 http://dx.doi.org/10.18623/rvd.v23.n1.4308

ASSESSMENT OF COCOA CROP YIELD UNDER IRRIGATION WITH THREE TYPES OF SPRINKLERS IN FIELD CONDITIONS

AVALIAÇÃO DO RENDIMENTO DA COLHEITA DE CACAU SOB IRRIGAÇÃO COM TRÊS TIPOS DE ASPERSORES EM CONDIÇÕES DE CAMPO

Article received on: 8/29/2025
Article accepted on: 11/28/2025

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The authors declare that there is no conflict of interest

Abstract
Background: Efficient irrigation plays a crucial role in optimizing water use and improving cacao productivity, especially in regions with limited water availability. This study aimed to evaluate the impact of different sprinkler types on irrigation efficiency and cacao yield in the Guayaquil-Balzar area of Ecuador. Methods: Three sprinkler models (Brazo Regulador, Banariego 5022, and Senniger) were assessed based on water distribution efficiency, irrigation time, fuel consumption, cost, and productivity outcomes. Crop evapotranspiration (ETc) was calculated using climatic data to determine the ideal irrigation frequency. Results: The ETc was estimated at 3.4 mm/day, and an irrigation frequency of 7 days was recommended. Among the tested sprinklers, the Brazo Regulador demonstrated the highest water distribution efficiency and lowest irrigation time, resulting in better productivity (224 flowers/tree) and lower operational costs. Banariego 5022 followed closely in terms of productivity (197.25 flowers/tree), while the Senniger, although efficient, had lower flower production and higher operational costs due to fuel consumption. Conclusions: The Brazo Regulador sprinkler was

Resumo
Contexto: A irrigação eficiente desempenha um papel crucial na otimização do uso da água e na melhoria da produtividade do cacau, especialmente em regiões com disponibilidade limitada de água. Este estudo teve como objetivo avaliar o impacto de diferentes tipos de aspersores na eficiência da irrigação e no rendimento do cacau na área de Guayaquil-Balzar, no Equador. Métodos: Três modelos de aspersores (Brazo Regulador, Banariego 5022 e Senniger) foram avaliados com base na eficiência da distribuição de água, tempo de irrigação, consumo de combustível, custo e resultados de produtividade. A evapotranspiração da cultura (ETc) foi calculada usando dados climáticos para determinar a frequência ideal de irrigação. Resultados: A ETc foi estimada em 3,4 mm/dia, e uma frequência de irrigação de 7 dias foi recomendada. Entre os aspersores testados, o Brazo Regulador demonstrou a maior eficiência na distribuição de água e o menor tempo de irrigação, resultando em melhor produtividade (224 flores/árvore) e menores custos operacionais. O Banariego 5022 ficou em segundo lugar em termos de produtividade

identified as the most effective and economical solution, offering an optimal balance between performance, productivity, and cost for cacao irrigation in the study region.

Keywords: Cacao, Irrigation Efficiency, Sprinkler Systems, Productivity, Ecuador**.**

(197,25 flores/árvore), enquanto o Senniger, embora eficiente, apresentou menor produção de flores e maiores custos operacionais devido ao consumo de combustível. Conclusões: O aspersor Brazo Regulador foi identificado como a solução mais eficaz e econômica, oferecendo um equilíbrio ideal entre desempenho, produtividade e custo para a irrigação do cacau na região estudada.

Palavras-chave: *Cacau. Eficiência de irrigação. Sistemas de aspersão. Produtividade. Equador.*

1 INTRODUCTION

Cocoa (*Theobroma cacao* L.) production serves as a foundational economic crop in Ecuador, which in 2021 cultivated over 600,000 ha with average productivity increasing to 0.56 t/ha—a notable rise over the previous decade (Burgo *et al*., 2025). Coastal provinces such as Guayas and Los Ríos account for approximately 52 % of national output, increasingly favoring the CCN-51 cultivar for its disease resistance and yield stability, despite lower sensory profile than fine-flavor national varieties (Zambrano *et al*., 2024) Accordingly, there is a strong imperative to optimize production systems that boost yield and water efficiency while safeguarding sustainability and quality.

Technified irrigation has accelerated in recent years across Ecuador through World Bank and AECID supported initiatives, implementing sprinkler systems over more than 6,300 ha, particularly benefiting coastal cocoa farms, where yields have effectively doubled from pre-2020 levels (World Bank Group, 2023). Such outcomes illustrate that well-managed irrigation can drastically elevate productivity even in variable climates.

Studies in Ecuador's cacao fields show that sub-foliar sprinklers and microsprinklers deliver high water distribution uniformity (CU), but performance is highly sensitive to operating pressure. Research from San Vicente in Los Ríos found that although Christiansen CU exceeded 90 %, optimal irrigated area was only achieved at pressures near 275 kPa (Tandazo *et al*., 2018). Broader regional assessments in Manabí and Chone propose annual irrigation requirements ranging from 641 to 1,062 mm, divided into 7 to 26 applications depending on soil water levels and evapotranspiration rates (Pére & Domínguez, 2019).

Physiologically, CCN-51 exhibits high stomatal conductance (250–

350 mmol m^{-2} s^{-1}) and water-use efficiency (WUE ≈ 2.3 mmol mol^{-1}) under full sun, maintaining yields above 1.2 t/ha even during dry seasons (Jaimez *et al*., 2022). Yet, emerging evidence highlights that agroforestry systems with controlled shade not only improve WUE but also enhance carbon sequestration and climate resilience (especially relevant given regional warming trends) (Kongor *et al*., 2024; Tinoco *et al*., 2025).

Controversies remain as to whether more expensive systems like drip irrigation (offering slightly higher CU (~97 %) versus ~96 % from micro-sprinklers) are justified in small farms, given the higher cost and marginal yield advantage. Cost-benefit and operational efficiency need careful assessment (Burgos *et al*., 2025). Additionally, while advanced tools like IoT-driven irrigation and machine learning optimization can save up to 10 % in water use, they remain largely out of reach for smallholder settings typical in tropical regions (Bassine *et al*., 2023; Ding & Du, 2023). The concept of deficit irrigation (targeted water limitation to maximize water productivity over yield) also warrants consideration in contexts of scarcity.

This study examines the impact of three sprinkler types on the performance of CCN-51 cocoa in an experimental plantation at La Guayaquil, Balzar canton (Guayas, Ecuador), during April–August 2024. It evaluates uniformity (CU), water-use efficiency (WUE), fruit yield (kg/ha), and operational costs. This combined analysis aims to produce evidence-based guidance for local growers, agronomy students, and extension agents regarding optimal irrigation choices.

The overarching goal is to assess how different sprinkler types affect productive performance in cocoa, focusing on water-use efficiency, productivity, and economic viability. Specific objectives include:

Objective 1: Evaluate the influence of different types of sprinklers on irrigation efficiency for cocoa.

Objective 2: Determine the influence of each sprinkler type on cocoa crop productivity.

Objective 3: Analyze operational costs associated with sprinkler use.

2 METHODS

2.1 Research approach

The research focused on application, with the aim of generating knowledge that could be used to solve a specific problem: improving irrigation efficiency for cocoa cultivation.

2.1.1 Type of research

This study was a field experimental research, as experiments were conducted to evaluate the influence of different types of sprinklers on irrigation efficiency and cocoa crop productivity. The level of knowledge was formative, as it explained the causal relationship between sprinkler types, irrigation efficiency, and crop productivity. Variables were manipulated to evaluate their impact on both irrigation efficiency and cocoa productivity.

2.1.2 Research design

The proposed research used an experimental design. This design allowed for the manipulation of the independent variable (types of sprinklers) to assess its impact on the dependent variables (irrigation efficiency and cocoa crop productivity). A uniformly sized cocoa crop plot was selected and divided into three smaller plots. Each plot was irrigated using a different type of sprinkler. The same amount of water was applied to all plots, and irrigation efficiency and productivity were measured in each one.

3 METHODOLOGY

3.1 Variables

The objective of this research was to evaluate the influence of different types of sprinklers on irrigation efficiency and cocoa crop productivity. Therefore, the variables were:

- Independent variable: Type of sprinkler
- Dependent variables:
  - Cocoa water requirement
  - Cocoa crop productivity
  - Irrigation efficiency
  - Cost analysis

3.2 Water requirement

The water requirement of cocoa is crucial for ensuring optimal growth and fruit production. This variable measures the amount of water applied in relation to the amount lost through evaporation. Understanding and managing the specific water needs of cocoa trees is essential.

3.3 Uniformity coefficient

The uniformity coefficient measures how evenly water is distributed over the crop. It was calculated by comparing the variability of actual water distribution with an ideally uniform distribution.

3.4 Irrigation efficiency coefficient

This coefficient indicates how efficiently the irrigation system delivers water to benefit the crop, compared to how much is lost. It is expressed as a percentage and is calculated by the ratio of beneficial water to total water applied.

3.5 Cocoa productivity

This variable measures the amount of fruit produced relative to the cultivated area.

2.2. Treatments

The treatments were defined by the types of sprinklers used, detailed in Table 1.

Table 1

Treatments

Sprinkler	Code	Outlets	Nozzle (mm)
B Adjustable Arm	ASPE000119	2	4
Banariego 5022	ASPE000106	2	2.5
Senniger Type	ASPE000165	1	2.5

Source: Argudo, 2023

Treatment 1 used the Banariego B adjustable arm sprinkler with two nozzles. Similarly, the Banariego 5022 sprinkler was used (also with two nozzles), and as treatment 3, the Senniger 2014HS sprinkler was applied. Flow rate, pressure, and working range were evaluated to understand irrigation uniformity and cocoa productivity.

3.6 Experimental design

The experimental design used was CRD (Completely Randomized Design), which allowed for control of plot differences. It was suitable to assess the influence of one factor (sprinkler type) on dependent variables (irrigation efficiency and crop productivity).

3.7 Data collection

3.7.1 Resources

- Bibliographic resources: Literature review was carried out using books, websites, and scientific journals, especially on soil, irrigation, and sprinkler efficiency, from the Agricultural Information Center of the Agrarian University of Ecuador.
- Materials and Equipment:
  - Laptop
  - Printer
  - Calculator
  - Notebook
  - Pencil
  - Digital Vernier Caliper
  - Stopwatch

- Evapotranspiration bucket
- Machete
- Shovels
- Stakes
- Strings
- Buckets
- Irrigation pump and piping
- Hoses
- Valves
- Manometer
- Rain gauge
- Sprinklers

- Human Resources: The student conducted the irrigation system evaluation under the guidance of a tutor and two academic advisors.

3.8 Methods and techniques

- Inductive and Deductive: After collecting the data, patterns and trends were analyzed, leading to hypothesis ormulation.
- Analysis and Synthesis: These were used to understand the functioning of different sprinklers and their influence on cocoa irrigation.
- Direct Observation: Applied to identify characteristics and differences among sprinklers, observing water distribution and its effect on cocoa plants.

3.8.1 Objective 1: evaluate the influence of different types of sprinklers on irrigation efficiency for cocoa

To meet the first objective, cocoa water requirements and the required irrigation depth were calculated. In-situ tests were conducted using soil samples to determine gravimetric moisture and analyze the soil's physical characteristics.

The CROPWAT program was used to calculate reference evapotranspiration using data from the Balzar, C. Robusta weather station (altitude: 40 m, latitude: 1.15° S, longitude: 79° 70' W). Climate data were input into CROPWAT to estimate reference evapotranspiration for Guayaquil.

Temperature: 25.6°C; Relative Humidity: 81%; Wind Speed: 135 km/day; Sunshine: 3 h/day; FAO's Kc for cocoa: 1.05 (Allen *et al*., 1998)

ETc = Eto * Kc Where:

- ETc: Crop evapotranspiration
- Eto: Reference evapotranspiration
- Kc: Crop coefficient

Table 2

Cocoa Crop Evapotranspiration

Parameter	Value
Reference evapotranspiration (Eto, mm/day)	3.21
Crop coefficient (Kc)	1.05
Crop evapotranspiration (ETc, mm/day)	3.38

Prepared by the author, 2024

3.8.2 Easily Available Water Depth (LFA)

LFA = ((FC - PWP) * z * MAD * BD)/(100 * dw) (1)

Soil depth for cocoa: 20–40 cm (main roots). Field capacity was measured by saturating the soil, drying samples at 105°C, and calculating moisture.

Table 3

Field Capacity

Sample	Wet Weight (g)	Dry Weight (g)	Difference (g)	Diff./Dry	Field Capacity (g/g)
Sample 1	980	785	195	0.2484	24.84
Sample 2	650	518	132	0.2548	25.48
Average					25.16

Source: Prepared by the author, 2024

3.8.3 Permanent Wilting Point (PWP)

Formula: PWP = (FC x 0.74) – 5 (2)

Table 4

Permanent Wilting Point

Sample	Field Capacity (%)	PWP (%)
Sample 1	24.84	13.36
Sample 2	25.48	13.86
Average		**13.61**

Source: Prepared by the author, 2024

Soil type: Clay loam; Bulk Density (BD): 1.4 g/cm³

Table 5

Easily Available Water (LFA)

Parameter	Value
Field Capacity (FC, %)	25
Permanent Wilting Point (%)	14
Root Depth (z, mm)	300
Management Allowed Depletion (%)	50
Bulk Density (g/cm³)	1.4
LFA (mm)	23

Source: Prepared by the author, 2024

3.8.4 Irrigation frequency

Formula: Frequency = LFA / ETc (3)

Table 6

Irrigation Frequency (days)

Parameter	Value
Crop Evapotranspiration (mm/day)	3.4
Easily Available Water (LFA, mm)	23
Irrigation Frequency (days)	6.7

Source: Prepared by the author, 2024

3.8.5 Gross irrigation depth

Formula: Lt = LFA / Ea Where:

- Lt: Gross irrigation depth (mm)
- LFA: Easily available water

- Ea: Application efficiency

Table 7

Gross Irrigation Depth

LFA (mm)	Ea (%)	Lt (mm)
23	80	28.7

Source: Prepared by the author, 2024

Water collectors were placed equidistantly in each irrigated area, and irrigation times were recorded. Christiansen's formula was used to calculate the uniformity coefficient.

3.9 Objective 2: determine the influence of each sprinkler type on cocoa crop productivity

Eight representative cocoa plants per sprinkler type were marked for observation. Flowering and fruit development were monitored after irrigation. The number of flowers and fertilized fruits was recorded to evaluate the success of pollination and fruit set.

3.10 Objective 3: analyze operational costs associated with sprinkler use

Costs for each sprinkler type were calculated considering:

- Number of sprinklers per module
- Unit price per sprinkler
- Fuel cost per hour
- Hours required per sprinkler to apply the gross depth

A cost-benefit analysis was conducted to determine which sprinkler provided the best economic and operational performance.

3.11 Statistical analysis

A descriptive-experimental statistical analysis was used, summarizing results using Tukey’s test at 5% significance.

Table 8

ANOVA (Andeva)

Source of Variation	Formula	df
Treatments	t - 1	2
Error	t(n-1)	21
Total	N - 1	23

Source: Prepared by the author, 2024

4 RESULTS

4.1 Evaluate the influence of different types of sprinklers on irrigation efficiency for cacao cultivation

In the Guayaquil-Balzar region, the Reference Evapotranspiration (ETo) was determined using the CropWat software, yielding a value of 3.2 mm/day. This value reflects the amount of water evaporated and transpired from a reference surface under optimal climatic conditions. The crop coefficient (Kc) for cacao was set at 1.05, used to adjust ETo to the specific water needs of the crop. Consequently, the crop evapotranspiration (ETc) was calculated at 3.4 mm/day, indicating that cacao requires a daily application of 3.4 mm of water to maintain healthy growth under the region's conditions.

The Readily Available Water (RAW), representing the amount of water accessible to the plants before another irrigation becomes necessary, was determined to be 24.0 mm. This ensured that the soil provided enough water to cacao roots without causing water stress. The field capacity (FC) of the soil was 25.0%, meaning the soil could retain up to 25% of its weight in water after irrigation. The permanent wilting point (PWP) was recorded at 13.6%, representing the threshold below which plants can no longer extract water efficiently. The soil bulk density (BD) was 1.4 g/cm^3, and the allowable depletion (AD) level was established at 50%, indicating the percentage of available water that can be used before causing water deficiency.

Based on the data obtained, a 7-day irrigation frequency was recommended. This interval ensures that the cacao crop receives the appropriate amount of water without completely depleting the soil between irrigations. The irrigation frequency was calculated by dividing the Readily Available Water (RAW) by the crop evapotranspiration (ETc), resulting in a 7-day interval. This approach balances efficient water use and prevents water stress, contributing to the healthy and productive development of cacao in the region.

Table 9

Water requirements for cacao crop in La Guayaquil area

Parameter	Value
Reference Evapotranspiration (ETo) (mm/day)	3.2
Crop Coefficient (Kc)	1.1
Crop Evapotranspiration (ETc) (mm/day)	3.4
Field Capacity (FC) (%)	25.0
Permanent Wilting Point (PWP) (%)	13.6
Bulk Density (BD) (g/cm³)	1.4
Allowable Depletion (AD) (%)	65.0
Readily Available Water (RAW) (mm)	23.0
Irrigation Frequency (days)	7

Source: Prepared by the author, 2024

Table 10

Irrigation time by sprinkler type

Treatment	Total Water Depth (mm)	Sprinkler Precipitation (mm/h)	Irrigation Time (h)
B Regulating Arm	28.7	7.0	4h 6m
Banariego 5022	28.7	6.4	4h 30m
Senniger Type	28.7	6.1	4h 42m

Table 10 displays the irrigation time required for each evaluated sprinkler, showing the total water depth applied (28.7 mm), the precipitation rate of the sprinklers in mm/hour, and the time required to apply the specified water depth. For the Regulating Arm, with a precipitation rate of 7 mm/h, the irrigation time was 4 hours and 6 minutes. For the Banariego 5022, with a precipitation rate of 6.4 mm/h, the time was 4 hours and 30 minutes. Finally, the Senniger Type, with a precipitation rate of 6.1 mm/h, required 4 hours and 42 minutes. This indicates that lower precipitation rates increase irrigation duration, as more time is needed to deliver the same volume of water.

4.2 Operating characteristics at average pressure of 6.8 PSI

The evaluated sprinklers (T1, T2, and T3) showed similar flow rates and operating characteristics at an average pressure of 6.8 PSI. The T1 sprinkler (Regulating Arm) had a flow rate of 587.86 l/h, a reach of 6.7 m, and a precipitation rate of 7 mm/h, offering the widest water distribution. T2 (Banariego 5022) had a flow rate of 496.58 l/h, a reach of 6.4 m, and a precipitation rate of 6.4 mm/h. T3 (Senniger Type) had the lowest precipitation rate at 6.1 mm/h, with a flow rate of 387.12 l/h and a reach of 5.8 m.

Table 11

Sprinkler performance at 6.8 PSI

Treatment	Sprinkler	Flow Rate (l/h)	Pressure (PSI)	Reach (m)	Precipitation Rate (mm/h)
T1	Regulating Arm	587.86	6.8	6.7	7.0
T2	Banariego 5022	496.58	6.8	6.4	6.4
T3	Senniger Type	387.12	6.8	5.8	6.1

Source: Prepared by the author, 2024

4.3 Operating characteristics at average pressure of 13.5 PSI

The data also present the behavior of the three sprinklers (T1, T2, and T3) under an average pressure of 13.5 PSI. T1 (Regulating Arm) had a flow rate of 651.73 l/h, a reach of 8.5 m, and a precipitation rate of 4.8 mm/h. T2 (Banariego 5022) had a flow rate of 547.74 l/h, a reach of 7.8 m, and the same precipitation rate (4.8 mm/h). T3 (Senniger Type) had the lowest values again, with a flow rate of 406.75 l/h, a reach of 7.1 m, and a precipitation rate of 4.4 mm/h.

Table 12

Sprinkler performance at 13.5 PSI

Treatment	Sprinkler	Flow Rate (l/h)	Pressure (PSI)	Reach (m)	Precipitation Rate (mm/h)
T1	Regulating Arm	651.73	13.5	8.5	4.8
T2	Banariego 5022	547.74	13.5	7.8	4.8
T3	Senniger Type	406.75	13.5	7.1	4.4

Source: Prepared by the author, 2024

4.4 Influence of each sprinkler type on cocoa crop productivity

To determine the effectiveness of each sprinkler system in cocoa crop productivity, flowering was used as a key indicator. The number of flowers per tree was recorded in each plot, corresponding to the three different sprinkler systems evaluated. An analysis of variance (ANOVA) indicated that the number of flowers per tree showed statistically significant variability between treatments, with a coefficient of variation (CV) of 17.28%.

The results showed that the B Regulating Arm sprinkler produced an average of 224.00 flowers per tree, while the Banariego 5022 sprinkler yielded an average of 197.25 flowers. These two sprinklers did not differ statistically from each other ($p > 0.05$), indicating that they were similarly effective in promoting flower development.

In contrast, the Senniger-type sprinkler registered the lowest flower production, with an average of 161.50 flowers per tree, a result that was statistically inferior compared to the other two treatments.

Table 11

Number of flowers per tree under different sprinklers

Sprinkler Type	Flowers/Tree	Grouping (Tukey Test)
B Regulating Arm	224.00	a
Banariego 5022	197.25	a b
Senniger Type	161.50	b
Coefficient of Variation	**17.28 %**	

Means sharing a common letter are not significantly different (Tukey 5%).
Source: Author's elaboration, 2024.

Subsequently, the average number of fertilized fruits per tree was assessed to determine fruit set success. According to the ANOVA, sprinkler type significantly influenced fruit set, with a coefficient of variation of 24.19%. Tukey’s test at a 5% significance level revealed that the B Regulating Arm sprinkler achieved the highest number of fruits per tree, with a mean of 29.75, statistically equivalent to the Banariego 5022 sprinkler, which produced an average of 22.13 fruits per tree.

Once again, the Senniger-type sprinkler showed the lowest performance, with an average of 19.88 fruits per tree, and was statistically different from the B Regulating Arm sprinkler. This high variability may reflect differences in irrigation efficiency among the sprinklers or variations in environmental or agronomic conditions.

Table 12

Number of fertilized fruits per tree under different sprinklers

Sprinkler Type	Fruits/Tree	Grouping (Tukey Test)
B Regulating Arm	29.75	a
Banariego 5022	22.13	a b
Senniger Type	19.88	b
Coefficient of Variation	**24.19 %**	

Means sharing a common letter are not significantly different (Tukey 5%).
Source: Author's elaboration, 2024.

4.5 Analyze the operating costs associated with sprinkler use

The economic analysis of irrigation treatments is essential in agricultural decision-making, as operational costs have a direct impact on the profitability of productive systems. In this regard, the variable costs associated with the use of three types of sprinklers in cocoa cultivation were evaluated, specifically examining monthly fuel expenses and the initial investment related to the sprinklers used per irrigation module.

Table 17 presents the monthly fuel costs based on the operational time of each system. The Senniger-type sprinkler, with an average operation time of 4.7 hours per irrigation, exhibited the highest monthly fuel cost, reaching $45.12, representing a heavier economic burden compared to the other treatments. The second-highest expense corresponds to the Banariego 5022 sprinkler, with $41.28, while the Regulating Arm sprinkler proved to be the most energy-efficient, with a monthly consumption of $39.36. These differences are directly linked to the duration required to complete each irrigation cycle, being shorter in the case of the Regulating Arm sprinkler.

Table 17

Monthly fuel costs by type of sprinkler

Sprinkler	Irrigation time (h)	Monthly cost ($)
Regulating Arm	4.1	39.36
Banariego 5022	4.3	41.28
Senniger Type	4.7	45.12

Source: Author’s elaboration, 2024.

Meanwhile, Table 18 outlines the costs related to the quantity and unit price of sprinklers required for a single irrigation module. Once again, the Senniger-type sprinkler represents the most expensive treatment, with a unit price of $1.25 and a requirement of 30 units per module, resulting in an initial investment of $37.50. In contrast, the Regulating Arm sprinkler demonstrates a more cost-effective solution, with a unit value of $0.90 and a total cost of $27.00 per module. The Banariego 5022, with a unit price of $1.00 and 30 units as well, accumulates a total of $30.00.

Table 18

Sprinkler acquisition costs per module

Sprinkler	Unit price ($)	Quantity	Subtotal ($)
Regulating Arm	0.90	30	27.00
Banariego 5022	1.00	30	30.00
Senniger Type	1.25	30	37.50

Source: Author’s elaboration, 2024.

6 DISCUSSION

The results of this research clearly demonstrate the influence of sprinkler type and operating pressure on irrigation efficiency in cocoa crops, consistent with theoretical principles and previous studies reviewed in the introduction. When comparing the hydraulic performance of the sprinklers, it was found that type T1 (Regulating Arm) at a pressure of 6.8 PSI delivered the highest flow rate (587.86 l/h) and a significant reach (6.7 m), which enabled better area coverage with a precipitation rate of 7 mm/h. This partially confirms the initial hypothesis that greater water distribution capacity leads to more uniform and effective irrigation.

However, at a higher pressure of 13.5 PSI, although the flow increased to 651.73 l/h, the precipitation rate decreased to 4.8 mm/h, suggesting reduced efficiency in water deposition. This aligns with findings by Tandazo *et al*. (2018), who emphasized that there is an optimal operating pressure to maximize irrigation performance in cocoa crops, warning that excessive pressure can reduce distribution uniformity. These results add new empirical evidence to this discussion by offering specific data on the hydraulic behavior of various sprinklers under different pressure levels.

Moreover, in terms of distribution uniformity (DU), sprinklers T1 and T2 achieved acceptable values, whereas module 3 exhibited DU below 75%, supporting the conclusions drawn by Pérez and Domínguez (2019), who stressed the critical role of both sprinkler type and operating conditions in ensuring irrigation efficiency. These observations reinforce the external validity of our findings and highlight the technical importance of proper irrigation system design.

Regarding the agronomic impact of irrigation on cocoa productivity, our findings revealed significant differences in flowering and fruiting depending on the type of sprinkler used. The Regulating Arm sprinkler recorded an average of 224 flowers and 29.75 fruits per tree, outperforming the Senniger type, which reported the lowest values (161.50 flowers and 19.88 fruits). These results are consistent with Arboleda *et al*. (2019), who found that efficient irrigation systems promote fruit set in crops sensitive to water variability, such as cocoa.

This study also reinforces the insights provided by Jaimez *et al*. (2022), who highlighted the physiological sensitivity of the CCN 51 cocoa cultivar to environmental and water-related factors. Our results demonstrate that water distribution uniformity and flow rates directly influence productivity, not only in terms of water volume but also in terms of proper coverage and soil infiltration.

In a broader context, cocoa cultivation is facing increasing pressures due to climate change, resource scarcity, and socio-economic shifts in the value chain. As Kongor *et al*. (2024) pointed out, sustainable cocoa production in the 2020s requires the integration of technological improvements and context-specific agronomic practices. In this light, the appropriate selection of sprinkler type, along with careful regulation of working pressure, becomes a key strategy for enhancing water use efficiency and increasing agricultural yield under variable conditions.

Additionally, the importance of irrigation in the socio-economic landscape of Ecuadorian cocoa production cannot be ignored. Zambrano *et al*. (2024) found that the COVID-19 pandemic exposed vulnerabilities in the cocoa value chain, with producers relying on efficient resource use to sustain their livelihoods. Similarly, Burgos *et al*. (2025) emphasized that small producers' access to reliable information and appropriate fertilization or irrigation strategies plays a central role in their competitiveness, especially in regions such as Guayas and Los Ríos, where much of Ecuador's cocoa is produced.

Moreover, Tinoco *et al*. (2024) underlined that cocoa agroforestry systems in the Ecuadorian Amazon benefit from tailored irrigation strategies that account for ecological and crop-specific dynamics. The data from our study complement these perspectives by showing how irrigation system selection can be adapted to the agro-ecological conditions and economic constraints faced by producers.

In summary, this study not only confirms theoretical assumptions and previous empirical findings but also contributes valuable practical evidence for improving irrigation systems in cocoa cultivation. The results have broader implications for agricultural sustainability, climate adaptation, and the socio-economic resilience of cocoa producers in Ecuador and beyond.

7 CONCLUSIONS

This study set out to evaluate the operational efficiency and economic impact of three different sprinkler types (T1 (Regulating Arm), T2 (Banariego 5022), and T3 (Senniger)) used in the irrigation of Theobroma cacao L. The objective was achieved by analyzing technical parameters (such as flow rate, reach, and uniformity), productivity metrics (flowers and fruits per tree), and operational costs (fuel consumption and sprinkler investment). Through field experimentation and comparative analysis, the study confirmed that the type of sprinkler significantly influences irrigation efficiency and ultimately impacts cacao productivity.

Among the evaluated sprinklers, the T1 (Regulating Arm) demonstrated the most effective performance in terms of water distribution uniformity and productivity output. It delivered higher flow rates and coverage, which translated into a greater number of flowers and fruits per cacao tree. However, its efficiency showed sensitivity to increasing pressure, suggesting the need for precise pressure regulation. Conversely, the Senniger sprinkler exhibited lower efficiency, resulting in reduced yields, reinforcing the correlation between irrigation performance and plant productivity.

From an economic standpoint, the T1 sprinkler also emerged as the most cost-effective option. It incurred the lowest fuel consumption and required the least initial investment, making it a more sustainable choice for small and medium-scale cacao producers. These findings underscore the necessity of tailored irrigation management that takes into account both agronomic and economic factors.

The study contributes to the growing body of research on precision agriculture and sustainable cacao production systems. However, several limitations must be acknowledged. First, the research was conducted under specific agro-climatic conditions in Ecuador, which may limit the generalizability of the results. Second, the assessment was carried out over a limited temporal scope; longer-term studies could provide more robust insights into the performance of irrigation systems across different seasons and cacao development stages.

Future research should explore the integration of automated soil moisture monitoring technologies to optimize irrigation scheduling and water use. Additionally, it would be beneficial to study the interaction between irrigation types and other agronomic factors, such as fertilization, pest control, and shade management, to develop a holistic irrigation strategy for cacao cultivation. Expanding the scope to include different cacao varieties and ecological zones could further enhance the applicability of the findings.

In conclusion, the study validates the hypothesis that efficient water distribution through well-selected sprinkler systems can significantly enhance cacao productivity. The Regulating Arm sprinkler (T1) stands out as the most promising tool for improving yield and resource efficiency, contributing to sustainable cacao production practices in Ecuador and similar agricultural contexts.

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Authors' Contribution

All authors contributed equally to the development of this article.

Data availability

All datasets relevant to this study's findings are fully available within the article.

How to cite this article (APA)

Haro, C. A. P., Sacoto, A. Y. L., Schuldt, A. S. C., & Arevalo, G. M. (2026). ASSESSMENT OF COCOA CROP YIELD UNDER IRRIGATION WITH THREE TYPES OF SPRINKLERS IN FIELD CONDITIONS. Veredas Do Direito, 23(1), e234308. https://doi.org/10.18623/rvd.v23.n1.4308