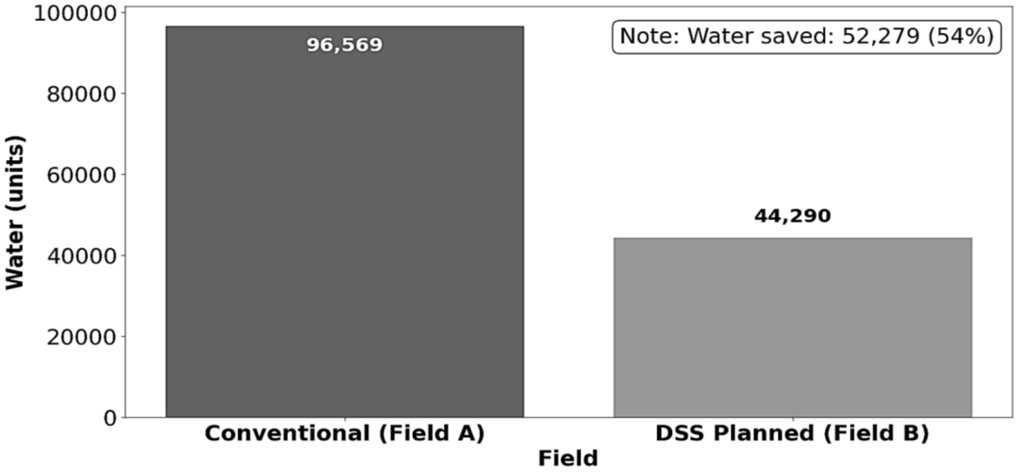

Fig 5. Irrigation Data.

Comparative Irrigation Performance and Water Use Efficiency

Fig. 5 illustrates the total irrigation usage for both regions. Respondents in Region A employing the traditional farming methods reported irrigation water usage for the entire season amounted to 96,569 liters. On the other hand, respondents in Region B, where the irrigation of the crops was controlled by the DSS approach, reported that only 44,290 L was used, which is 46.01% of the irrigation water employed by the conventional system. The irrigation schedule produced by the DSS approach conserved 22,810,839 cubic feet of water. This figure is indicative that the irrigation planned by the DSS approach, in conjunction with real-time on-farm conditions, augments water usage and sustains irrigation. More importantly, this was achieved without compromising the quality of the crops produced. The following will further elaborate on the increase in crop production.

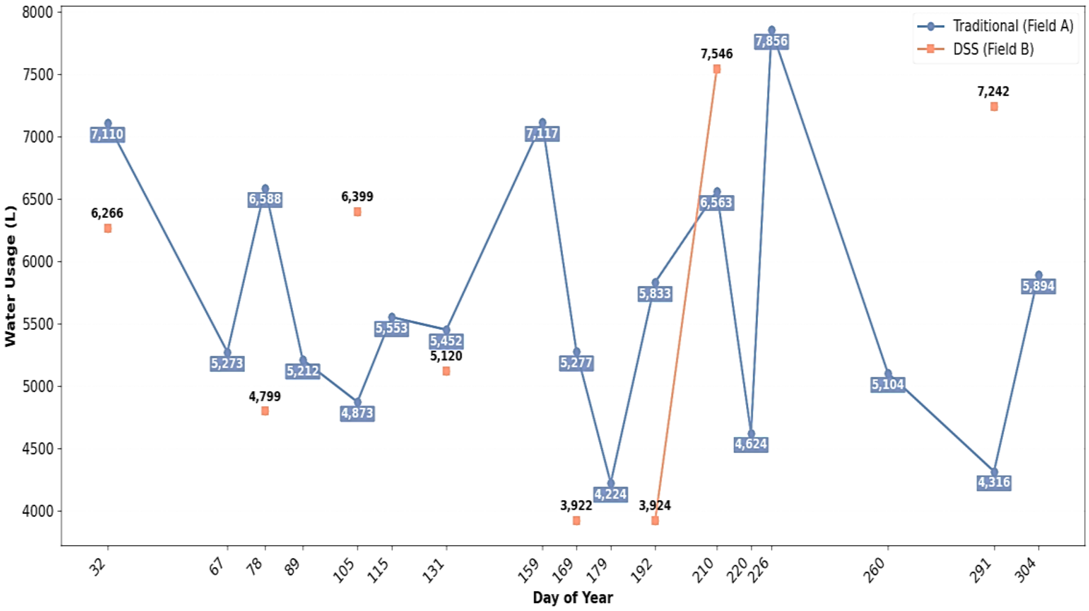

Fig 6. Water Consumption Efficiency Statistics.

Fig. 6 provides a full set of irrigation schedules per farm, broken down by irrigation application day of the year and the day's water use. Day 01 corresponds to 1 Jan of the studied year. As per the conventional irrigation methods, the farmer watered the field without considering the actual prerequisite. On the contrary, because instantaneous sensor data indicated water needs for Field B, the DSS approach did not propose irrigation. This information is also shown in **Fig. 7** in order to depict the efficiency of the water consumed.

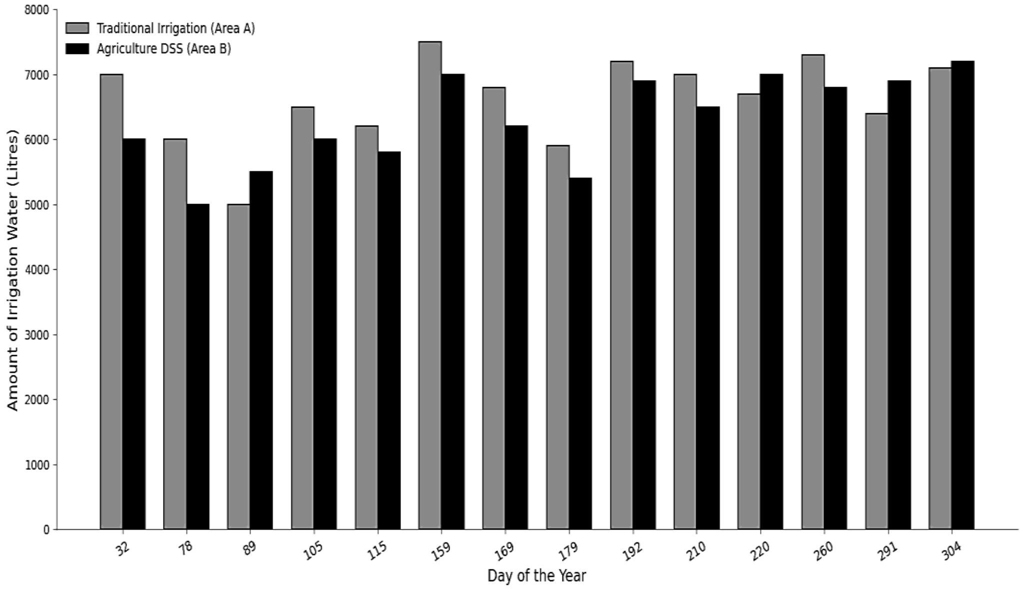

Fig 7. Effectiveness of Water Utilization in Traditional Irrigation as Compared to DS's Algorithm Irrigation.

Modern irrigation practices positively impact WUE. The gaps between precipitation and water demands of crops are quite glaring in the arid/semi-arid zones, and thus, irrigation management is pivotal. To increase WUE, a number of farmers have shifted to the use of different practices and technological tools for better management of agricultural water practices.

The latest evaluation of WUE design in precision instruments showed smart models used instant irrigation planning, control and monitoring. The water is controlled to irrigate crop at various development stages by intelligent systems and to control the amount of water, as highlighted in **Table 3**.

Table 3. New Technology in Agriculture to Enhance WUE

Methods	Details	References
ML-based WUE evaluation	The machine learning evaluation processes of WUE showed that there are geographical variances in terms of WUE. The efficiencies of WUE in the east were higher than the middle and West.	[14, 15]
Slack and super-efficiency models	Super-efficacy model of slack orientation was applied to examine the WUE of agriculture in the region.	
Geospatial and irrigation system	Geospatial systems help in determining the contribution of an element in the process of irrigation.	
Irrigation on cloud systems and IoTs	Irrigation planning and automations have been improved by the implementation of various pivotal technologies including distributed systems and IoT networks.	[16]
Multi-stakeholder remedies to precarity of water	Assessing various methods used to attain transformative changes towards solving water usage problems.	[17]
Nuclear techniques for moisture measurement	Innovative techniques using cosmic-ray neutron sensors (CRNS) and neutron meters assessed soil moisture by hydrogen detection, improving irrigation management and WUE monitoring.	
Negative pressure irrigation technology	Engineered negative pressure irrigation systems tailored to crop responses and environmental factors, enhancing energy and water efficiency in irrigation methodologies.	
IoT precision irrigation at landscape scale	Implemented IoT-driven precision irrigation across 11 pumping stations spanning 5,911 fields, including decision-making technologies for state-level water resource planning.	

Since the efficiencies of irrigation resource optimization cannot be determined based on individual parameters alone, this study explored multiple parameters for soil moisture-based irrigation scheduling. As a result, multiple methods were analyzed, and future improvements to the irrigation planning based on instantaneous crop dataset WUE were crafted. Their study demonstrated that the incorporation of DSS with prevailing technologies would greatly enhance the scheduling efficiency and accuracy by enhanced meteorological dataset (rainfall, winds, humidity, and temperature), crop data (crop stage and type), soil data (bulk density, soil type, and moisture), and irrigation data (frequency and method). The purpose of the investigation is conceptualized in terms of explaining some of the efficiency parameters, particularly water use. This highlights the usefulness of remote sensing technologies, which facilitate a great deal of monitoring for the farmer as well as the researcher dealing with intelligent irrigation, both in traditional systems and in systems with sensors.

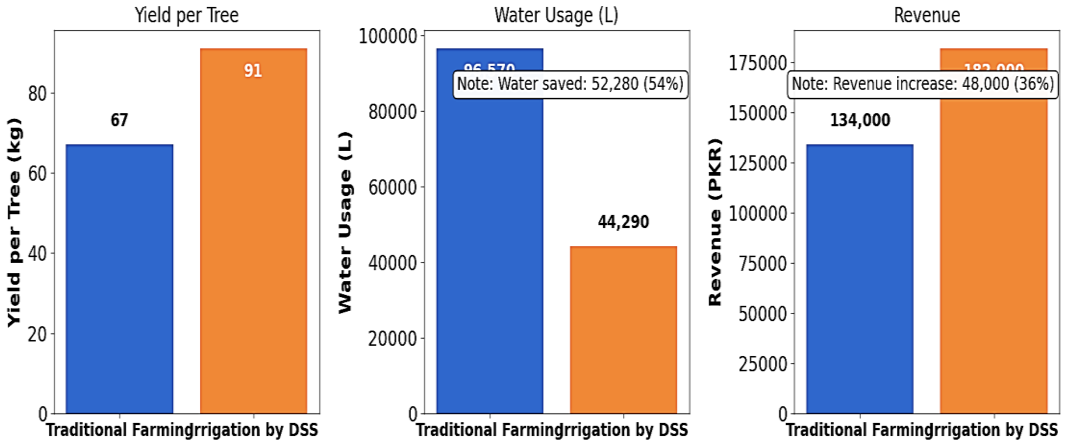

Fig 8. Improvement in the Harvest of the Lemons.

Impact of DSS-Based Irrigation on Lemon Yield and Farm Income

Fig. 8 illustrates the overall productivity achieved at the end of the year in Fields A and B. The data clearly indicates that the lemon production in Field B, watered according to the recommendations of the DSS approach based on actual-time factors, was much greater at 91 kg/tree. In contrast, the production was 67 kg/tree in Field A, which used standard irrigation methods. The yield augmented by 35% by the use of the DSS approach for irrigation. The data also indicates that the overall production/acre in Field A and Field B is 4690 kg and 6370 kg, respectively.

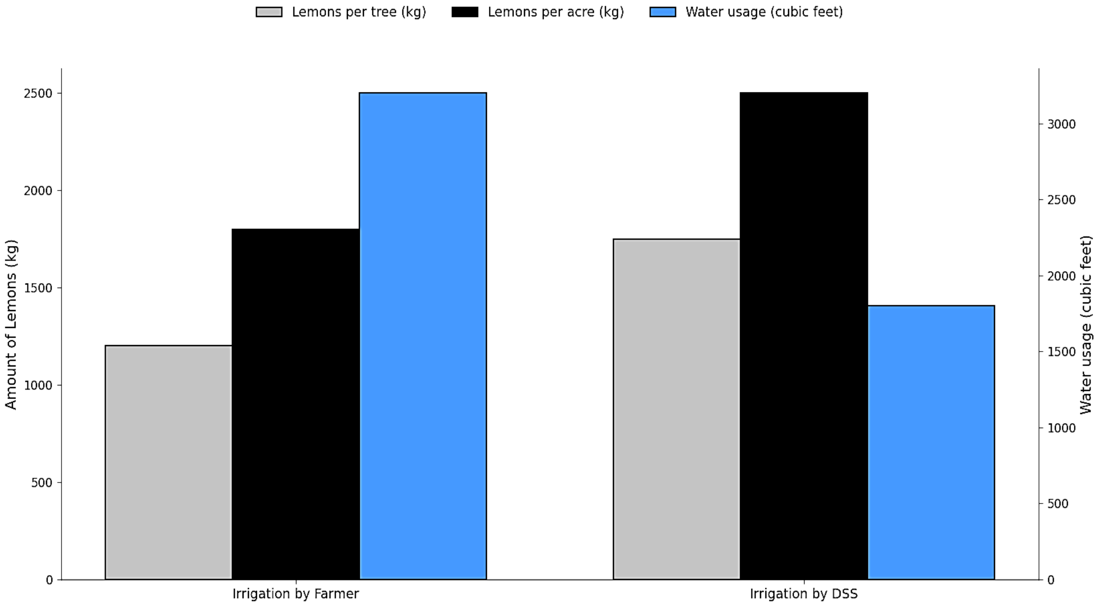

Fig 9. Water Use Efficacy Based on Irrigation Occurrence and Amount of Conventional and Sensor-Oriented Systems.

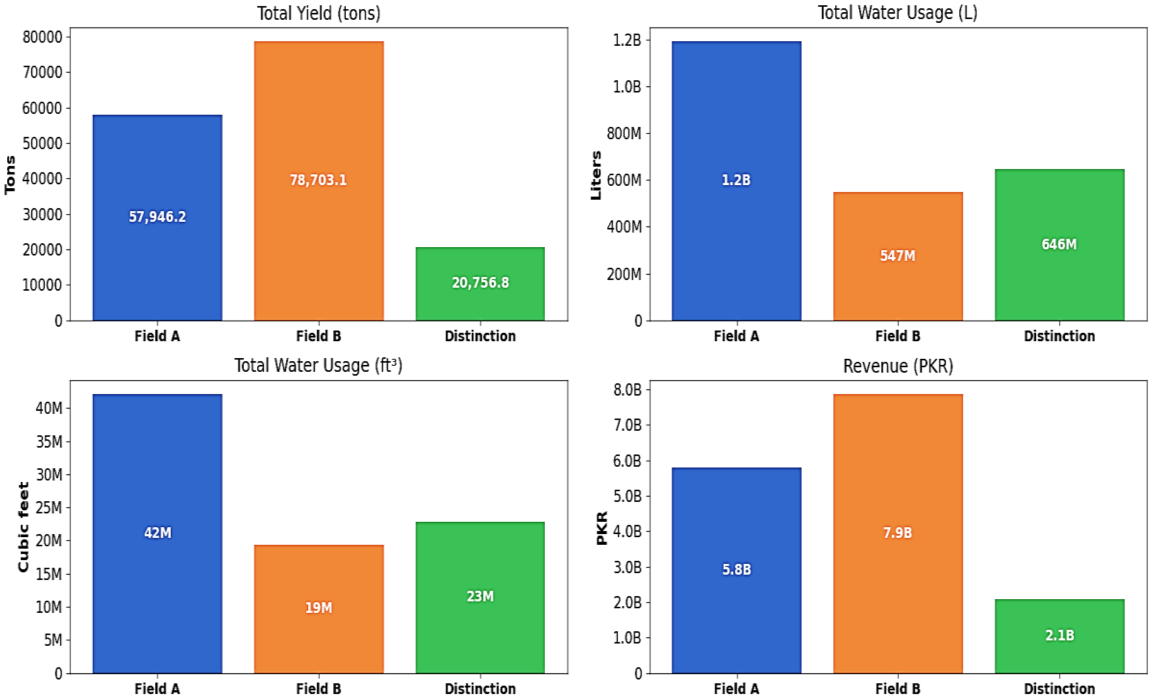

Fig 10. Potential Yield Rise from Repeated Yearly Lemon Crop Cultivation in Pakistan.

The overall income earned in Field B (DSS approach-oriented irrigation) from water conservation and increased production was 182,000 PKR, representing a 35% increase compared to Field A (conventional irrigation). Agriculturalists from Field B expressed satisfaction with the results from the IoT tools and supporting DSS approach, as they experienced a 35% gain in the harvest of the lemons with a 50% reduction in irrigation water usage. **Fig. 9** provides a summary of the findings from both farming regions with respect to the productivity of the crops and the irrigation water consumed.

National-Scale Implications and Potential Productivity Gains

The data depicted in **Fig. 9** can help in boosting the production of pistachios within the country and provides a comparison of the irrigation system of both modern farming and traditional farming in Pakistan with the aid of the agricultural decision support systems (ADSS). The amount of the land to be devoted to the is growing of lemons in Pakistan is also approximated to be 5,000 hectares (12,355 acres) in plantation density of about 70 trees/acre. We have shown that the traditional irrigation system yields a crop of about 67 kg of lemons/tree; hence, 70 trees/acre could give an approximate harvest of 4690 kg lemons/acre. Potential savings from our study are summarized in **Fig. 10**. The data is from one study, but the savings potential is considerable, and the potential savings are likely to be even greater if the methodology is applied to other citrus yields.

The decision support system significantly improved the average production per tree by 35% and achieved this using 50% less water. The results demonstrate the ability to utilize water savings to potentially open previously inactive land to agriculture without increasing overall water use.

V. CONCLUSION

The focus of this comparative study has been the evolving citrus production industry with the potential integration of IoT-enabled support systems. With DSS support, the strategy employed unarguably boosted the efficiency of water utilization, increased lemon production, and improved profit margin. The system provided the farmers with the ability to make instantaneous decisions on water optimization in real time, resulting in water conservation and improved crop productivity. Along with enhancing productivity, the program provided a pathway to scalable, sustainable practices, especially in water-scarce systems. Predictive and adaptive control modelling ought to be the focus of future research to create a leap in efficient and climate-resilient adaptive strategies for irrigation. Additionally, the implementation of data-driven systems in agriculture for the first time in this region would undoubtedly enhance efficient water resource management and positively impact targeted environmental sustainability by improving precision in agricultural practices.

CRediT Author Statement

The author reviewed the results and approved the final version of the manuscript.

Data Availability

No data was used to support this study.

Conflicts of Interests

The authors declare no conflict of interest.

Funding
No funding agency is associated with this research.

Competing Interests

There are no competing interests.

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