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Article

Improving the productivity and competitiveness of banana plantations through efficient irrigation systems

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Abstract: The Urabá region, known for its banana production, faces significant challenges due to seasonal droughts that affect crop productivity. The implementation of innovative technologies, such as efficient irrigation systems, is presented as a potential solution to improve the sustainability and profitability of plantations. This study validates the implementation of an irrigation system in a banana (*Musa spp.*) plantation located in the region of Urabá, in order to meet the water needs of the crop during periods of drought. A case study was carried out in a banana plantation in the region of Urabá, considering the maximum and minimum monthly losses due to drought, and a random sample was used to measure the weight before and after the implementation of the irrigation system, in order to carry out an economic analysis. The study shows that the implementation of a sprinkler irrigation system increases the average weight of the harvested bunches by 20%, which is reflected in an annual increase of 30.3% of exported boxes, obtaining satisfactory results in terms of internal rate of return, cost-benefit ratio and return on investment. The implementation of irrigation systems makes it possible to increase competitiveness in international markets, especially in regions such as Urabá, where the use of these technologies is still incipient.

Keywords: banana crop; irrigation system; productivity; competitiveness; economic analysis; financial viability

1. Introduction

The region of Urabá in Colombia is known as "the best corner of America" because of its privileged geographical location, which makes it an ideal place for banana production and marketing, with direct access to seaports. Urabá has 35,000 hectares of banana plantations, and this agribusiness generates approximately 25,000 direct jobs and 75,000 indirect jobs, bringing economic benefits to a region that has historically suffered from violence and inequality. However, this region is experiencing the serious consequences of climate change, with long summers and heavy rainfall, which has a direct impact on crop yields and export competitiveness in relation to other banana-exporting countries such as Ecuador, Guatemala or Costa Rica.

According to projections, by the end of the 21st century, the temperature in the Urabá region will increase between 2.61 and 2.7 degrees Celsius, and annual rainfall will increase between 10% and 20% (Bolaños and Betancur, 2018). This increase in annual rainfall will be concentrated in the winter seasons, so it will not mean hydric relief for plantations in the summer seasons, on the contrary, it will stress the crops in the rainy season due to excess water. Likewise, climate change would alter rainfall patterns, causing severe droughts that would significantly affect banana production cycles and crop yields (Olivares et al., 2021; Toro-Trujillo et al., 2016).

The Musa Paradisiaca crop, which refers to the plants that produce bananas (*Musa spp.*), requires deep soils with pH values that must be between slightly acidic and slightly alkaline, which typically corresponds to a pH range of approximately 5.5 to 7.5, with a structure that allows good drainage and with a low presence of calcium carbonates. Similarly, the banana crop is extremely demanding for factors involved in the production system, such as soil water availability, nutrition and disease control, highlighting the prompt physiological response of the plant under drought stress (Souza et al., 2021). In a scenario of water scarcity, the roots of Musa Paradisiaca send signals to close the stomata in order to keep the plant hydrated, which has a negative impact on fruit yield and crop productivity due to the loss of carbon in the exchange of gases with the external environment (Surendar et al., 2013).

In this sense, drought conditions in banana crops cause a weight loss in the harvested fruit and a decrease in productivity and competitiveness (Uwimana et al., 2021), which affects fruit quality, trade, export volume, and sales revenue (Suvittawat, 2015). Therefore, water scarcity is one of the main factors affecting banana productivity (Panigrahi et al., 2019), such that the negative effect of water scarcity can affect between 6.88% and 26.18% of the weight of the bunch, depending on the development stage of the plant and its water deficit (Martínez, 2013), and even regions with less than 1100 mm of annual rainfall can suffer yield losses of between 20% and 65% compared to the yield potential (Panigrahi et al., 2021).

Considering that the net amount of water available for banana production comes from irrigation and rainwater, additional water applications are needed to increase yields. Irrigation systems are particularly important as they can meet water demand during droughts, thereby avoiding short-term yield losses (Uwimana et al., 2021). Moreover, these systems can improve soil organic carbon stock and soil macronutrient availability, ensuring sustainability in the medium and long term (Pramanik et al., 2024). Therefore, water scarcity in banana cultivation areas justifies the adoption of irrigation technologies (Hiremath et al., 2023). Consequently, more than 66% of the world's Musa Paradisiaca crops are grown under irrigated conditions (Carr, 2009). Despite this fact, in the Urabá region, barely 5% of the crop area is under irrigation systems, as these systems are generally expensive and require experimentation and resource allocation that banana growers do not include in their cost structure. However, in countries such as Ecuador, it has been shown that banana farms have a higher tolerance to increases in water costs compared to other crops (Franco-Crespo and Sumpsi, 2017). This situation directly affects the productivity of the agro-industrial sector in the Urabá region, which requires process innovation and the implementation of technologies to improve competitiveness in international markets (Gollin and Rogerson, 2014).

The Urabá region offers four types of irrigation systems: surface, sprinkler, micro-sprinkler, and drip irrigation systems. Surface irrigation systems distribute water through gravity-fed canals, resulting in high labor costs for canal adaptation and maintenance. This inefficient system requires excessive water use and reduces the planted area due to channel adequacy (Pawar et al., 2017; Zubelzu et al., 2023). Sprinkler irrigation systems use high-pressure sprinklers to distribute water uniformly across the plantation. This efficient system has reasonable maintenance costs but requires a high number of sprinklers and low labor. It involves significant implementation and usage costs and filters water from the subsoil (Pratibha et al., 2023; Santamarta et al., 2022). Micro-sprinkler irrigation systems are similar to sprinkler systems but use micro-sprinklers that deliver water as fine rain. This efficient system provides high water fractionation and uniform application. It requires many micro-sprinklers, skilled labor, and a high initial investment (Coelho et al., 2022; Sarwar et al., 2024; Wu et al., 2024). Drip irrigation is a water-saving method that slowly delivers water to plant roots through low-pressure devices. It provides high water fractionation but involves significant implementation and operating costs, as well as subsoil water filtering (Hiremath et al., 2023; Panigrahi et al., 2019; Pawar et al., 2017; Pratibha et al., 2023).

Previous studies have emphasized that determining the economic viability of irrigation projects is critical to their success (Marques et al., 2023). These studies highlight that net present value (NPV) and internal rate of return (IRR) analyses are essential tools for assessing the potential returns and financial viability of implementing irrigation systems (Ağizan and Bayramoğlu, 2021). Additionally, cost-benefit analyses are necessary to determine whether a financial analysis yields a positive NPV, which indicates economic soundness, particularly in humid regions (Adusumilli et al., 2016; Paoletti and Shortridge, 2020). While some studies have examined the financial viability of irrigation systems and stressed the importance of sustainable operations and cost recovery (Davidson et al., 2005), there remains a need for detailed financial studies and reforms that account for the specific conditions of each situation. These studies would help validate whether the rates of return are attractive (Narayanamoorthy, 2022). Among the feasible options for irrigation systems, it is important to select those that generate the greatest economic advantage, productivity, and competitiveness (Muhammad et al., 2014; Rana et al., 2021).

Therefore, this study validates the implementation of an irrigation system to enhance productivity and competitiveness in banana plantations in the Urabá region of Colombia. The findings can inform investment decisions and promote the broader adoption of efficient irrigation systems, ultimately contributing to the sustainability and profitability of banana production in the region.

2. Materials and methods

The case study to validate the implementation of an irrigation system in a banana plantation focuses on a 74.5 ha farm in the Urabá region. In recent years, more than 6500 records have been collected using a rain gauge to obtain information on rainfall, establishing the monthly values shown in **Table 1**. The average monthly rainfall indicates a significant drought in the first quarter of the year, while the months of May, June and September represent rainy periods. To obtain optimal banana production in a humid and tropical zone, banana plantations require an average of 4–5 mm of water per day, between 140–150 mm of water per month, and an average of 1756 mm of water per year. However, as shown in **Table 1**, in the Urabá region, the rainfall from January to March does not cover the crop's needs. Therefore, the use of irrigation systems is essential to cover the water deficit and guarantee optimal fruit production.

Table 1. Average rainfall per month (mm).

Month	Average
January	62.6
February	8.0
March	128.8
April	289.6
May	342.2
June	339.0
July	220.0
August	249.2
September	308.2
October	299.8
November	301.6
December	230.0

Currently, rainwater is the only source of water for the plantation of this study. This situation justifies an irrigation system to supply the crop during the months when rainfall is insufficient to provide water without compromising the weight per bunch harvested. In the last five years, the productivity of the banana plantation in the region of Urabá has been affected by the climate change and the bad summers that become more severe each year, experiencing a gradual decrease in productivity, and an average reduction of 13.7% of exported boxes per year, representing a decrease of 45.6% in five years. As a result, the farm under study lost $563,914 in income from banana exports during the same period, based on a price of $8.2 per 17.4 kg-box FOB ($0.47/kg). Similarly, the weight of 1,389 bunches was sampled to obtain the average weight per bunch harvested per week, and it was found that the average net weight per bunch harvested was 16.9 kg (bunch weight minus stem weight). As shown in **Table 2**, the weight measurements covered one year of operations to obtain a representative weight per bunch and to compare it with the implementation of an irrigation system.

Table 2. Average net weight per bunch/week before irrigation (kg).

Week	Average weight	Week	Average weight	Week	Average weight
1	20.30	19	18.70	37	22.78
2	20.31	20	18.82	38	22.71
3	17.86	21	18.59	39	21.54
4	20.54	22	18.15	40	21.44
5	19.64	23	18.37	41	24.53
6	20.32	24	18.37	42	21.15
7	19.24	25	19.62	43	22.64
8	19.71	26	19.80	44	21.97
9	21.02	27	18.62	45	23.59
10	19.69	28	19.12	46	25.20
11	19.91	29	19.21	47	21.26
12	19.93	30	19.04	48	20.33

Table 2. (*Continued*).

Week	Average weight	Week	Average weight	Week	Average weight
13	19.45	31	19.54	49	20.24
14	18.80	32	20.28	50	20.14
15	18.14	33	20.42	51	21.43
16	19.13	34	20.14	52	22.59
17	19.23	35	19.48		
18	19.23	36	21.32		

The area of the farm under study (AF) is 74.5 ha, the average net weight per bunch (AWB) in the farm of this study is 16.9 kg, the average of harvested bunches per hectare per month (HBHM) in the region of Urabá is 172 bunches/hectare. Similarly, the theoretical minimum loss per bunch due to water deficit in the plantation (LOSSmin) is 6.88%, and the theoretical maximum loss per bunch due to water deficit (LOSSmax) is 26.18% (Martínez, 2013). Based on the above, it is possible to calculate the minimum and maximum loss of monthly export bananas in months of drought (LEBmin and LEBmax) using Equation (1) and Equation (2).

$$\mathrm{LEBmin} = \mathrm{AF} \times \mathrm{AWB} \times \mathrm{HBHM} \times \mathrm{LOSSmin} \tag{1}$$

$$\mathrm{LEBmax} = \mathrm{AF} \times \mathrm{AWB} \times \mathrm{HBHM} \times \mathrm{LOSSmax} \tag{2}$$

Considering that January, February and March are the months of severe drought in the plantation, the cumulative loss of export bananas in these months ranged from 44,716 kg to 170,155 kg. By monetizing this loss of bananas at a reference price of \$0.47/kg (price agreed with international customers), a loss of sales of between \$21,017 and \$79,973 would be expected due to the water deficit in the fruit during the summer season. In addition, the lack of water in banana plantations during the summer season generates an irreversible effect on the crop in the remaining months of the year, slows down the return of production per unit, slows down foliation and alters the productive cycles of the crop, which also generates adverse effects in the medium and long term.

In order to improve the productivity and competitiveness of the farm under study, we proceed to identify the irrigation systems suitable for the farm of this study and select the most appropriate system based on the technical concept issued by the company that provides irrigation systems in the Urabá region. The decision-making process considered the resources available to the investor and the criteria of experts from the irrigation and drainage staff of the farm. A random sample of bunches is taken to measure the weight after the implementation of the irrigation system, and a comparison of the average weight of the bunches is calculated. Weight data will be collected from the bunches cut for export using a TRU-TEST XR3000 scale. A t-test for comparison of independent means is used to validate the difference in weight, and the results are compared with the theoretical weight loss caused by water deficit in banana plantations (Martínez, 2013).

As in previous studies, it is necessary to demonstrate the economic advantages of irrigation systems in banana cultivation. This can be achieved through the calculation of positive NPV, IRR, benefit-cost ratio (BCR), and payback period (PP) (He et al., 2019; Hiremath et al., 2023; Kiruthika and Kumar, 2020). Since the final weight of the bunch directly affects the financial aspects of the crop harvest (Soares et al., 2013), financial indicators such as NPV, IRR, BCR, and PP are analyzed in this study. These indicators make it possible to determine the profitability and viability of implementing the irrigation system in the banana plantation. Equation (3) shows that NPV measures the difference between the present value of cash inflows and the present value of cash outflows over *n* periods, where R_t represents the net profit at month *t*, C_0 is the initial investment (net profit at month 0), and *r* represents the discount rate. Equation (4) defines IRR as the discount rate that makes the NPV of all cash flows equal to zero. Equation (5) calculates the BCR as the ratio of the present value of incomes (I_t) to the present value of costs (C_t). Equation (6) shows that PP represents the time required to recover the initial investment from the net profits, and it is calculated by finding the time *t* at which the cumulative net profits equal the initial investment. On a monthly basis, it is calculated as the ratio of initial investment to the annual net profits.

$$\mathrm{NPV} = \sum_{t=0}^{n} \frac{R_t}{(1+r)^t} - C_0 \tag{3}$$

$$\sum_{t=0}^{n} \frac{R_t}{(1+\mathrm{IRR})^t} - C_0 = 0 \tag{4}$$

$$\mathrm{BCR} = \frac{\sum_{t=0}^{n} \frac{I_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{C_t}{(1+r)^t}} \tag{5}$$

$$\mathrm{PP} = \frac{C_0}{\sum_{1}^{12} R_t} \tag{6}$$

3. Results

The selection of an appropriate irrigation system was based on the options available in the Urabá region that meet the specific needs of banana crops. The irrigation system must evenly distribute water across the plantation to keep the plants hydrated and maintain optimal relative humidity (van Asten et al., 2011). Additionally, the system's efficiency was analyzed considering factors such as available groundwater, implementation costs, and operational aspects like maintenance expenses.

After evaluating the characteristics, advantages, and drawbacks of various irrigation systems, and considering the technical input from the plantation's irrigation and drainage staff as well as the available financial resources, a sprinkler irrigation system was determined to be the best option. This decision is supported by studies showing that banana plants irrigated with conventional micro-sprinklers and sprinklers produce a higher number of bunches compared to those using drip irrigation (Arantes et al., 2018). **Figure 1** illustrates the supply system, pipes, and sprinklers of the selected system. A surface irrigation system was ruled out due to the farm's lack of slopes. The micro-sprinkler system was considered too expensive due to the extensive equipment required for the farm's size, and drip irrigation was deemed unsuitable for banana crops because of the need for overhead, non-buried pipes.

Figure 1. Sprinkler irrigation system implemented in the banana plantation.

The total implementation cost of the sprinkler irrigation system was $2513 per hectare, with a single payment made on the day the system was commissioned. To validate production, 1018 bunches were weighed after the irrigation system became operational. A significant sample was obtained due to the randomness and rigor of the measurements, with the average weight per bunch per week presented in **Table 3**. This table shows an average annual net weight of 20.3 kg per bunch, representing an increase of 3.39 kg per bunch and a 20.0% increase compared to banana production prior to the implementation of the irrigation system (16.9 kg).

The *t*-test for comparison of independent means was used to compare the average net weight per bunch per week before (Group 1) and after (Group 2) irrigation, based on the data provided in **Tables 2** and **3**, each with a sample size of 52. The mean and standard deviation for Group 1 were 16.91 and 1.3402, respectively, and for Group 2 were 20.30 and 1.6379, respectively. The *t*-test confirmed a significant difference between the average net weights per bunch per week, with a t-statistic of 11.55, which falls outside the 99% region of acceptance [−2.62, 2.62]. Similarly, the mean difference ($x2 - x1 = 3.39$) falls outside the 99% region of acceptance [−0.77, 0.77], with a p-value < 0.00001. This allows us to conclude that there is a statistically significant difference in mean weights between crop production with and without an irrigation system at the 0.01 significance level.

Table 3. Average net weight per bunch/week after irrigation (kg).

Week	Average weight	Week	Average weight	Week	Average weight
1	20.30	19	18.70	37	22.78
2	20.31	20	18.82	38	22.71
3	17.86	21	18.59	39	21.54
4	20.54	22	18.15	40	21.44
5	19.64	23	18.37	41	24.53
6	20.32	24	18.37	42	21.15
7	19.24	25	19.62	43	22.64
8	19.71	26	19.80	44	21.97
9	21.02	27	18.62	45	23.95
10	19.69	28	19.12	46	25.20
11	19.91	29	19.21	47	21.26
12	19.93	30	19.04	48	20.33
13	19.45	31	19.54	49	21.35
14	19.15	32	20.28	50	20.14
15	18.14	33	20.42	51	21.43
16	19.13	34	20.14	52	22.59
17	19.23	35	19.48		
18	19.23	36	21.32		

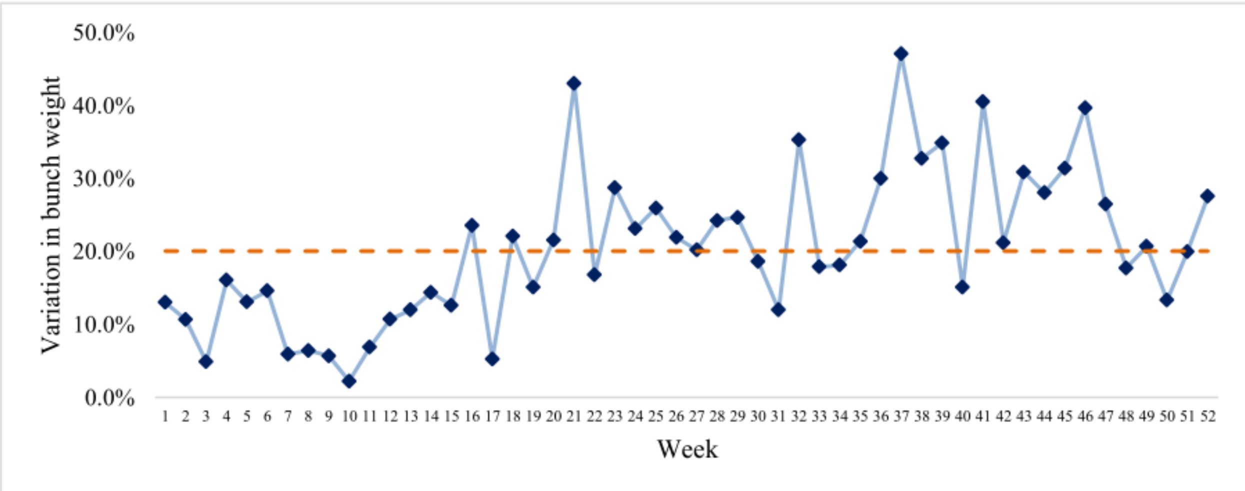

Figure 2. Variation of the average net weight per bunch.

Figure 2 compares the average weekly weight per bunch before and after the implementation of the irrigation system. It demonstrates that the average weekly weight per bunch was higher post-irrigation, indicating increased crop productivity following the implementation of the system. Specifically, the increase in average fruit weight is reflected in a 6.1% increase in width and a 1.9% increase in length of the second hand. Notably, three periods showed productivity increases of more than 40%, while only two periods had productivity increases of less than 5%.

For the financial evaluation of the irrigation system, the cash flow for the first year of operation was calculated by analyzing the initial investment, fixed costs, variable costs, expected profit, and net profit on a monthly basis. The implementation cost represents the initial investment, while the fixed cost represents the monthly salary of an operator for the irrigation system ($450/month). Monthly variable costs depend on the electricity consumed by the irrigation system and planned maintenance, which includes the purchase and replacement of sprinklers, pipes, bolts, nuts, washers, cables, motor coolers, and other items. Monthly income is calculated by multiplying the increase in net weight per bunch (3.39 additional kg per bunch due to irrigation) by the number of bunches harvested per month (based on historical productivity shown in **Table 4**), with the total kilograms monetized at a reference selling price of $0.47/kg. Values for the first semester of the second year of operation are adjusted using an inflation rate of 1.5%.

Table 4. Production of banana bunches per month.

Month	Production of bunches	Month	Production of bunches
1	7392	7	11,296
2	10,172	8	10,101
3	9138	9	8972
4	16,711	10	11,858
5	11,595	11	10,137
6	10,030	12	10,483

Table 5. Cash flow for the irrigation system implementation.

Month	Initial investment ($)	Fixed costs ($)	Variable costs ($)	Expected income ($)	Net profit ($)
0	187,294	0	0	0	−187,294
1	0	450	300	11,774	11,024
2	0	450	350	16,202	15,402
3	0	450	250	14,556	13,856
4	0	450	200	26,617	25,967
5	0	450	150	18,468	17,868
6	0	450	120	15,976	15,406
7	0	450	135	17,993	17,408
8	0	450	50	16,089	15,589
9	0	450	45	14,291	13,796
10	0	450	40	18,888	18,398
11	0	450	85	16,147	15,612
12	0	450	110	16,698	16,138
13	0	457	305	11,951	11,190
14	0	457	355	16,445	15,633
15	0	457	254	14,774	14,063
16	0	457	203	27,017	26,357
17	0	457	152	18,745	18,136
18	0	457	122	16,215	15,637

The cash flow for the irrigation system over 18 months is presented in **Table 5**, showing that the average profit from the first investment period is $16,527. The NPV was calculated using the initial investment, net monthly benefits, and a discount rate or investor opportunity rate (IOR) of 1.0%. The IRR accounts for the net benefits of each period, while the BCR compares the present value of the expected benefits with the present value of the initial investment, fixed costs, and variable costs. The payback period represents the time required for the accumulated benefits to equal the initial investment.

A summary of the financial indicators is presented in **Table 6**, which highlights that the net present value of the irrigation system in the medium term is $83,263, indicating that profits exceed both the initial investment and the operation and maintenance costs. The IRR obtained from the cash flow is 5.29% per month, which exceeds the investor's opportunity rate, making the project economically attractive. Additionally, the benefit-cost ratio of the project is 1.42, meaning that the present value of the income exceeds the present value of the expenses, and that for every dollar invested in the irrigation system, a profit of $1.42 is generated in the medium term. Furthermore, the payback period, based on the project's cash flow, occurs in the 12th month of implementation, allowing the initial investment to be recovered in less than one year.

Table 6. Financial indicators.

Indicator	Value
Net present value (NPV)	$83,263
Internal rate of return (IRR)	5.29%
Benefit-cost ratio (BCR)	1.42
Payback period in months (PP)	11.43

4. Discussion

Consequently, the implementation of a sprinkler irrigation system has increased the productivity and competitiveness of the plantation, with the net weight per bunch rising by an average of 20%. Before the installation of the irrigation system, the banana plantation produced an annual export of 82,172 boxes. With an increase of 3.39 kg per bunch, and considering the monthly production of banana bunches established in **Table 4**, a production increase of 433,402 kg was achieved, equivalent to 24,908 additional export boxes (334.3 boxes exported per hectare). This represents a 30.3% increase in exported boxes, resulting in an additional expected income of $204,247 for the first year of the irrigation system's operation.

Similar to previous studies conducted in regions such as India, the economic impact of irrigation systems on banana cultivation in this study shows a higher benefit-cost ratio and increased income for adopters of these irrigation technologies. These financially feasible systems lead to an increase in cropped area, irrigation intensity, and cropping intensity (Hiremath et al., 2023; Kiruthika and Kumar, 2020). In fact, the increase in income even demonstrates the economic viability of irrigation systems for small and marginal farmers (Kiruthika and Kumar, 2020).

Based on the results, this study contributes to the promotion of agricultural research focused on optimizing production systems to achieve high yields (Hu et al., 2020; Rada and Fuglie, 2019; Yang et al., 2020), generating higher export earnings, and fostering social development, business growth, and employment opportunities in the agro-industrial sector. Given that the Urabá region has a lower percentage of crops under irrigation and that banana farms are more tolerant of increases in water costs compared to other crops (Franco-Crespo and Sumpsi, 2017), the productivity of the agroindustry in Urabá requires a constant pursuit of process innovation, personnel training, and technology implementation. These efforts are essential for improving competitiveness and contributing to environmental sustainability (Ramírez-Orellana et al., 2021).

As demonstrated in this study, the use of methodologies that include both technical and economic analysis can promote production technologies and generate higher yields and profits in agribusiness, even in the face of climate change challenges. Additionally, the implementation of irrigation systems in the Urabá region is expected to increase the competitiveness not only of the banana industry but also of other agro-industries such as corn, cassava, cocoa, and rice, enabling mixed plantations that require fewer agrochemical applications compared to monoculture systems (Vera-Aviles et al., 2020). Therefore, this study encourages banana producers to collaborate in order to contribute to the country's export growth, improve food quality, and support sustainable economic development to meet the needs of the current generation without compromising the ability of future generation (He et al., 2018), particularly in a region like Urabá, which has historically been affected by armed conflict in Colombia.

5. Conclusion

This study analyzed the implementation of an irrigation system in a banana plantation to ensure an adequate water supply during the summer, thereby improving the productivity and competitiveness of the plantation. The irrigation system ensured adequate crop yields, resulting in an average increase of 20% in the net weight per harvested bunch, thus compensating for the water deficit during the banana plant's development phase.

The increased productivity of the plantation led to a 30.3% annual increase in export boxes, translating into additional sales income of $204,247 and enhancing competitiveness in international markets. Consequently, this study underscores the relevance and viability of implementing irrigation systems in regions that need to boost competitiveness in international markets, such as Colombia, and encourages banana producers to collaborate in expanding the country's exports. This will, in turn, enhance national competitiveness against other banana-exporting countries such as Costa Rica, Honduras, Ecuador, and Guatemala.

Due to limitations in our current dataset, which primarily focuses on banana harvest and financial indicators, we were unable to conduct a regression analysis to control for factors and other variables affecting banana productivity. We recognize this as a significant limitation and propose it as an important direction for future research. Additionally, future studies should conduct technical and economic analyses of the use of irrigation systems in crops alternated with bananas in the Urabá region, such as corn, cassava, cocoa, and rice.

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References

Adusumilli, N., Davis, S., & Fromme, D. (2016). Economic evaluation of using surge valves in furrow irrigation of row crops in Louisiana: A net present value approach. Agricultural Water Management, 174, 61–65. https://doi.org/10.1016/j.agwat.2016.04.024

Ağizan, S., & Bayramoğlu, Z. (2021). Comparative Investment Analysis of Agricultural Irrigation Systems. Journal of Tekirdağ Ziraat Fakültesi Dergisi, 18(2), 222–233. https://doi.org/10.33462/jotaf.745548

Arantes, A. de M., Donato, S. L. R., Siqueira, D. L. de, & Coelho, E. F. (2018). Gas Exchange In 'Pome' Banana Plants Grown Under Different Irrigation Systems. Engenharia Agrícola, 38(2), 197–207. https://doi.org/10.1590/1809-4430-eng.agric.v38n2p197-207/2018

Bolaños, S., & Betancur, T. (2018). State of the Art on Climate Change and Groundwater (Spanish). Ejemplos en Colombia. Revista Politécnica, 14(26), 52–64. https://doi.org/10.33571/rpolitec.v14n26a5

Carr, M. K. V. (2009). The Water Relations and Irrigation Requirements of Banana (Musa Spp.). Experimental Agriculture, 45(3), 333–371. https://doi.org/10.1017/s001447970900787x

Coelho, E. F., Santos, M. R. dos, Souza, E. de A., et al. (2022). Root distribution and its relations with soil chemical attributes and yield of banana under fertigation with and without soil covering. Acta Scientiarum. Agronomy, 44, e53296. https://doi.org/10.4025/actasciagron.v44i1.53296

Davidson, B., Malano, H. M., & George, B. A. (2005). The financial viability of irrigation management companies: A case study of Cu Chi irrigation system, Vietnam. Irrigation and Drainage Systems, 19(2), 129–143. https://doi.org/10.1007/s10795-005-2752-4

Franco-Crespo, C., & Sumpsi Viñas, J. M. (2017). The Impact of Pricing Policies on Irrigation Water for Agro-Food Farms in Ecuador. Sustainability, 9(9), 1515. https://doi.org/10.3390/su9091515

Gollin, D., & Rogerson, R. (2014). Productivity, transport costs and subsistence agriculture. Journal of Development Economics, 107(1), 38–48. https://doi.org/10.1016/j.jdeveco.2013.10.007

He, X., Gao, X., & Wang, H. (2019). Technical and economic analysis of the coupling of optical axis heat supply and thermal storage peaking of 200 MW unit. IOP Conference Series: Earth and Environmental Science, 267(4), 042042. https://doi.org/10.1088/1755-1315/267/4/042042

He, Y., Li, D., Wu, S. J., et al. (2018). Quality and Operations Management in Food Supply Chain. Journal of Food Quality, 2018, 1–2. https://doi.org/10.1155/2018/9871379

Hiremath, D., Makadia, J. J., & Rudrapur, S. (2023). Economic Impact and Decomposition Analysis of Income Change vis-à-vis Drip and Conventional Irrigation Technology in Bananas: A Case Study of the South Gujarat Region in India. Journal of Irrigation and Drainage Engineering, 149(12). https://doi.org/10.1061/jidedh.ireng-10072

Hu, J., Huang, Q., & Chen, X. (2020). Environmental regulation, innovation quality and firms' competitivity—Quasi-natural experiment based on China's carbon emissions trading pilot. Economic Research-Ekonomska Istraživanja, 33(1), 3307–3333. https://doi.org/10.1080/1331677x.2020.1771745

Kiruthika, S., & Kumar, D. S. (2020). Socio-economic impacts of the adoption of MIS (Micro-irrigation system) among small and marginal farmers of Coimbatore district, India. Journal of Applied and Natural Science, 12(3), 312–318. https://doi.org/10.31018/jans.v12i3.2312

Marques, P. A. A., Aleman, C. C., & Eslamian, S. (2023). Economic Viability of Irrigation Techniques. In: Handbook of Irrigation Hydrology and Management: Irrigation Fundamentals. CRC Press. pp. 207–222.

Martínez, R. (2013). Controlled deficit irrigation effect in the productivity of the banana tree (Spanish). Revista Ciencias Técnicas Agropecuarias, 22(2), 51–55.

Muhammad, D., Mosleh, M., & Khan, S. U. H. (2014). Assessment and evaluation of solar irrigation system in Bangladesh. In: Proceeding of the 2014 3rd International Conference on the Developments in Renewable Energy Technology (ICDRET). pp. 1–6.

Narayanamoorthy, A. (2022). Financial Performance of India's Irrigation Sector: Past, Present and Future. In: Global Issues in Water Policy. Springer Science and Business Media B.V. pp. 139–158.

Olivares, B. O., Rey, J. C., Lobo, D., et al. (2021). Fusarium Wilt of Bananas: A Review of Agro-Environmental Factors in the Venezuelan Production System Affecting Its Development. Agronomy, 11(5), 986. https://doi.org/10.3390/agronomy11050986

Panigrahi, N., Thompson, A. J., Zubelzu, S., et al. (2021). Identifying opportunities to improve management of water stress in banana production. Scientia Horticulturae, 276, 109735. https://doi.org/10.1016/j.scienta.2020.109735

Panigrahi, P., Raychaudhuri, S., Thakur, A. K., et al. (2019). Automatic drip irrigation scheduling effects on yield and water productivity of banana. Scientia Horticulturae, 257, 108677. https://doi.org/10.1016/j.scienta.2019.108677

Paoletti, J. M., & Shortridge, J. E. (2020). Improved representation of uncertainty in farm-level financial cost-benefit analyses of supplemental irrigation in humid regions. Agricultural Water Management, 239, 106245. https://doi.org/10.1016/j.agwat.2020.106245

Pawar, D. D., Dingre, S. K., & Bhoi, P. G. (2017). Productivity and Economics of Drip Irrigated Banana (Musa Spp.) under Different Planting and Fertigation Techniques in Sub Tropical India. Communications in Soil Science and Plant Analysis. https://doi.org/10.1080/00103624.2017.1282505

Pramanik, S., Patra, S. K., Ghosh, S., et al. (2024). Drip-Mediated Deficit Irrigation and Sub-Optimal Fertigation Management Strategy can Boost Yield, Soil Nutrient Availability, Plant Utilization and Soil Organic Carbon in Banana Plantation. Journal of Soil Science and Plant Nutrition, 24(2), 3843–3860. https://doi.org/10.1007/s42729-024-01804-y

Pratibha, P., Suresh, K., Jagrati, B. D., et al. (2023). Banana Cultivation under Drip and Conventional Irrigation Methods in Karnataka: An Economic Analysis. Environment and Ecology, 41(4B), 2625–2632. https://doi.org/10.60151/envec/zsan3337

Rada, N. E., & Fuglie, K. O. (2019). New perspectives on farm size and productivity. Food Policy, 84, 147–152. https://doi.org/10.1016/j.foodpol.2018.03.015

Ramírez-Orellana, A., Ruiz-Palomo, D., Rojo-Ramírez, A., et al. (2021). The Ecuadorian Banana Farms Managers' Perceptions: Innovation as a Driver of Environmental Sustainability Practices. Agriculture, 11(3), 213. https://doi.org/10.3390/agriculture11030213

Rana, J., Kamruzzaman, M., Hosain Oliver, M., et al. (2021). Financial and factors demand analysis of solar powered irrigation system in Boro rice production: A case study in Meherpur district of Bangladesh. Renewable Energy, 167, 433–439. https://doi.org/10.1016/j.renene.2020.11.100

Santamarta, J. C., Machín, N., & Cruz-Pérez, N. (2022). Irrigation Efficiency in Banana Crops in the Canary Islands. The Open Agriculture Journal, 17(1), 1–7. https://doi.org/10.2174/18743315-v16-e221226-2022-49

Sarwar, A., Medellín-Azuara, J., & Viers, J. H. (2024). Economics of microirrigation systems. In: Microirrigation for Crop Production: Design, Operation and Management. Elsevier Science. pp. 157–173.

Soares, J. D. R., Pasqual, M., Lacerda, W. S., et al. (2013). Utilization of artificial neural networks in the prediction of the bunches' weight in banana plants. Scientia Horticulturae, 155, 24–29. https://doi.org/10.1016/j.scienta.2013.01.026

Souza, E. A., Coelho, E. F., Santos, M. R., et al. (2021). Agronomic performance of 'BRS Princesa' banana under fertigation and mulching. Semina: Ciências Agrárias, 42(3), 979–998. https://doi.org/10.5433/1679-0359.2021v42n3p979

Surendar, K. K., Devi, D. D., Ravi, I., et al. (2013). Water Stress Affects Plant Relative Water Content, Soluble Protein, Total Chlorophyll Content and Yield of Ratoon Banana. International Journal of Horticulture. 3(17), 96–103. https://doi.org/10.5376/ijh.2013.03.0017

Suvittawat, A. (2015). Production Analysis of Banana Supply Chain Management in Thailand. Management and Organizational Studies, 2(1), 66–71. https://doi.org/10.5430/mos.v2n1p66

Toro-Trujillo, A. M., Arteaga-Ramírez, R., Vázquez-Peña, M. A., & Ibáñez-Castillo, L. A. (2016). Irrigation requirements and yield prediction in banana crop using a simulation model in Urabá Antioquia, Colombia (Spanish). Tecnologia y Ciencias Del Agua, 7(6), 105–122.

Uwimana, B., Zorrilla-Fontanesi, Y., van Wesemael, J., et al. (2021). Effect of Seasonal Drought on the Agronomic Performance of Four Banana Genotypes (Musa spp.) in the East African Highlands. Agronomy, 11(1), 4. https://doi.org/10.3390/agronomy11010004

van Asten, P. J. A., Fermont, A. M., & Taulya, G. (2011). Drought is a major yield loss factor for rainfed East African highland banana. Agricultural Water Management, 98(4), 541–552. https://doi.org/10.1016/j.agwat.2010.10.005

Vera-Aviles, D., Suarez-Capello, C., Llugany, M., et al. (2020). Arthropod Diversity Influenced by Two Musa-Based Agroecosystems in Ecuador. Agriculture, 10(1), 235. https://doi.org/10.3390/agriculture10060235

Wu, P., Wang, Y., Li, Y., et al. (2024). Evaluating optimized irrigation strategies on crop productivity and field water utilization under micro sprinkling irrigation in typical cropping systems of the Huang-Huai-Hai Plain. European Journal of Agronomy, 154, 127093. https://doi.org/10.1016/j.eja.2024.127093

Yang, B., Zhang, W., Meng, X., et al. (2020). Effects of a funnel-shaped canopy on rainfall redistribution and plant water acquisition in a banana (Musa spp.) plantation. Soil and Tillage Research, 203, 104686. https://doi.org/10.1016/j.still.2020.104686

Zubelzu, S., Panigrahi, N., Thompson, A. J., et al. (2023). Modelling water fluxes to improve banana irrigation scheduling and management in Magdalena, Colombia. Irrigation Science, 41(1), 69–79. https://doi.org/10.1007/s00271-022-00818-7