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Boosting Sugarcane Yields in Low-Yielding SRA-Blocked Farms through Pilot-Testing of Auto-Furrow Irrigation System and Biofertilizer Application in Paniqui, Tarlac, Philippines

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Abstract

Sugarcane is a vital crop in the Philippines, yet its production remains constrained by rising input costs, labor shortages, and increasing water scarcity. This study evaluated the performance of the Auto Furrow Irrigation System (AFIS), a solar-powered, sensor-based surface irrigation technology developed by Central Luzon State University, in combination with a biofertilizer produced by UPLB-BIOTECH to enhance sugarcane productivity in a low-yielding SRA block farm. Pilot testing was conducted during the 2023–2024 cropping season in Paniqui, Tarlac. Data were analyzed using a randomized complete block design (RCBD) with three replications, and treatment means were compared using the least significant difference (LSD) test. Results showed that AFIS, combined with biofertilizer, significantly improved crop growth and yield parameters compared with conventional practices. Stalk height increased from 328 cm to 363 cm, millable tillers from 14 to 16, and stalk diameter from 26 mm to 31 mm. Yield performance also improved substantially, with sugarcane yield increasing from 111–122 TC ha^{-1} under conventional irrigation to 164–189 TC ha^{-1} under AFIS. Water productivity, calculated using total irrigation water and computed effective rainfall, rose from 6 kg m^{-3} to 12 kg m^{-3}. Sugar recovery improved from 1.6 to 1.9 Lkg TC-1, resulting in higher sugar output per hectare (301–347 vs. 156–206 Lkg ha^{-1}). Statistically, AFIS with biofertilizer showed significant differences at the 5% significance level in stalk height, stalk diameter, stalk weight, yield, and sugar production. Economic analysis further indicated higher profitability under AFIS, with a benefit–cost ratio of 2.34 and a return on investment of 134%, compared with 1.36 and 36% under the conventional system. Although AFIS required a higher initial investment, its approximately 2-year payback period remained economically acceptable. The results demonstrate that integrating AFIS with biofertilizer can substantially increase sugarcane yield, water-use efficiency, and net economic returns. However, these findings are based on a single site and one cropping season; therefore, multi-location and multi-year evaluations are recommended to validate system performance under diverse field conditions.

Introduction

Sugarcane is the fifth-largest crop by value in the Philippines, following rice, bananas, corn, and coconuts. Despite its economic importance, the area planted to sugarcane has steadily declined in recent years, largely due to farmers shifting to shorter-duration and more immediately profitable crops such as corn and bananas (Sevilla, 2021). This decline has occurred alongside escalating production constraints within the sector.

Beginning in 2022, rising fuel and fertilizer prices further burdened sugarcane growers by increasing farm input and operational costs (Schmidhuber & Qiao, 2022), thereby threatening the financial viability of many smallholders.

National sugarcane productivity remains low, with average yields stagnating at approximately 57.36 TC ha^{-1}, well below the national target of 75 TC ha^{-1} (Paulino *et al.*, 2025). Yields in several low-performing block farms monitored by the Sugar Regulatory Administration (SRA) are even lower, averaging only 45–50 TC ha^{-1}. These local challenges reflect broader concerns in the global agriculture sector. Climate projections indicate that net crop water requirements may increase by up to 25% by 2080 despite improvements in irrigation efficiency (Fischer *et al.*, 2007; Nikolaou *et al.*, 2020). Changes in precipitation patterns, rising temperatures, and extended growing seasons will further intensify crop water demand. In addition, extreme weather events, such as irregular rainfall, heat extremes, and prolonged droughts, will continue to threaten food security and constrain the performance of both rainfed and irrigated production systems (Nikolaou *et al.*, 2020). These trends underscore the urgent need to adopt climate-resilient and resource-efficient water management strategies.

Efficient and precise irrigation is essential for sustaining sugarcane production, particularly in environments where water availability is increasingly constrained. In the Philippines, furrow irrigation remains the dominant practice; however, conventional scheduling often leads to over- or under-irrigation, resulting in low water productivity and inconsistent crop performance. To address these challenges, the Automated Furrow Irrigation System (AFIS) was developed as an integrated solution that combines crop modeling, irrigation management strategies, soil and crop sensors, and automated controls to support real-time, adaptive water delivery. Field evaluations by Espino *et al.* (2020) demonstrated that AFIS can substantially enhance production efficiency, with reported gains of up to 58% in cane yield and approximately 47% savings in irrigation water compared to traditional methods. Complementary evidence from Ahmed *et al.* (2023) further underscores that smart irrigation technologies can strengthen water management and contribute to progress toward multiple Sustainable Development Goals (SDGs).

Nutrient management is another critical factor influencing sugarcane productivity. Appropriate rates and timing of fertilizer application can enhance yield while minimizing costs. Padilla *et al.* (2020) reported that integrating Nutrio biofertilizer with only half of the recommended inorganic fertilizer rate increased cane and sugar yields by approximately 10–30%. Recent findings by Aguado-Santacruz *et al.* (2024) further demonstrate that systemic biofertilizers consistently improve both yield and harvest quality, underscoring their potential as a sustainable nutrient management strategy for sugarcane production.

Integrating AFIS with biofertilizer has the potential to improve nutrient uptake, enhance soil health, and reduce reliance on costly inorganic fertilizers. However, there is limited field-based evidence on the combined effects of these technologies under the diverse conditions of Philippine sugarcane block farms. Addressing key constraints, particularly inefficient water use, rising input costs, and low yield performance, is essential to strengthening the competitiveness of the Philippine sugar industry.

This study aims to enhance sugarcane productivity in low-yielding SRA block farms through pilot testing of the Auto Furrow Irrigation System (AFIS) integrated with biofertilizer during the 2023–2024 first cropping season. Specifically, the study seeks to: (1) determine whether the AFIS and biofertilizer package can increase cane yield (TC ha^{-1}) by at least 30% compared to conventional furrow irrigation and standard fertilization practices within the single cropping cycle; (2) evaluate improvements in water productivity (kg m^{-3}); and (3) assess the economic viability of AFIS and biofertilizer adoption, focusing on Benefit–Cost Ratio (BCR), Return on Investment (ROI), and Payback Period (PP) to support its potential scalability for wider adoption and future cropping cycles. Agronomic and yield parameters were statistically analyzed using analysis of variance (ANOVA) to determine treatment effects and validate performance differences between irrigation practices.

Materials and Methods

Experimental Site and Field Design

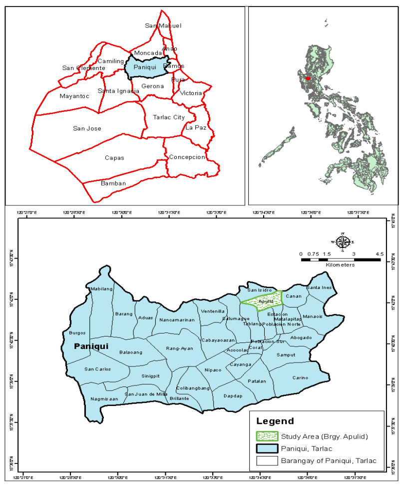


Figure 1. Location of the study area showing the geographical position of the experimental site within the region.

The study was conducted in Brgy. Apulid, Paniqui, Tarlac, Philippines (Figure 1). The experimental site was managed under the North Cluster Producers Cooperative (NCPC), which has an average sugarcane yield of 45–50 ton-cane per hectare (TC ha^{-1}). The field experiment was conducted from December 2023 to December 2024 on a one-hectare sugarcane farm (10,000 m^2) with a 1.5 m furrow spacing and a 1% bed slope.

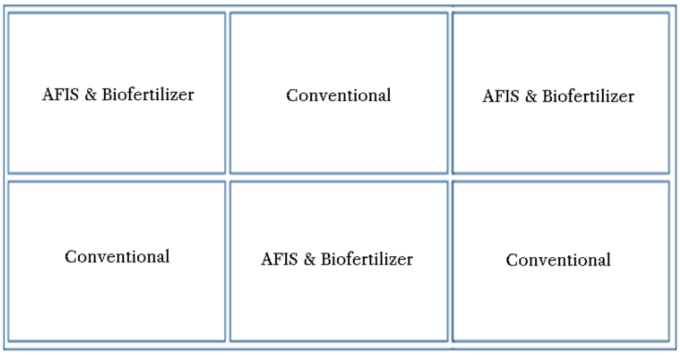


Figure 2. Field layout showing the arrangement of experimental blocks.

The experimental site was divided equally between two treatments: AFIS combined with a biofertilizer and conventional farming practices, with 5,000 m^2 allocated to each. A randomized complete block design (RCBD) with three replications was implemented, resulting in a total of six plots (Figure 2). Each plot measured 50 m × 33 m (1,650 m^2) and contained 22 furrows spaced at 1.5 m, with 1.5 m buffer strips maintained between plots to minimize edge effects. Blocks were defined based on field position to account for spatial heterogeneity in soil and slope gradients. Within each block, the two treatments were assigned randomly using the Statistical Tool for Agricultural Research (STAR). Because AFIS and the biofertilizer were implemented as a combined package in this pilot study, their individual effects could not be isolated, which represents a key limitation in interpreting treatment effects.

Fabrication of AFIS and System Layout

The selected site was characterized based on soil type, slope, infiltration rate, and other key physical soil properties, which were essential for designing the AFIS. Its components were fabricated based on the existing model developed by Espino *et al.* (2020). The field layout was structured into blocks, each containing furrows 50 meters in length. Soil moisture sensors were installed within each block to facilitate automated furrow irrigation (Figure 3). Furthermore, the master control unit (MCU) and field control unit (FCU) were strategically positioned near the sugarcane crops to ensure efficient signal transmission and seamless system operation.

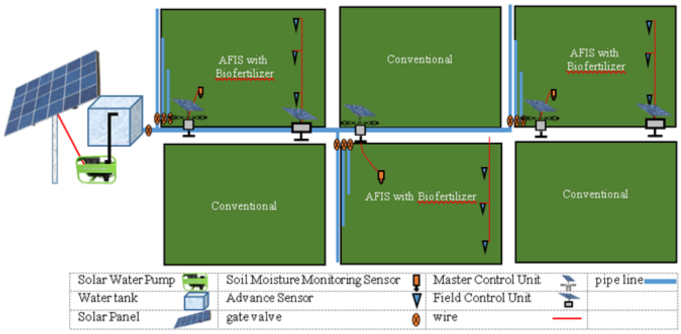


Figure 3. System layout illustrating the integration of key components used in the irrigation setup.

System Execution

The AFIS was designed with three operational modes: automated, semi-automated, and manual, to ensure continuous functionality under varying field conditions. In automated mode, the system independently initiates irrigation based on real-time soil moisture readings, activating the valves once the preset threshold is reached without requiring human intervention. In semi-automated mode, operators can manually trigger or stop irrigation by sending command messages to the controller, allowing remote management when automated decisions need verification. A manual mode is also integrated via on-site physical switches that enable direct activation or deactivation of valves when automated or semi-automated functions are disrupted due to technical issues. Soil moisture sensors were programmed to transmit data to the cloud every hour and to send SMS messages every six hours, providing continuous monitoring and supporting timely decision-making across all operational modes.

Calibration and Placement of Soil Moisture Sensor

Table 1. Calibration result of soil moisture sensors, showing calibration curve and sensor accuracy.

Irrigation Method	Block	Sensor	Calibration Curve	R^2
AFIS	Block 1	S1	y = 2.8787x + 16.382	0.96
	Block 2	S2	y = 2.9463x + 19.990	0.95
	Block 2	S3	y = 3.1970x + 19.294	0.96

To ensure accurate performance of the soil moisture sensors under field conditions, a thorough calibration process was first conducted in the laboratory. Soil samples were collected directly from the study site to replicate field conditions closely and were selected from representative sections of the experimental area. The samples were air-dried, sieved to remove stones, plant residues, and other foreign materials, and then oven-dried at 105°C until a constant weight was achieved, ensuring complete moisture removal. The dry soil was placed in a container large enough to provide proper contact between the sensor probe and the soil. Water was added incrementally to simulate a full range of moisture conditions, from dry to fully saturated, and sensor readings were recorded at each stage. After each reading, the samples were weighed and returned to the oven to determine the actual moisture content by subtracting the wet weight and dry weight. The collected data were plotted and subjected to linear regression to generate calibration curves. The derived calibration equations (Table 1) were subsequently uploaded to the AFIS microcontroller, enabling precise soil moisture measurement for real-time monitoring and adaptive irrigation management. Soil moisture in each experimental plot was continuously monitored using calibrated capacitance-type sensors installed at a depth of 30 cm to represent the principal active root zone during the early and grand growth stages of sugarcane.

Planting

Mechanized planting equipment was utilized to optimize the planting process. This equipment was specifically designed to create furrows in the soil, ensuring precise placement of sugarcane setts in a horizontal orientation. The PHIL 2006-2289 sugarcane variety was planted in the experimental area at an estimated density of 45,000 setts.

Soil Analysis

Table 2. Chemical properties of soil at the study site, including pH, organic matter, P,K, Ca and Mg.

Soil Texture	pH	OM %	PPM			Mg
			P	K	Ca	
Silt loam	6.05	1.7	182	113	2214	185

Soil analysis was conducted in February 2024, and the collected samples were submitted to the Soil Laboratory of the Sugar Regulatory Administration-Luzon Agricultural Research and Extension Center (SRA-LAREC) for analysis. The results of the laboratory analysis are summarized in Table 2.

Fertilizer Recommendation

Table 3. Recommended fertilizer application rates (bags ha^{-1}) for sugarcane showing split applications of nitrogen (46-0-0) and potassium (0-0-60).

Fertilizer Recommendation, bags ha^{-1}			
First Dose		Second Dose	
46-0-0	0-0-60	46-0-0	0-0-60
3.5	2.5	3.5	2.25

Fertilizer was applied in two split doses to optimize nutrient uptake by the sugarcane crop. The first application consisted of 3.5 bags of urea (46-0-0) and 2.5 bags of potassium (0-0-60). The second application included an additional 3.5 bags of urea and 2.25 bags of potassium, ensuring a balanced nutrient supply throughout the crop's critical growth stages (Table 3).

Inorganic Fertilizer and Nutrio® Biofertilizer Application

Soil analysis was conducted to determine the appropriate fertilizer recommendations. In the AFIS treatment, only half the recommended inorganic fertilizer rate was applied to ensure agronomic parity while incorporating biofertilizer, whereas the conventional treatment received the full recommended fertilizer rate. Inorganic fertilizers were used in two split doses at 2 and 4 months after planting to optimize nutrient availability during critical growth stages. The biofertilizer, which contains endophytic bacteria, a nitrogen-fixing organism, was applied one week after each inorganic fertilizer application at a rate of 20 sachets per hectare (SERD Personnel Editor, 2025). To ensure compatibility, the biofertilizer was applied separately from inorganic fertilizers, and the recommended application interval was strictly adhered to to prevent any antagonistic interactions.

Agronomic Parameters

Stalk height was measured every 15 days to monitor growth trends. In each block, 20 samples were randomly selected for measurement. Stalk height was measured from the base of the plant to the last visible dewlap using a steel tape, ensuring accurate and consistent data collection.

Tiller count data were collected monthly, 4 to 7 months after planting (MAP). A total of 20 linear meters per block was assessed. The tiller count at seven MAP served as an indicator of the number of millable stalks at harvest, providing valuable insights into crop productivity and growth performance.

Stalk diameter was measured at the bottom, middle, and top sections of the sugarcane stalk during harvest using a Vernier caliper to ensure precise and consistent data collection.

Water Productivity

Water productivity (WP) is the amount of crop yield produced per unit of water used and was calculated as the ratio of crop yield to the total volume of water applied, including both irrigation and effective rainfall. This metric was used to evaluate the efficiency of water use under the AFIS combined with biofertilizer treatment compared with conventional practice.

Irrigation

To ensure a high germination rate of the cane setts, initial irrigation was applied one week after planting to provide sufficient soil moisture for germination. To prevent water stress, a 50% management allowable depletion (MAD) was adopted, a standard approach widely used in irrigation planning (British Columbia Ministry of Agriculture, 2015). In the AFIS treatment, irrigation was automatically regulated based on real-time soil moisture readings, with the system programmed to activate once the sensor detected 50% MAD- equivalent to a 19% moisture content in the study area- which serves as the threshold for optimal plant growth. In contrast, irrigation under conventional practice followed the standard method commonly used by the sugarcane planters in the locality.

Effective Rainfall

Effective rainfall (ER) was estimated according to FAO (2025) guidelines based on monthly rainfall data. Monthly rainfall (P) was converted to ER using the following FAO-recommended equations: For $P < 250$ mm per month, $ER = P \times (125 - 0.2P)/125$; For $P \geq 250$ mm per month, $ER = 125 + 0.1P$.

Statistical Analysis

The results obtained in this study were statistically analyzed using the Statistical Tool for Agricultural Research (STAR) software. An analysis of variance following a randomized complete block design (RCBD) was performed to evaluate the effects of the irrigation management strategies on the agronomic performance, yield, sugar juice content, and sugar production. The normality of residuals was verified using the Shapiro–Wilk test. Treatment means were compared using the Least Significant Difference (LSD) test at the 5% level of significance to determine statistically significant differences among treatments.

Economic Viability

The economic viability of the Automated Furrow Irrigation System (AFIS) integrated with a biofertilizer was evaluated using cost–benefit analysis conducted over one full sugarcane cropping season. This assessment covered machinery, labor, and operational inputs. The primary economic indicators examined were Return on Investment (ROI), Payback Period (PP), and Benefit–Cost Ratio (BCR), following standard procedures in agricultural project analysis (Gittinger, 1982; Kay *et al.*, 2016).

The total annual cost (TAC) for each production system was calculated as the sum of annual operating costs (AOC) and annual fixed costs (AFC):

$$TAC = AOC + AFC$$

The gross return (GR) was determined by multiplying the total cane yield by the prevailing market price:

$$GR = \text{Total Cane Yield (Lkg ha}^{-1}\text{)} \times \text{Market Price (PHP Lkg}^{-1}\text{)}$$

Net financial return (NR) was calculated as:

$$=NR = GR - TAC$$

The Benefit–Cost Ratio (BCR) is a financial metric used to evaluate the economic viability of a project investment. It is determined using the ratio of the present value of benefits (PVB) to the present value of costs (PVC), following the standard cost–benefit framework of Shively (2012) and Boardman *et al.* (2018):

$$BCR = \text{Present Value of Benefits } (PV_B) / \text{Present Value of Costs } (PV_C)$$

Return on Investment (ROI) is a financial metric used to measure profitability. It is computed using the formula:

$$ROI\ (\%) = NR/TAC \times 100$$

Investment recovery was evaluated using the Payback Period (PP), which estimates the number of years required for the project to recover its initial investment (Gittinger, 1982; Blank & Tarquin, 2012):

$$PP = \text{Initial Investment}/\text{Annual Net Return}$$

This analytical framework enabled a rigorous comparison between AFIS combined with biofertilizer application and the conventional furrow irrigation system. The results provide clear economic benchmarks that can support decision-making and potential large-scale adoption by sugarcane growers and policymakers.

Ethics and Compliance

Permission to conduct the field trial was obtained from the participating farmers' cooperative through a Collaborative Research Agreement (CRA), and a Memorandum of Agreement (MOA) with the Sugar Regulatory Administration (SRA) was settled, ensuring institutional support, shared responsibility, and technical cooperation for the AFIS initiative. No human or animal subjects were involved, and all activities followed institutional and national guidelines for responsible agricultural research. Telemetry and sensor data did not capture personal information. The authors declare no conflicts of interest related to the biofertilizer manufacturer or AFIS suppliers. All data generated or analyzed are available from the corresponding author upon reasonable request. The study was conducted responsibly, ensuring originality, proper citation, appropriate authorship, and no duplicate submission.

Results and Discussion

System Performance of AFIS

Observed Data and Data Transmission

The soil moisture sensors transmitted a total of 9376 out of 10,800, or 86.81%, of the expected raw data points from the start of operation. Furthermore, 13.19% (1424) data points were not transmitted due to technical and signal issues at the sites. For field-advanced sensors, the speed of data transmission between the sensors and the AFIS microcontroller and vice versa ranged from 100 to 300 milliseconds, depending on the distance between the sensors and the microcontroller. The field advance sensor successfully transmitted all of the signals needed to close the gates.

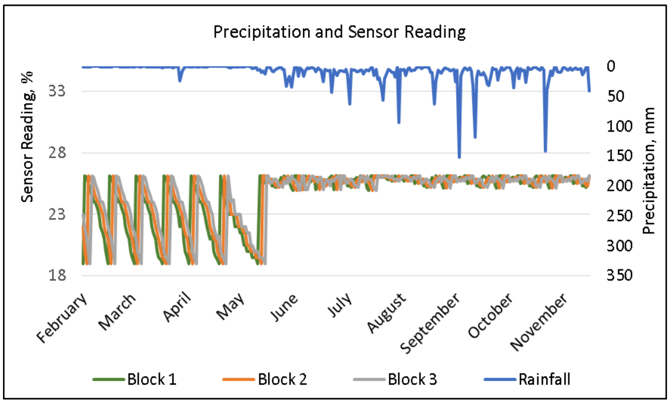


Figure 4. Precipitation and sensor readings illustrating the relationship between the daily rainfall events and soil moisture sensor reading throughout the monitoring period.

For the opening and closing of all three (3) valves, it took 16 seconds each, serving as a gate while the sensors were connected to the AFIS microcontroller. Gate opening was triggered when soil moisture was below 50% MAD, and the advancing water had reached the field advance sensor location. The soil moisture sensor that reads below 50% MAD triggers the gate to open. Figure 4 shows the transmitted data from soil moisture sensors and precipitation that occurred during the study. The precipitation data were obtained from the NASA POWER Data Access Viewer (NASA, 2024), a platform that provides free climate and solar data derived from satellite-based models. This resource is specifically designed for agricultural research, offering reliable, comprehensive environmental datasets.

Observed Upload and Receive Response Time

The system achieved an upload efficiency of 86.5% and a receive efficiency of 85.6%, indicating reliable GSM communication for timely sensor data transmission and control command reception. This level of performance ensures that irrigation decisions at the block level are executed promptly, supporting precise water management. According to wireless network performance benchmarks (Jawad *et al.*, 2017), a packet delivery success rate of 85% or higher is considered highly efficient for IoT applications, especially in precision agriculture. A delivery success rate below 75% is considered unreliable because it may result in delayed or lost irrigation commands, potentially affecting crop health.

Irrigation water applied, m^3 ha^{-1}

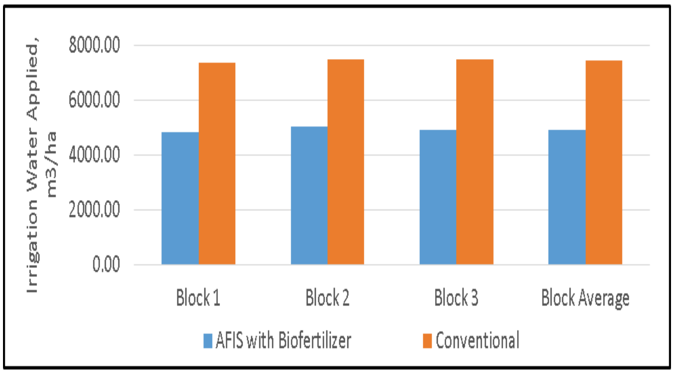


Figure 5. Irrigation water applied (m^3 ha^{-1}) across the different treatments during the study period.

Table 4. Least Significant Difference (LSD) test result (α = 0.05) for irrigation water applied (m^3 ha^{-1}), showing significant differences among treatments.

Treatment	Mean	Group
AFIS w/ biofertilizer	4,914.1	a
Conventional	7,449.6	b

Note: Means with the same letter are not significantly different.

The volume of irrigation water applied per block under both the AFIS and conventional irrigation methods is presented in Figure 5. Results demonstrate that AFIS significantly reduced water consumption, with an average application of 4,914.1 m^3 ha^{-1}, compared with 7,449.6 m^3 ha^{-1}

under the conventional method, equivalent to a 34% decrease. This substantial reduction highlights the efficiency of AFIS in conserving water while maintaining crop productivity, making it a sustainable irrigation strategy for sugarcane farming, especially in water-scarce regions. Statistical analysis (Table 4) further showed that the amount of water applied in sugarcane blocks was significantly influenced by the irrigation treatments at 5% level of significance.

Effective Rainfall

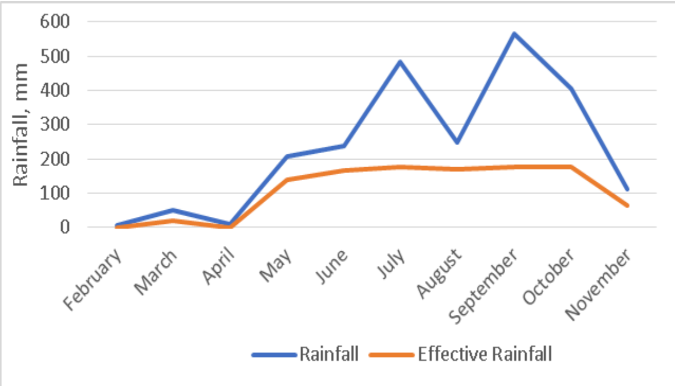


Figure 6. Actual and effective rainfall (mm) recorded during the study period.

Figure 6 shows the monthly distribution of rainfall and effective rainfall (ER) from February to November 2024. Total rainfall varied widely across months, with very low values early in the season and a sharp peak in September. ER remained consistently lower than total rainfall, representing only the portion retained in the soil after runoff and deep percolation losses. The largest gaps between rainfall and ER occurred during high-rainfall months, indicating that much of the precipitation did not contribute to usable soil moisture.

Agronomic Data and Analysis

Agronomic parameters and corresponding statistical analyses on stalk height, millable tillers, and stalk diameter are summarized in Tables 5 and 6, respectively. Sugarcane grown under AFIS reached an average height of 362.5 cm, significantly taller than the 327.9 cm recorded under conventional practice, with differences significant at the 5% significance level. Similarly, Misra *et al.* (2020) emphasized that water stress reduces stalk height and diameter by 18.28% and 7.5%, respectively, thereby affecting overall plant development.

The AFIS-biofertilizer treatment also yielded a higher number of millable tillers per linear meter (lm) (15–17) compared with the conventional method (14–15). On average, AFIS-biofertilizer generated 16.3 millable tillers, exceeding the 14.3 millable tillers recorded in the conventional plot. Although this difference was not statistically significant at the 5% level, the numerical increase suggests a potential agronomic advantage that could improve yield performance.

Stalk diameter was likewise improved under the AFIS-biofertilizer treatment, averaging 30.9 mm compared with 26.5 mm under conventional practice. This difference was statistically significant at the 5% level, underscoring the benefits of optimized water management combined with biofertilizer application in promoting stalk development. Similar trends were reported by Gu *et al.* (2017), who found that adequate soil moisture enhances cellular expansion and results in thicker stalk formation. In addition, Schultz *et al.* (2014) documented a 13.5% net increase in sugarcane stalk yield when nitrogen-fixing biofertilizers were applied, further demonstrating the positive impact of biologically enhanced nutrient availability on vegetative growth. These findings collectively support the effectiveness of integrating automated irrigation with biofertilizers to improve stalk structure and overall crop productivity.

Table 5. Measured agronomic parameters of sugarcane, including plant height (cm), millable tiller number (pcs ha $^{-1}$), and stalk diameter (mm).

Agronomic Data	Replication	AFIS w/ biofertilizer	Conventional
Stalk height, cm	Block 1	353.2	321.8
	Block 2	373.2	329.4
	Block 3	361.2	332.4
	Block average	362.5	327.9
Millable Tiller Count, pcs lm^{-1}	Block 1	15	14
	Block 2	17	15
	Block 3	17	14
	Block average	16.3	14.3
Stalk diameter, mm	Block 1	31.6	25.0
	Block 2	30.3	26.2
	Block 3	30.9	28.1
	Block average	30.9	26.5

Table 6. Least Significant Difference (LSD) test results (α = 0.05, n=60) for sugarcane stalk height (cm), millable tiller number (pcs lm $^{-1}$), and stalk diameter (mm), showing significant differences among treatments.

Agronomic Data	Treatment	Mean	Group
Stalk height, cm	AFIS w/ biofertilizer	362.5	a
	Conventional	327.9	b
Millable tiller, pcs lm^{-1}	AFIS w/ biofertilizer	16.3	a
	Conventional	14.3	a
Stalk Diameter, mm	AFIS w/ biofertilizer	30.9	a
	Conventional	26.4	b

Note: Means with the same letter are not significantly different.

Yield per hectare, TC ha^{-1}

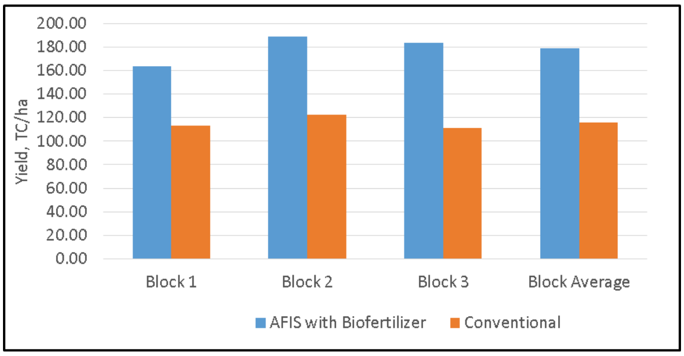


Figure 7. Yield per hectare (TC ha $^{-1}$) of sugarcane under different irrigation and fertilizer treatments.

Tons of cane per hectare is a key profitability indicator in sugarcane production. This study found that AFIS-biofertilizer blocks yielded 54.7% more than conventionally irrigated blocks, ranging from 163 to 188 TC ha^{-1}, compared to 111 to 122 TC ha^{-1} in conventional systems (Figure 7).

Table 7. Analysis of variance (ANOVA) for sugarcane yield (TC ha^{-1}) under different irrigation treatments, indicating significant differences among treatments at α = 0.05.

Source	DF	Sum of Square	Mean Square	F Value	Pr (>F)
Block	2	293.4220	146.7110	2.33	0.3003
Treatment	1	5990.7280	5990.7280	95.15	0.0103
Error	2	125.9240	62.9620		
Total	5	6410.0741			

The analysis of variance (Table 7) revealed a significant effect of irrigation treatment on sugarcane yield, as indicated by the treatment p-value of 0.0103, which is below the 0.05 significance threshold. This demonstrates that the irrigation method used had a measurable influence on crop performance. In contrast, the block effect was not significant (p = 0.3003), suggesting that field variability among blocks did not substantially contribute to yield differences.

Table 8. Least Significant Difference (LSD) test results (α = 0.05, n=60) for sugarcane yield (TC ha^{-1}), showing significant differences among treatments.

Treatment	Mean	Group
AFIS with biofertilizer	178	a
Conventional practice	115	b

Note: Means with the same letter are not significantly different.

The LSD test (Table 8) further confirmed these results. Sugarcane irrigated using AFIS-biofertilizer achieved a markedly higher mean yield (178 TC ha^{-1}) compared with the conventional practice (115 TC ha^{-1}). The separation of means into distinct groups (a and b) indicates that the AFIS-biofertilizer combination significantly outperformed the conventional method.

These results are consistent with previous literature. Padilla *et al.* (2020) reported a 10–30% increase in cane and sugar yields with the application of biofertilizers, along with a 50% reduction in inorganic fertilizer requirements. Several studies have also emphasized the sensitivity of sugarcane to water stress. Gentile *et al.* (2015) documented a 9.1% reduction in cane yield under drought conditions, underscoring the crop's dependence on adequate soil moisture. Similarly, Aguado-Santacruz *et al.* (2024) reported a 25–35% increase in sugarcane yield following the use of biofertilizers, demonstrating their positive effect on crop growth and nutrient uptake. Furthermore, Wu *et al.* (2022) highlighted that optimized irrigation and nutrient management are essential for achieving maximum sugarcane productivity.

These results align with previous literature. Simarmata (2024) reported a 20–40% increase in crop yields with the use of biofertilizer, along with a reduction in inorganic fertilizer requirements. Studies also highlight sugarcane's sensitivity to water stress: Gentile *et al.* (2015) documented a 9.1% yield reduction under drought conditions, while Wu *et al.* (2022) emphasized that optimized irrigation and nutrient management are critical for maximizing sugarcane productivity.

Water Productivity, kg m^{-3}

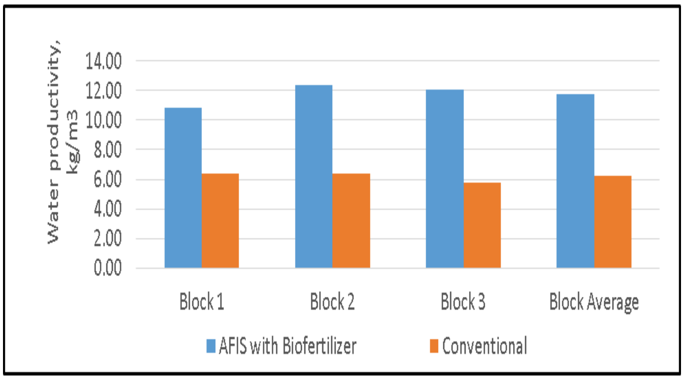


Figure 8. Water productivity (kg m^{-3}) of sugarcane under different irrigation and fertilizer treatments.

Water productivity results showed that sugarcane blocks irrigated under AFIS achieved substantially higher water productivity, ranging from 10.9 to 12.4 kg m^{-3}. In contrast, those irrigated using the conventional furrow method recorded lower values of 5.8 to 6.4 kg m^{-3} (Figure 8). This corresponds to an 89.5% increase in water productivity under AFIS, demonstrating the system's superior capability to optimize water use.

Table 9. Analysis of variance (ANOVA) for water productivity under different irrigation treatments, indicating significant differences among treatments at $\alpha = 0.05$.

Source	DF	Sum of Square	Mean Square	F Value	Pr (>F)
Block	2	0.5602	0.2801	0.60	0.6247
Treatment	1	46.3148	46.3148	99.32	0.0099
Error	2	0.9326	0.4663		
Total	5	47.8077			

The analysis of variance (Table 9) revealed a highly significant effect of irrigation treatment on sugar yield (DF=1, p = 0.0099), indicating that irrigation methods had a substantial influence on sugarcane performance. In contrast, block effects were not significant (DF=1, p = 0.6247), suggesting that field variability among blocks did not meaningfully affect sugar yield.

Table 10. Least Significant Difference (LSD) test result ($\alpha = 0.05$) for water productivity (kg m^{-3}) of sugarcane under different irrigation and fertilizer treatments, showing significant differences among treatments.

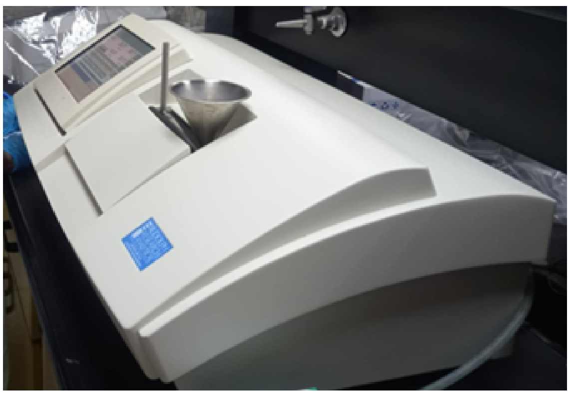
Source	Mean	Group
AFIS with biofertilizer	118	a
Conventional practice	6.2	b

Note: Means with the same letter are not significantly different.

The LSD test (Table 10) further confirmed the advantage of AFIS with biofertilizer. Sugarcane irrigated under AFIS produced an average sugar yield of 11.8 kg m^{-3}, nearly double that of 6.2 kg m^{-3} under conventional practice. The means were assigned to separate groups (a and b), indicating a statistically significant difference between treatments.

These results are consistent with previous findings. Quitos (2025) observed a 54% increase in water productivity using a sensor-based furrow irrigation system, while Espino *et al.* (2020) reported a 132% improvement. Such comparisons reinforce the effectiveness of automated irrigation technologies in enhancing water-use efficiency.

Sugarcane Juice Analysis



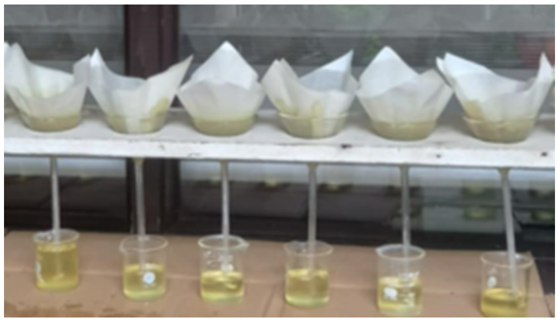


Figure 9. Sugar juice analysis showing laboratory measurement of juice quality parameters. (Up) Polarimeter used to determine soluble solids and sucrose content. (Down) Filtration and collection of juice samples for laboratory analysis, illustrating the preparation process for measurement of sucrose concentration and juice purity.

After collecting the data on yield parameters, sugarcane stalk samples from the field experimental area were taken to SRA-LAREC for juice extraction and further analysis (Figure 9).

Table 11. Sugar recovery (Lkg TC -1) and number of bags produced per hectare (Lkg ha^{-1}) under experimental conditions, showing differences among treatments.

Parameters	Replication	AFIS w/ Nutrio	Conventional
Sugar Recovery, Lkg TC^{-1}	Block 1	1.84	1.60
	Block 2	1.84	1.44
	Block 3	1.89	1.71
	Block average	**1.86**	**1.58**
Bags of sugar produced, Lkg ha^{-1}	Block 1	301.41	180.89
	Block 2	347.23	206.87
	Block 3	347.02	155.50
	Block average	**331.88**	**181.09**

The sugar recovery from harvested sugarcane stalks, expressed as 50-kg bags per ton of cane (Lkg TC^{-1}), together with the total number of bags produced, is presented in Table 11. Sugarcane cultivated under AFIS with biofertilizer achieved an average sugar recovery of 1.9 Lkg TC^{-1}, which was numerically higher than the 1.6 Lkg TC^{-1} recorded under conventional practice. This improvement may be attributed to better water management and enhanced nutrient availability.

Table 12. Analysis of variance (ANOVA) for sugarcane recovery (Lkg TC^{-1}) and number of bags produced per hectare (Lkg ha^{-1}) under different Irrigation treatments at $\alpha = 0.05$.

Parameters	Source	DF	Sum of Square	Mean Square	F Value	Pr (>F)
Sugar recovery, Lkg TC^{-1}	Block	2	0.0147	0.0074	0.47	0.6786
	Treatment	1	0.1291	0.1291	8.32	0.1021
	Error	2	0.0310	0.0155		
	Total	5	0.1748			

Bags of sugar produced, Lkg ha^{-1}	Block	2	1370.7641	6853821	1.02	0.4947
	Treatment	1	34110.9600	34110.9600	50.84	0.0191
	Error	2	1341.9952	670.9976		
	Total	5	36823.7193			

The analysis of variance for sugar recovery (Lkg TC^{-1}) (Table 12) indicated no significant difference between irrigation treatments (DF=1, p = 0.1021), suggesting that AFIS and conventional furrow irrigation produced comparable sugar recovery values. Block effects were likewise non-significant (DF=2, p = 0.6786), indicating minimal field variability for this parameter. Though the LSD test (Table 13) showed a slightly higher mean sugar recovery under AFIS with biofertilizer. The literature indicates that drought stress during critical growth stages—such as tillering and stem elongation—can adversely affect sugarcane productivity by reducing leaf development, stem elongation, and ultimately green leaf area, which plays a key role in sucrose accumulation (Hussain *et al.*, 2018; Hoang *et al.*, 2019).

Table 13. Least Significant Difference (LSD) test result for sugarcane recovery (TC ha^{-1}) and sugar produced (Lkg ha^{-1}) under different irrigation treatments, showing significant differences among treatments in terms of bags of sugar produced.

Parameters	Source	Mean	Group
Sugar recovery, Lkg TC^{-1}	AFIS with biofertilizer	1.9	a
	Conventional practice	1.6	a
Bags of sugar produced, Lkg ha^{-1}	AFIS with biofertilizer	331.9	a
	Conventional practice	181.1	b

Note: Means with the same letter are not significantly different.

Projected sugar yield per hectare was estimated by multiplying total cane yield (TC ha^{-1}) by sugar recovery (Lkg TC^{-1}). Sugarcane blocks irrigated with AFIS produced between 301.4 and 347.2 Lkg ha^{-1}, nearly double the 155.5-180.9 Lkg ha^{-1} recorded under conventional practice. The irrigation treatment had a significant effect on total sugar produced, as reflected by the p-value of 0.0191 (Table 12). The AFIS-biofertilizer treatment attained a substantially higher sugar yield compared with conventional practice, and these means were classified into statistically distinct groups by the LSD test (Table 13).

Although AFIS with biofertilizer did not significantly increase sugar recovery, it markedly enhanced total sugar production per hectare. These results demonstrate that AFIS, when combined with biofertilizer, improves sugar output primarily by increasing cane yield rather than by altering juice quality. Overall, the findings highlight the potential of automated irrigation systems to strengthen sugarcane productivity under field conditions.

Summary of Key Agronomic and Production Outcomes

Table 14. Summary of key agronomic and production outcomes, including plant growth, yield, and sugar recovery, under the experimental conditions.

Treatment	Agronomic Data			Irrigation, m^3	Yield, TC ha^{-1}	Water productivity kg m^{-}	Sugar recovery, Lkg TC^{-1}	Bags of sugar produced, Lkg ha^{-1}
	Stalk height, cm	Millable tiller, pcs lm^{-1}	Stalk diameter, mm					
AFIS with biofertilizer	362.5	16	30.9	4914.1	178.7	11.8	1.9	331.9
Conventional	327.9	14	26.5	7449.6	115.5	6.2	1.6	181.1

The consolidated results (Table 14) show clear advantages of the AFIS with biofertilizer over conventional furrow irrigation. AFIS produced taller stalks, more millable tillers, and larger stalk diameters, resulting in a higher cane yield (178.7 vs. 115.5 TC ha^{-1}). Despite using less irrigation water, AFIS achieved nearly double the water productivity of the conventional system. Higher sugar recovery under AFIS also translated into a greater number of 50-kg sugar bags per hectare.

Economic Analysis

The economic analysis considered several key assumptions to ensure a realistic estimation of investment performance across project sites. These included prevailing market prices for pumps and solar panels, drilling and installation costs, and the capital required for deploying the AFIS infrastructure. Asset lifetime, particularly for pumps and photovoltaic components, was also factored into the analysis to account for system depreciation and replacement cycles. In addition, site-specific variations in annual interest rates and financing conditions were considered, recognizing that these parameters can influence the overall economic feasibility of irrigation technologies. By integrating these costs and financial assumptions, the analysis provides a more robust evaluation of the long-term economic viability of AFIS under diverse field and investment conditions.

Table 15. Economic analysis of AFIS with biofertilizer and conventional practice, including cost, returns, and benefit-cost ratios (BCR) under the experimental conditions.

Particulars	Conventional	AFIS
2 Pumps and Prime movers Cost, 20 yrs. (1 pump/10 year)	87,000.00	
Solar pump, panel, and accessories (pipelines, ball valve, water tank), 20 yrs.		430,415.00
Drilling Cost	20,000.00	20,000.00
Investment for AFIS (automation, actuator)		100,000.00
Annual Depreciation of pump and prime mover and solar pump	8265.00	17216.60
Annual Depreciation, Drilling	1,900.00	1,900.00
Annual Depreciation for AFIS		4,000.00
Interest (12% annually)	8,700.00	39,696.88
Total fixed cost	18,865.00	62,813.48
Cost of pumping/m^3	1.50	1.50
Volume of water supplied, m^3	7,449.57	4,914.11
Pump operation and Maintenance	11,174.36	7,371.17
labor cost for irrigation	26,000.00	10,000.00
Cost of Sugarcane Production (cane setts, lease rate, land preparation, fertilizer, biofertilizer, planting, harvesting)	141,772	131,772
Cane yield, tc/ha	115.51	178.71
Lkg/tc	1.56	1.86
Bags/ha	179.93	332.38
Net bags of sugar (65% of total)	116.95	216.05
Selling price Php/bag	2,300.00	2,300.00
Gross cost of production/ha	197,811.36	211,956.65
Gross return	268,985.00	496,915.00
Net total income	71,173.64	284,958.35
Benefit Cost Ratio	1.36	2.34
ROI, %	35.98	134.44
Payback Period, yrs.	1.50	1.93

All costs are in Philippine Pesos (₱).
Asset lifetimes: Pumps, prime movers, solar pump system, and AFIS automation equipment – 20 years
Discount / interest rate: 12% annually.
Selling price of sugar: ₱2,300 per bag.
Labor, fertilizer (including Biofertilizer), planting, and harvesting costs are included in total production cost.

The economic analysis (Table 15) revealed that sugarcane production using the AFIS and biofertilizer incurred higher initial costs than the conventional method due to additional materials and installation expenses. However, cost analysis demonstrated that the AFIS is a cost-effective technology. It showed significantly improved profitability, achieving a benefit-cost ratio (BCR) of 2.34 and a return on investment (ROI) of 134.4%, compared to a 1.4 BCR and 36% ROI under conventional irrigation. Despite a higher initial investment, AFIS had a payback period of 1.9 years, which remains economically feasible compared to 1.5 years for the conventional practice.

Automated irrigation systems have shown strong potential for improving the economic performance of sugarcane production. Thompson and McDonnell (2016) reported that investments in irrigation automation can generate substantial financial gains, yielding an annualized return of approximately USD 3,000 and enabling producers to recover their initial capital investment in just over two years. Similarly, Espino *et al.* (2020) found that automated furrow irrigation systems achieved a benefit–cost ratio of 2.88, markedly higher than the 1.45 obtained under conventional furrow irrigation. These findings underscore the economic advantages of adopting automated irrigation technologies, particularly in improving profitability and reducing long-term operational costs in sugarcane farming.

Conclusion

The study demonstrated that the automated furrow irrigation system (AFIS) combined with biofertilizer significantly enhanced sugarcane production performance compared with conventional furrow irrigation. AFIS-treated plots attained substantially higher cane yield (178.71 vs. 115.51 TC ha $^{-1}$), greater sugar output (331.89 vs. 181.09 Lkg ha $^{-1}$), and markedly improved water productivity (11.77 vs. 6.21 kg m^{-3}), indicating strong gains in water-use efficiency. Improvements in agronomic characteristics—including stalk height, millable tillers, and stalk diameter—further supported the positive effects of the integrated intervention. Economic analysis confirmed the system's viability, reflected by a benefit–cost ratio of 2.34, a return on investment of 134.44%, and a payback period of 1.93 years.

These findings were derived from a single-site, single-season pilot study, and the observed outcomes reflect the combined effects of AFIS and the biofertilizer, as their individual contributions were not independently quantified. Successful field deployment of the system will require farmer training, regular maintenance, and careful consideration of cost sensitivity (±10–20%), along with operational risks such as GSM signal interruptions and sensor drift. Environmental benefits—including reduced water use, lower runoff potential, improved soil health associated with biofertilizer application, and decreased energy demand resulting from more precise irrigation scheduling—further underscore the value of the integrated system in promoting resilient and sustainable irrigation management.

Future research should focus on multi-site, multi-season evaluations across diverse soil types and climatic conditions to strengthen the robustness and generalizability of the findings. Factorial experimental designs are recommended to isolate the individual and interactive effects of AFIS and biofertilizer. Comparative assessments against other irrigation technologies, together with studies on telemetry reliability and farmer adoption dynamics, will be essential to guide scaling strategies and support the wider adoption of automated irrigation solutions in Philippine sugarcane farms.

The positive results from this study signify a strong foundation for future expansion. With continued validation and refinement, AFIS and biofertilizer have the potential to become key technologies in advancing sustainable, high-efficiency sugarcane production across the Philippines.

Ethical Statement

The study was conducted in accordance with established ethical standards for agricultural field research. Informed consent was obtained from all farmer-cooperators and participating personnel prior to field implementation. Confidentiality of personal, farm, and location-specific information was strictly maintained, and all data were used solely for research purposes. The study was designed and implemented to minimize any physical, environmental, or economic risks, and no harm resulted from the installation or operation of the irrigation system. All field activities complied with institutional guidelines, local regulations, and community practices. After completion of the study, data were securely stored and accessed only by authorized personnel, and all research materials were managed responsibly to avoid any residual impacts.

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

MMC: Conceptualization, Project administrator; Supervision, funding acquisition, Writing (Original draft), Methodology, and Writing-Review and Editing; **EVR:** Investigation, Formal Analysis, and Visualization; **PJPS:** Supervision, Writing-Review and Editing; **APM**: Investigation and Visualization; **JBC**: Investigation and Visualization; **GMCC**: Data Curation and editing; **FDCM**: Data Curation and editing; **ANE**: Supervision; **JPCS**: Writing-Review and Editing; **RADL**: Writing-Review and Editing; **LCO**: Supervision, Writing-Review and Editing.

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