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Development and Performance Evaluation of an Auto-Drip Irrigation System for Sugarcane Production

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Abstract

A field experiment was conducted from December 2023 to December 2024 in Paniqui, Tarlac, Philippines, to address the increasing input costs, labor shortages, and water scarcity affecting sugarcane production. This study developed and evaluated an Auto-Drip Irrigation System (ADIS) to improve sugarcane growth, yield, and water productivity. The study assessed data transmission efficiency, growth parameters, and yield per hectare, water productivity, and sugar recovery. Results showed that soil moisture sensors successfully transmitted 97.04% of data points, ensuring effective irrigation control. ADIS improved stalk height (350.56 cm vs. 327.87 cm), stalk diameter (28.59 mm vs. 26.45 mm), and stalk weight (1.55–1.63 kg vs. 1.40–1.42 kg) compared to conventional furrow irrigation. Yield per hectare was significantly higher under ADIS, ranging from 140.41 to 156.49 TC/ha, a 28.77% increase over conventional practice (111.07–122.41 TC/ha). Water consumption was reduced by 42.72% (4,266.81 m^3/ha vs. 7,449.57 m^3/ha), while water productivity increased by 56.67% (9.56–10.86 kg/m^3 vs. 6.25–6.9 kg/m^3). Sugar recovery was slightly higher in ADIS (1.61 Lkg/TC vs. 1.58 Lkg/TC), leading to a 32.90% significant increase in sugar yield per hectare (225.35–255.08 bags/ha vs. 155.50–180.89 bags/ha). Statistical analysis confirmed that ADIS has a significant impact on yield and water efficiency. These findings highlight ADIS as a sustainable solution for enhancing sugarcane productivity and optimizing water use.

Introduction

Sugarcane is a vital crop in the global agricultural landscape, serving as the primary source of sugar and a major feedstock for ethanol production (Dinesh Babu *et al.*, 2022). However, its cultivation is highly water-intensive, requiring approximately 1,500-2,500 mm of water per growing season to sustain optimal growth (Khalifa *et al.*, 2020; Ashour *et al.*, 2025). In the Philippines, water scarcity has emerged as a constraint to sugarcane productivity. Recent reports from the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA, 2024) indicate a decline in rainfall during the dry months and increasingly erratic precipitation patterns linked to El Niño events, further intensifying the risks of drought and water stress in major sugarcane-producing regions. Under these conditions, efficient water management is therefore essential to sustain productivity and address the increasing challenges of water scarcity.

In most Philippine sugarcane areas, irrigation is either rainfed or conducted through conventional methods, which often result in excessive and inefficient water application. Conventional irrigation typically achieves only 30-40% water-use efficiency compared to 80-90 % attainable with well-designed drip irrigation systems

(Gunarathna *et al.*, 2018). These inefficiencies are largely due to losses from evaporation, deep percolation, and runoff, leading to overall inefficient use of water resources (Sela, 2019). To overcome these limitations, the adoption of innovative technologies is crucial.

The Auto-Drip Irrigation System (ADIS) offers a promising solution by integrating automation technologies with precision drip irrigation. This system utilizes soil moisture sensors and programmable controllers to deliver water directly to the rootzone in response to real-time field conditions. Through automated control and precise water delivery, ADIS minimizes water wastage while improving yields (Kale, 2023). Despite these advantages, automated irrigation systems have not been widely implemented or evaluated in Philippine sugarcane production, leaving a significant gap in local research and practical application.

The rapid advancement of the Internet of Things (IoT) has further expanded opportunities for automation in agriculture. IoT-based irrigation systems enable seamless integration of sensors, embedded controllers, and wireless communication networks to facilitate accurate and timely irrigation scheduling. Numerous studies have demonstrated the effectiveness of IoT-based irrigation systems in improving water management and crop performance in vegetable, rice, and maize production (Sharifnasab *et al.*, 2023; Rafrin *et al.*, 2024; Sutomo *et al.*, 2025). However, research on its application in high water-demand crops such as sugarcane remains limited, particularly under tropical field conditions.

Given these challenges, this study was undertaken to develop and evaluate an ADIS for sugarcane production in the Philippines. Specifically, the research aims to assess the system's performance in enhancing growth, yield, and water productivity compared to the conventional irrigation method. By addressing the existing research gap, the study seeks to generate locally validated data that can guide the sustainable intensification of sugarcane production, promote efficient water resource management in the country's sugar industry, and contribute to the broader goal of sustainable agricultural development in the region.

Materials and Methods

Development of the Automated Drip Irrigation System

a. Design Concept and Consideration

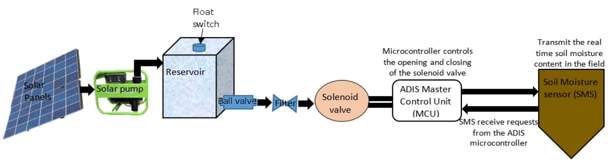

Figure 1. Schematic Diagram of ADIS design

The Auto-Drip Irrigation System (ADIS) was designed to optimize water management through an integrated system of sensors, controllers, and automated components, as illustrated in Figure 1. The system featured a 3-horsepower solar pump and a 6 m^3 reservoir serving as the primary water source for irrigation. The operation of the system was sensor-driven, with the solenoid valve automatically triggered based on real-time soil moisture data. The soil moisture sensor continuously monitored field conditions, activating the solenoid valve when soil moisture levels dropped to 50% Management Allowable Depletion (MAD) threshold. Once irrigation water reaches the designated sensor level, the system automatically shuts off, ensuring efficient water use and preventing over-irrigation. The microcontroller was programmed to manage these automated processes, executing embedded commands to regulate system operations. The system was powered by a solar energy setup, and the ADIS microcontroller included a battery storage unit to ensure continuous operation even during periods of low sunlight.

In this study, commercially available electronic components, including sensors and controllers, were sourced locally, with Arduino-based products selected for their compatibility and adaptability. These components were modified and integrated to meet the specific design requirements of the ADIS, ensuring a cost-effective and efficient irrigation solution.

a. ADIS Microcontroller Assembly

The ADIS microcontroller serves as the central processing unit for data collection, processing, and transmission between sensors and other input/output peripherals. It automates irrigation by controlling the opening and closing of the solenoid valves based on real-time data from soil moisture sensors. The microcontroller requests and processes soil moisture data at programmed intervals, ensuring precise water management.

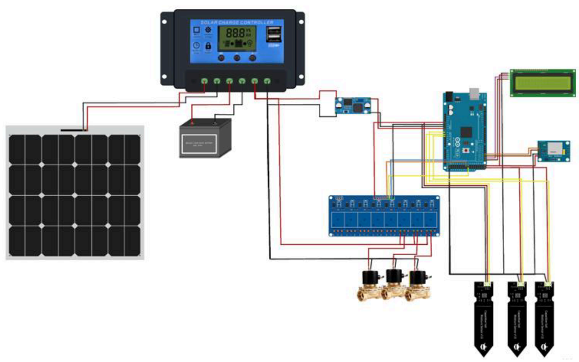

Figure 2. Schematic Diagram of ADIS MCU Schematic Diagram of ADIS MCU

The system comprises several key components, including the microcontroller unit, which integrates a processor, memory, and input/output peripherals to execute programmed irrigation tasks (Figure 2). A prototype screw terminal block shield secures wiring and sensor connections while housing the microcontroller. A liquid crystal display (LCD) presents real-time soil moisture readings for monitoring, while a GSM module was integrated into the microcontroller design, allowing communication between the phone and the Arduino. Additionally, a weatherproof enclosure protects it from environmental conditions, ensuring durability.

To ensure continuous operation, the system is powered by a solar energy setup consisting of a solar panel, a charge controller, and a rechargeable sealed lead-acid battery. This setup allows energy storage during daylight hours, ensuring uninterrupted functionality at night or during low-light conditions. By integrating these components, the ADIS microcontroller enhances irrigation efficiency by automating water distribution, optimizing resource use, and reducing manual labor in sugarcane farming.

a. Soil Moisture Sensor Calibration

The soil moisture sensor assembly underwent laboratory testing and calibration to ensure accuracy and reliability in field measurements. Soil samples were collected from the study site and prepared systematically. Initially, fresh soil samples were gathered from a representative area, where they were air-dried and manually sieved to remove any rocks, plant debris, or other non-organic materials. To achieve a consistent baseline moisture level, the soil samples were oven-dried at 105°C for one week until a constant weight was attained. Once dried, the samples were placed into a calibration container sufficiently large to accommodate the sensing area of the soil moisture sensor. The sensor probes were then inserted into the container, and a moisture gradient was created by gradually adding water to the samples. The sensor readings were recorded sequentially, from the driest state to full saturation, to capture the complete range of soil moisture variability. Following the sensor readings, the samples were weighed and subsequently oven-dried once again to determine their dry weight. The data collected from this process were plotted and analyzed using linear regression analysis to establish a calibration curve. The resulting equation from the calibration curve was then used in programming the soil moisture sensor.

b. Soil Moisture Sensor Program

The soil moisture sensor program was designed to communicate with the ADIS microcontroller, responding to requests by transmitting real-time soil moisture data during scheduled transmission periods. This system utilizes a capacitive analog soil moisture sensor, which is integrated with an Arduino-based microcontroller to ensure accurate monitoring of soil moisture content.

The capacitive analog soil moisture sensor operates by detecting moisture levels through capacitive sensing rather than traditional resistive methods, enhancing durability and precision. The raw analog data collected by the sensor is processed and converted into gravimetric moisture content using a pre-calibrated formula embedded in the microcontroller. This calibration process was established through prior soil testing to ensure accuracy in field conditions. The computed soil moisture values are then displayed on the microcontroller's LCD screen, providing real-time insights into the field's moisture status for efficient irrigation management.

c. ADIS Microcontroller Program

The microcontroller program was designed to efficiently process and execute commands, enabling the seamless operation of the entire automated irrigation system. The ADIS microcontroller was programmed to communicate with various sensors, including the soil moisture sensor for real-time soil moisture content monitoring. Based on the data received from these sensors, the microcontroller analyzes the information and makes automated decisions to optimize irrigation. When the soil moisture sensor detects moisture levels below the predefined threshold, the microcontroller activates the system by opening the solenoid valve, initiating the water flow. Conversely, the soil moisture sensor confirms that the required moisture level has been reached, and the microcontroller signals to close the solenoid valve, effectively terminating the irrigation process.

d. Computation of Power Supply of the System

The power supply system was strategically designed to ensure the continuous operation of the ADIS in the field. To accurately determine the system's energy requirements, the power consumption of each component was calculated based on its operational current. The total energy demand was assessed by computing the working current of each electrical component, allowing for an accurate estimation of overall power consumption. The battery capacity was then divided by the total working current to estimate its operational lifespan without recharging. For this study, the system was designed to function for a maximum of 24 hours per day. Additionally, the solar power rating was analyzed in relation to the estimated daily battery discharge to determine the required charging duration, ensuring a reliable and sustainable energy source for the system's uninterrupted performance.

Performance Evaluation of ADIS

a. Data Transmission Evaluation

The sensors were assessed based on their ability to reliably transmit essential data to the ADIS microcontroller. This evaluation was conducted through a reliability test, which measures the likelihood that the system will operate without failure for a specified period under defined conditions. The assessment ensured that the sensors consistently provided accurate data, enabling the microcontroller to make precise irrigation decisions and maintain optimal system performance.

b. Field Layout and Design

The field experiment was conducted from December 2023 to December 2024 at Bgry. Apulid, Paniqui, Tarlac, Philippines (15° 41' 19.08" N, 120° 34' 11.21" E) on a 3,600 m^2 sugarcane plantation with a uniform bed slope of 1%.

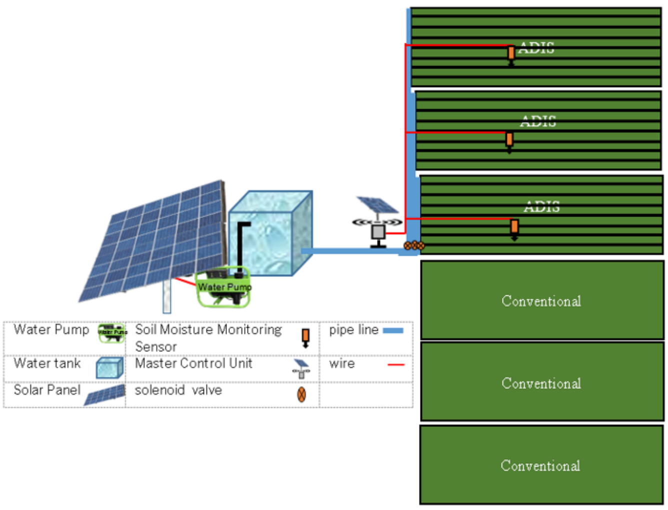

Figure 3. Experimental Field Layout and Design

The experimental area was systematically divided into two treatments: half of the site (1,800 m^2) was allocated for the ADIS, while the remaining 1,800 m^2 followed the conventional farmer's practice. To ensure statistical reliability, the field was further subdivided into blocks measuring 600 m^2 each, with three replications per treatment. The detailed layout of the experimental design is presented in Figure 3.

The pump is powered by a hybrid solar water pump, which can operate using both solar energy and electricity. This setup ensures a reliable and sustainable water supply for irrigation. The pump delivers water to a storage tank, which then distributes it through flat drip tape with emitters spaced 30 cm apart, providing a discharge rate of 3 liters per second (lps), and was designed for surface irrigation.

a. Crop Establishment

The PHIL 2006-2289 sugarcane variety was planted for all blocks with an estimated density of 45,000 setts per hectare. An area of 36 m x 50 m plot was utilized for each treatment. Each block contains 8 furrows using a furrow spacing of 1.5 m. A comprehensive soil analysis was conducted at the study area to establish the appropriate fertilizer recommendation rate. Inorganic fertilizers were strategically applied in two split doses, at two and four months after planting, to maximize nutrient availability and uptake.

b. Growth and Yield Parameters

The agronomic performance of the two irrigation systems was evaluated and compared based on key growth parameters, overall yield (tons of cane per hectare, TC/ha), sugar production (50 kg bags per hectare, Lkg/ha), and water productivity. To ensure a representative assessment, 20 plant samples per block were randomly selected for individual plant measurements, including stalk height (cm), stalk diameter (mm), and the number of millable tillers.

Data collection was systematically conducted at specific growth intervals, specifically at 4, 5, 6, 7, and 12 months after planting (MAP). Plant height was measured using a measuring stick, while stalk diameter was determined with a digital Vernier caliper. The number of tillers per plant was manually counted. To determine yield, harvested sugarcane stalks were weighed using a calibrated scale, and the total yield was then converted from kilograms per linear meter to tons per hectare (TC/ha) for standardization.

c. Data Analysis

At the physiological maturity stage, a statistical analysis was conducted to compare the crop performance under both irrigation treatments. Data analysis was performed using the Statistical Tool for Agricultural Research (STAR), and significance was determined at the 5% and 1% levels of significance through t-test evaluation.

Results and Discussion

ADIS Master Control Unit Assembly

The ADIS master control unit (MCU) controls all the activity of the system. It sends and receives a request from the sensors and is connected to the solenoid valve.

The MCU incorporated several key components, as shown in Figure 4. At its core, it has a microcontroller, which is a single-chip computer system that integrates a processor, memory, and programmable input/output peripherals. These microcontrollers served as the central processing unit for executing programmed tasks and handling data collection, processing, manipulation, and communication with other devices.

To facilitate circuit construction and secure connections, prototype screw terminal block shields were utilized. These shields combined prototyping functionality with screw terminal blocks, providing a convenient platform for constructing necessary circuits and establishing secure connections with wires and sensors. Additionally, it served as the mounting location for the microcontrollers.

To display readings from the soil moisture sensor, an interface in the form of a liquid crystal display (LCD) was incorporated into the microcontroller. This display presented relevant information in a clear and user-friendly manner. A GSM module was integrated into the microcontroller design, allowing the microcontroller to send and receive data via SMS, ensuring continuous monitoring and control of the irrigation process.

The solenoid valve played a crucial role in the automated irrigation system, regulating water flow based on signals received from the microcontroller. When the soil moisture sensors detected that soil moisture had reached the 50% MAD threshold, the microcontroller transmitted a signal to the master control unit, triggering the solenoid valve to open, allowing water to flow into the drip lines. Once the sensor detected the presence of water, the microcontroller sent another signal to close the solenoid valve, effectively stopping irrigation. For added flexibility and control, a latching push button switch was integrated into the system, enabling manual operation of the microcontroller's power state. This feature allowed operators to turn the system on or off as needed, ensuring both automated efficiency and manual override capability when required.

The microcontrollers were powered by solar power systems comprising solar panels, charge controllers, and rechargeable sealed lead-acid batteries. During the day, the solar panels harnessed solar energy to charge the batteries, which then supplied power to the microcontrollers during the night or periods of limited sunlight. These power supply components were seamlessly integrated into the overall design of the ADIS microcontrollers, enabling their efficient operation within the automated irrigation system.

Figure 4. ADIS Master Control Unit

Soil Moisture Sensor Calibration

Before deploying the soil moisture sensors in the field, a calibration process was conducted for all sensors used in the study. The collected data were plotted and analyzed using linear regression to establish a calibration curve. The resulting calibration equation (Table 1) was then programmed into the ADIS microcontroller, enabling it to accurately convert analog sensor readings into gravimetric moisture values for real-time monitoring and irrigation decision-making.

Table 1. Calibration values of Soil Moisture Sensors

Irrigation Method	Block	Sensor	Calibration Curve	R^2
ADIS	Block 1	S1	y = 3.2426x + 5.2353	R^2= 0.97
	Block 2	S2	y = 3.1005x + 7.7451	R^2= 0.97
	Block 3	S3	y = 2.8321x + 19.392	R^2= 0.95

ADIS Program

a. Programming and Automation of ADIS

The microcontroller and sensor programs were developed using the C programming language. These programs were written and compiled in the Arduino Integrated Development Environment (IDE) before being uploaded to the microcontroller. The microcontroller processes the inputs from sensors and controls outputs, such as solenoid valves, ensuring seamless automation of the irrigation process.

b. Automation Flowchart and Pump Operation

The finalized automation scheme for the ADIS is illustrated in Figure 5, showcasing the continuous interaction between the microcontroller, sensors, and solenoid valves. This automation framework ensures efficient water distribution by integrating real-time soil moisture monitoring and automated valve control.

In addition to managing irrigation flow, the system also includes an automated solar-powered water pump that operates based on water level thresholds. The pump is automatically activated when the water level drops to 1 meter from the bottom of the water tank and deactivated once the level exceeds 1.45 meters, ensuring efficient water usage while preventing overflow. These flowcharts illustrate the logical sequence of system functions, highlighting the integration of renewable energy, precision irrigation, and automation technologies to enhance agricultural water management.

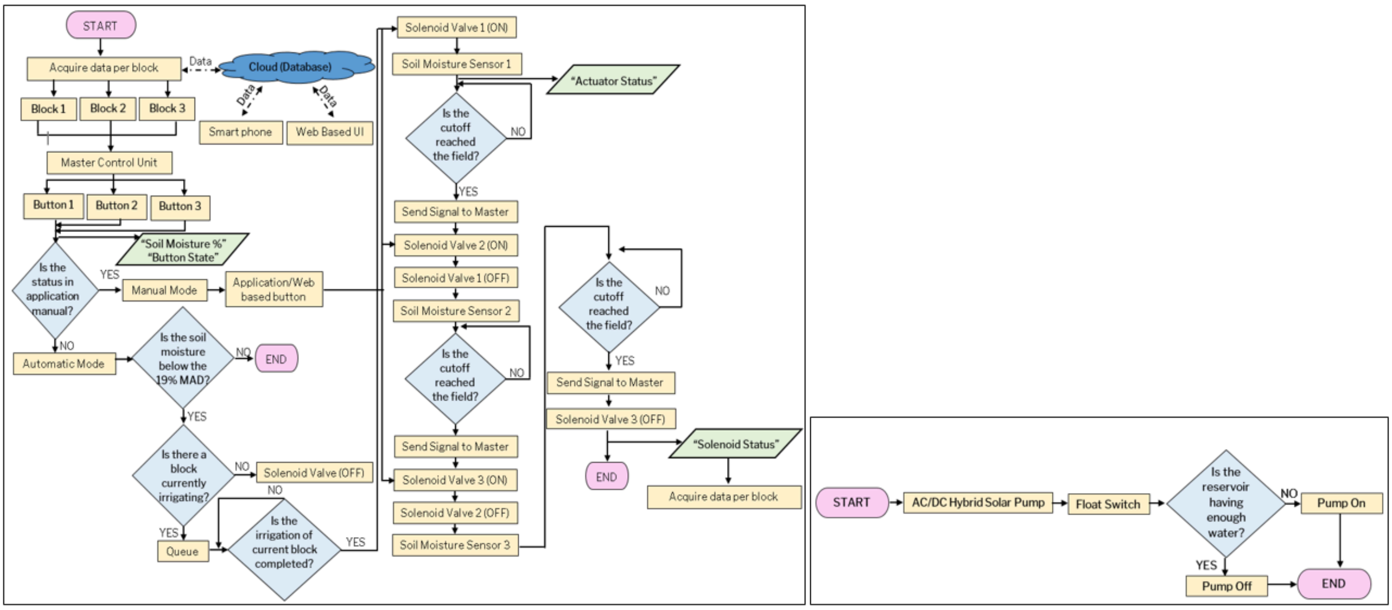

Figure 5. Flowchart of the ADIS automation scheme and the solar water pump

c. Power Supply Calculation

Table 2. Power Consumption of MCU

Components	Current Use (A)	Voltage (V)	Power Usage (W)	Number of Modules/ Components	Average Power Consumption	Average Time Use (hr)	Total Power Rating (W)
Arduino Mega 2560	0.2	9	1.8	1	1.8	24	43.2
Capacitive Soil Moisture Sensor	0.02	5	1	1	1	24	24.0
GSM Sim800L Module	1	5	5	1	5	24	120.0
LCD I2C	0.2	5	1	1	1	24	24.0
Relay	0.07	5	0.35	6	2.1	0.033	0.0693
Solenoid valve	0.35	12	6	3	18	0.0028	0.05
NRF24L01 with adapter	0.25	5	1.25	1	1.25	4	5.0

The power consumption and energy requirements for the MCU are crucial to the successful operation of the automated furrow irrigation system. The Arduino Mega 2560, which serves as the central processing unit, consumes 1.8 watts of power and operates continuously, resulting in a daily consumption of 43.2 watts. The capacitive soil moisture sensor, essential for monitoring soil moisture, operates at a minimal 1 watt, consuming 24 watts daily due to its continuous operation. The GSM Sim800L Module, critical for wireless communication, is the most power-intensive component, with a daily consumption of 120 watts. The LCD I2C display, used for data visualization, also operates at 1 watt and consumes 24 watts daily. The relay, responsible for controlling other components, has a lower power demand, consuming approximately 0.0693 watts per day. Solenoid valve, vital for executing mechanical actions, consumes about 0.05 watts daily, while the NRF24L01+ wireless communication module operates at 1.25 watts and consumes 5 watts over its average 4-hour daily use (Table 2). The battery capacity is calculated at 240 watt-hours (W-h), paired with a 35W solar panel and a solar charge controller with 95% efficiency. The charging time from a dead battery to full capacity is approximately 7.22 hours, while charging from half to full takes around 3.61 hours.

System Performance of ADIS

a. Observed Data and Data Transmission

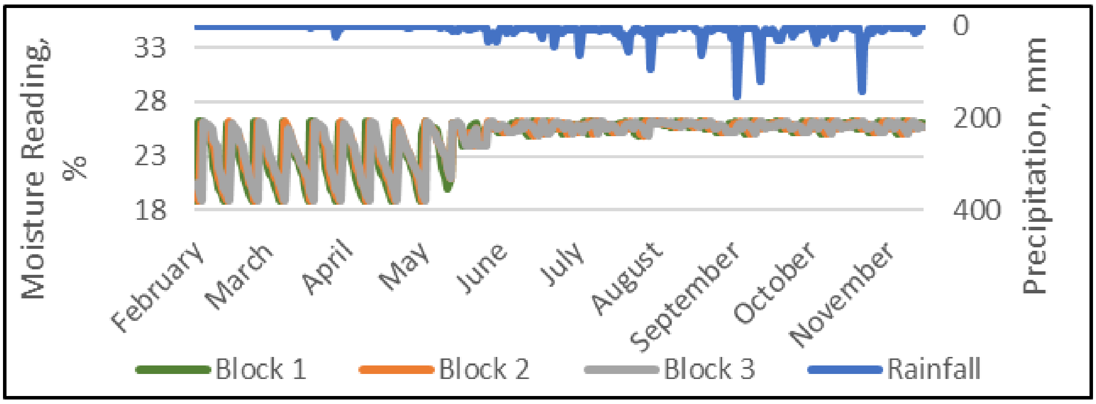

Figure 6. Precipitation and sensor reading

The soil moisture sensors were programmed to transmit readings every hour to the ADIS controller daily. The data transmission speed between the soil moisture sensors and the ADIS controller ranged from 100 to 300 milliseconds, depending on the distance between the sensors and the controller. From the start of operation, the sensors successfully transmitted 6,986 out of the expected 7,200 raw data points, achieving a transmission rate of 97.03%. The remaining 2.97%, or 214 data points, were not recorded due to technical issues and signal interruptions at the project sites. Despite these minor losses, the sensors effectively transmitted all signals necessary for controlling the irrigation system. For automated irrigation control, the sensors triggered the opening and closing of valves based on real-time soil moisture readings. When soil moisture levels dropped below 50% MAD, the system activated the valves, initiating irrigation. Conversely, once moisture levels reached the depth of the soil moisture sensors, the valves closed automatically. Each of the three valves required 1-2 seconds to fully open the valve upon receiving signals from the ADIS microcontroller. Additionally, precipitation data were incorporated into the analysis to assess their influence on soil moisture levels. This data was sourced from NASA's POWER Data Access Viewer (NASA, 2024). It is a widely used platform that provides free climate and solar datasets derived from satellite-based models, designed for agricultural and research applications.

b. Growth and Yield Data and Analysis

Table 3. Measured agronomic data

Treatment	Replication	Stalk height, cm	Millable Tiller Count, pcs/linear meter	Stalk diameter, mm	Weight per stalk, kg
ADIS	Block 1	347.60	16	28.60	1.63
	Block 2	357.00	16	27.56	1.55
	Block 3	347.20	15	29.60	1.56
Conventional	Block 1	321.8	14	25.01	1.42
	Block 2	329.4	15	26.23	1.44
	Block 3	332.4	14	28.1	1.40

Table 4. T-test of stalk height, millable tiller, and stalk diameter

Agronomic Data	Treatment	N	Mean	Std. Dev	Std. Error	t-value	p-value
Stalk height	ADIS	60	350.56	8.40	3.76	4.82	0.0013
	Conventional	60	327.87	6.35	2.84		
Millable tiller	ADIS	60	15.67	0.55	0.24	3	0.0039
	Conventional	60	14.33	0.71	0.32		
Stalk Diameter	ADIS	60	28.59	0.83	0.37	3.14	0.014
	Conventional	60	26.45	1.28	0.57		
Stalk weight/stalk	ADIS	60	1.58	0.03	0.01	9.06	0.0000
	Conventional	60	1.42	0.02	0.01		

The agronomic data and statistical analysis of stalk height, diameter, weight, and millable tillers are summarized in Tables 3 and 4. The agronomic performance of sugarcane under ADIS demonstrated clear advantages over conventional furrow irrigation. Stalk height was significantly enhanced under ADIS, indicating that consistent water availability positively influences vegetative growth. This observation is consistent with previous studies highlighting the sensitivity of plant height to water stress, where drought conditions markedly reduced sugarcane height (Hemaprabha *et al.*, 2004; Misra *et al.*, 2020).

Similarly, the number of millable tillers was higher under ADIS, suggesting that improved water management supports tiller development and may contribute to a greater proportion of commercially viable canes. Prior research corroborates these results, showing that water stress can alter tiller production, reducing the number of large, millable tillers while increasing smaller, less productive ones (Zhao *et al.*, 2010).

Stalk diameter and weight also responded positively to ADIS, reflecting enhanced biomass accumulation likely due to improved water availability. These findings are in line with studies demonstrating that water stress can significantly reduce stalk diameter and individual cane weight (Ramesh & Mahadevaswamy, 2000; Misra *et al.*, 2020). These results suggest that ADIS not only mitigates the adverse effects of water stress but also provides agronomic advantages that could translate into higher sugarcane yield.

c. Yield per hectare, TC/ha

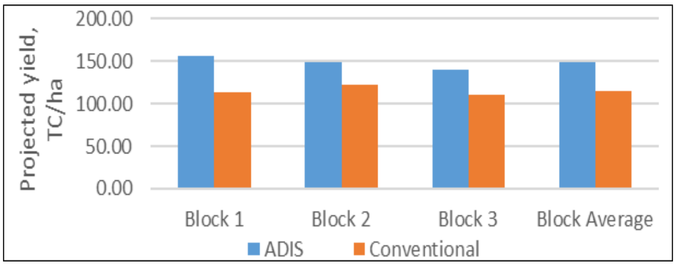

Figure 7. Yield per hectare, TC/ha

Tons of cane per hectare (TC/ha) is a crucial profitability indicator in sugarcane production. This study revealed that sugarcane grown under the ADIS outperformed conventionally irrigated blocks, yielding 28.77% more cane. The ADIS-treated blocks produced between 140.41 and 156.49 TC/ha, significantly higher than the 111.07 to 122.41 TC/ha recorded under conventional irrigation (Figure 7).

Table 5. T-test of yield per hectare

Treatment	N	Mean	Std. Dev	Std. Error	t-value	*p*-value
ADIS	60	148.53	5.79	2.59	10.26	0.0000
Conventional	60	115.34	4.34	1.94		

Statistical analysis confirmed that these differences were highly significant, highlighting the effectiveness of ADIS in supporting higher cane output (Table 5). These findings are consistent with a previous study of Kalyankar (2017), which reported substantial yield improvements under drip irrigation compared to traditional methods.

d. Amount of water applied, m^3/ha

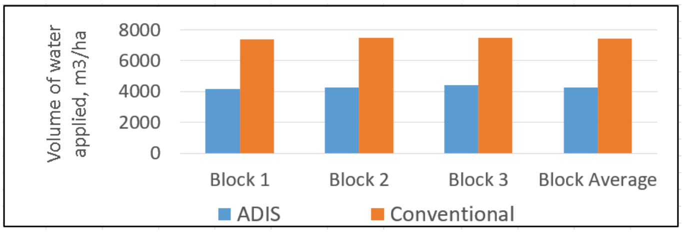

Figure 8. Volume of water applied, m^3/ha

Table 6. T-test of the volume of water applied

Treatment	N	Mean	Std. Dev	Std. Error	t-value	*p*-value
ADIS	3	4,278.54	139.27	80.41	-35.85	0.0000
Conventional	3	7,449.57	63.83	36.85		

The volume of water applied per block under both the ADIS and conventional is presented in Figure 8. Results indicate that ADIS significantly reduced water consumption by 42.72%, demonstrating substantially higher efficiency. Statistical analysis (Table 6) further confirmed that the method of irrigation significantly influenced the total water applied, with differences evident at both the 5% and 1% levels of significance. This indicates that adopting ADIS can considerably improve water-use efficiency in sugarcane production without compromising crop performance.

e. Effective Rainfall

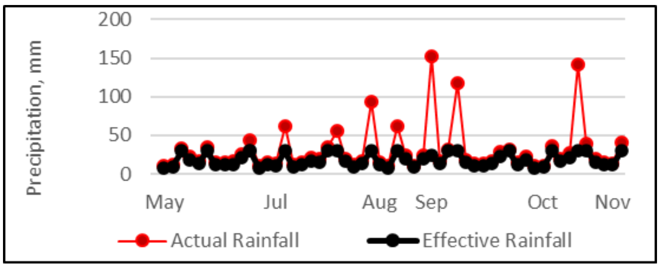

Figure 9. Actual and effective rainfall, mm

In this study, effective rainfall was estimated using the widely recognized 10-30 rule of thumb, an empirical method commonly applied in agricultural water management. This approach considers daily rainfall amounts below 10 mm as ineffective, as most of the water is lost to evaporation and does not adequately infiltrate the soil to reach the crop's root zone. On the other hand, rainfall exceeding 30 mm per day is largely excluded from effective rainfall calculations since a significant portion is lost through runoff and deep percolation (Academy, 2019). The computed values for effective rainfall are illustrated in Figure 9.

f. Water Productivity

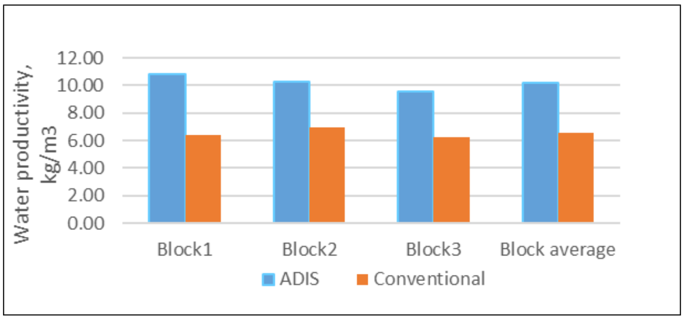

Figure 10. Water productivity, kg/m^3

Table 7. T-test of water productivity

Treatment	N	Mean	Std. Dev	Std. Error	t-value	p-value
ADIS	60	10.22	0.65	0.37	8.74	0.0009
Conventional	60	6.52	0.33	0.19		

Water productivity was assessed by dividing the cane yield by the total irrigation applied plus effective rainfall, as stated by Tayade *et al.* (2020). Results indicate that ADIS-irrigated sugarcane blocks achieved significantly higher water productivity, ranging from 9.56 kg/m^3 to 10.86 kg/m^3, whereas blocks irrigated using the conventional method recorded lower values, ranging from 6.25 kg/m^3 to 6.9 kg/m^3 (Figure 10). This represents a 56.67% increase in water productivity under ADIS, demonstrating its efficiency in optimizing water use. Furthermore, statistical analysis (Table 7) revealed a highly significant difference between the two irrigation treatments, confirming the superior performance of ADIS in enhancing water productivity.

g. Sugarcane Juice Analysis

Table 8. Sugar recovery and projected number of bags produced per hectare

Treatment	Replication	Sugar Recovery, Lkg/TC	Bags of sugar produced, bags/ha
ADIS	Block 1	1.63	255.08
	Block 2	1.58	235.12
	Block 3	1.61	225.35
Conventional	Block 1	1.60	180.89
	Block 2	1.69	206.87
	Block 3	1.40	155.50

Table 9. T-test of sugar recovery and bags of sugar produced per hectare

	Treatment	N	Mean	Std. Dev	Std. Error	t-value	*p*-value
Sugar Recovery	ADIS	60	1.61	0.0207	0.0093	1.04	0.3532
	Conventional	60	1.56	0.1055	0.0472		
Bags of sugar	ADIS	60	239.13	10.77	4.82	6.25	0.0002
	Conventional	60	179.93	18.24	8.16		

Sugarcane stalk samples collected from the experimental field were analyzed at the Sugar Regulatory Administration-Luzon Agricultural Research and Extension Center, where juice extraction and further evaluation were conducted. The sugar recovery, expressed in 50-kg bags per ton of cane (Lkg/TC), along with the total number of bags produced, is presented in Table 8, while statistical analysis is detailed in Table 9.

Sugarcane grown under ADIS exhibited a slightly higher sugar recovery compared to conventional practice, although this difference was not statistically significant at the 5% level. Even small improvements in sugar recovery can contribute to greater overall yield. In contrast, the bags of sugar produced per hectare were significantly higher in ADIS, with statistical analysis confirming a highly significant difference between treatments. These results highlight the potential of ADIS to enhance overall sugar production.

Conclusion

This study highlights the effectiveness of the ADIS in improving sugarcane productivity while optimizing water use. With a high data transmission efficiency of 97.04%, ADIS ensured precise irrigation control, leading to improved stalk height, diameter, and weight. Yield per hectare increased by 28.77% compared to conventional furrow irrigation. ADIS also enhanced water efficiency, reducing irrigation consumption by 42.72% and increasing water productivity by 56.67%. While sugar recovery showed a slight improvement, total sugar yield per hectare significantly increased.

The ADIS presents a practical strategy for improving sugarcane production in the Philippines. This study underscores the importance of modern irrigation technologies in improving production efficiency, addressing resource constraints, and supporting long-term sustainability in the sugar industry. Future research should consider the cost implications, maintenance requirements, cost-benefit analysis, and potential scalability of ADIS for local farms to further assess its feasibility and promote broader adoption among sugarcane growers.

Ethical Statement

The study adhered to standard ethical guidelines throughout its conduct. Before field activities, informed consent was obtained from all farmer-cooperators and participating personnel, ensuring that they fully understood the project objectives, procedures, and their voluntary involvement. All personal, farm, and location-specific information was treated with strict confidentiality and used solely for research purposes. The research team ensured that no physical, environmental, or economic harm resulted from the installation and operation of the Auto-Drip Irrigation System (ADIS). All fieldwork was carried out with respect for property boundaries, local regulations, and community practices. After the study, data were securely stored and accessible only to authorized project members. Equipment was removed or turned over responsibly, ensuring that no ecological disturbance or community burden remained. The research complied with the institutional guidelines of Central Luzon State University and aligned with ethical standards for agricultural field experimentation.

Conflict of Interest Statement

The authors declare no conflict of interest related to the conduct and publication of this research. All procedures followed were in accordance with institutional and ethical standards, and there were no financial or personal relationships that could have influenced the outcomes of this study.

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Declaration of Generative AI and AI-Assisted Technologies

During the preparation of this work, the author(s) utilized ChatGPT for grammar correction. Following the use of this tool/service, the author(s) conducted a review and made necessary modifications, assuming full responsibility for the content of the publication.

Data Availability

All data supporting the findings of this study are available within the paper.

Author Contributions

EVR: Writing-Original draft, Methodology, Validation, Formal Analysis, Visualization; **MMC:** Conceptualization, Project administrator; Supervision, funding acquisition, and Writing-Review and Editing; **WCM**: Writing-Review and Editing; **JVF:** Writing-Review and Editing; **CGSA**: Writing-Review and Editing; **JPCS**: Writing-Review and Editing

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