



Effect of irrigation frequency on cocoa (*Theobroma cacao* L.) bean quality in Ghana's major production zone

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ABSTRACT

The productivity and quality of cocoa, a key economic crop in Ghana, are increasingly threatened by erratic rainfall and climate variability. This study investigates how different irrigation frequencies affect cocoa bean quality across three major production regions in Ghana: Western, Central, and Eastern. The study adopts a field-based experimental design assessing three irrigation regimes: morning, evening, and every two days. Key quality parameters evaluated included bean count, moisture content, and purity levels. Standardized post-harvest processing and laboratory techniques were employed, and data were analysed using ANOVA with Tukey's test for mean separation at $p < 0.05$. Results showed that irrigation frequency significantly influenced bean count and purity levels, with notable regional variations. In the Western Region, morning irrigation yielded the highest bean count (125.7) and purity (97.77%). Conversely, in the Central Region; evening irrigation produced the highest bean count (113), while in the Eastern Region; a two-day interval gave the highest count (122). Moisture content remained relatively stable (6.8–7.2%) across treatments and regions, indicating that post-harvest drying practices were effectively managed. However, purity decreased with increased irrigation frequency, highlighting a trade-off between yield and quality under intensive watering. These findings suggest that optimising irrigation schedules based on regional agro-climatic conditions can significantly improve cocoa yield without compromising quality. The study underscores the need for climate-adapted irrigation strategies and offers data-driven insights for resource allocation in Ghana's cocoa sector. It also highlights the importance of integrating quality-focused irrigation management into broader climate resilience and sustainable cocoa production frameworks. This research provides a practical foundation for policymakers, cocoa extension officers, and farmers seeking to enhance cocoa quality and market competitiveness under water-scarce conditions.

Keywords: Cocoa bean quality, Irrigation scheduling, Bean count, Climate resilience, Post-harvest quality, Water management, Regional variation

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Introduction

Cocoa (*Theobroma cacao* L.) cultivation is pivotal for agricultural development and economies of tropical countries due to its worldwide production amounting to over 5.2 million tonnes per year (ICCO, 2023). Cocoa is the most crucial raw material for the \$130 billion chocolate industry and directly cultivates about 50 million smallholder



farmers and their families, mostly located in West Africa, Southeast Asia, and Latin America (Fountain and Hütz-Adams, 2020). Climate change poses increasing risks to the sustainability of cocoa production, with shifting precipitation patterns and heightened drought incidences undermining traditional cultivation zones (Läderach *et al.*, 2021). These environmental stresses have elevated the focus on irrigation management systems governed by the stark environmental water availability (Dewi *et al.*, 2020). The post-harvest value of cocoa beans is determined by several factors, including genetic, environmental, and management dynamics that influence the ultimate market price and the ease with which they are processed. Of the various quality parameters, bean count or the number claimed to be present in a 100g portion of beans is considered one of the most important indicators of the size of cocoa beans and thus affects the operational efficiency of the processing as well as the yield of butter extracted from cocoa (Afoakwa *et al.*, 2021). The desire for certain moisture content increases the efficiency of handling the yield after harvest and the chemical changes during fermentation. Moisture content, less than 6-7%, is ideal for maintaining the quality and shelf stability of cocoa and the development of flavour.

The availability of water during the pod developmental phase determines the biochemical composition of cocoa beans and their shape. According to Ndukwu *et al.*'s (2011) study, water stress during pod filling is known to reduce the size of the beans and also affect how carbohydrates are utilised within the beans. However, the direct impact on quality measures remains poorly assessed. Also, Ayegboyan and Akinrinde (2016) observed strong genotype-environment interactions in drought sensitivity, affirming that irrigation management may require adjustment for different cocoa varieties. The problem of seeking optimal irrigation frequency and specifically defined quality poses a challenge for industry operators wishing to optimise irrigation while sustaining the desired quality standards. Based on model outcomes under changing climate conditions, there is increasing concern over water availability in the main growing zones for cocoa in Ghana, predicting a reduction of around 30 to 40 per cent in the land suitable for growing cocoa by 2050 if current frameworks remain (Bunn *et al.*, 2019). Thus, calls for new measures to be established, where irrigation is emerging as a significant one, albeit there is low adoption

within traditional cocoa farming systems. Resource allocation strategies highlighted are critical given the need for more reliable data on the optimal use of controlled methodologies, where, according to Niether *et al.* (2020), the need for large capital expenditures focused on irrigation networks makes proposed guidance on controlled amounts and applied frequency crucial for making informed decisions. Understanding quantitative relationships between irrigation scheduling and quality outcomes would provide valuable decision support for producers navigating climate uncertainties.

The cocoa crop's developmental response to irrigation follows its evolution as an understory species of humid forests. Cocoa is drought-tolerant to some extent, practising leaf curling and stomatal closure, but scenarios of water deficit stretch too far, deplete photosynthesis and carbon sink allocation to growing pods (Carr and Lockwood, 2019). Moderate water deficit at the pod filling stage is associated with low final bean size, a change in the biochemical composition, which may alter flavour and nutritional profile, like minerals and vitamins (Ackah and Dompey, 2021). Excessive irrigation, on the other hand, stunts the development of flowers and fruits, and sometimes influences their set, initiating a crucial balance from water management systems. Cacao beans' significance transcends agricultural productivity. The bean's nutritional value is remarkable, holding over 300 chemical compounds such as bioactive polyphenols and fatty acids (Aprotosoai *et al.*, 2016). The health-promoting molecules measured among water-stressed and well-watered cocoa, claimed to be theorised by Souza *et al.* (2020) through metabolomics examinations, showed bean dose with irrigation control bore significant differences in hectare's worth of flavanol content. Also, Konaté *et al.* (2024) confirmed that cocoa beans contain flavonoids that bolster the cardio system, improve functions of endothelial cells, diminish inflammation, and tune up insulin sensitivity. Similarly, Ried *et al.* (2012) confirmed modest but statistically significant reductions in blood pressure among hypertensive populations after cocoa consumption.

On the other hand, inadequate quality control in cocoa production poses risks to public wellness. Mycotoxin contamination, for example, is an everlasting issue with ochratoxin A and aflatoxins in improperly dried beans, and a higher moisture content is strongly associated with fungal growth (Copetti *et al.*, 2014). Cocoa of low quality

also lacks some of its beneficial compounds because suboptimal conditions during cultivation would result in reduced polyphenol production and retention (Racine *et al.*, 2019). These challenges affect the quality of cocoa products and the potential to access foreign markets, hence the low price. Recent works in cocoa production irrigation emphasise enhancement of vegetative growth and superficial yield indices, overshadowing more intricate aspects of bean quality (Niether *et al.*, 2020). When the quality of cocoa beans is considered, quantitative criteria were not applied; instead, qualitative approaches were taken (Saleh *et al.*, 2018). This gap in research has inhibited the development of precise irrigation frequency in most of the cocoa production zones in Ghana. But with increasing emphasis on water as a limited resource, the need for optimisation in irrigation systems is highlighted, as shown by Saleh *et al.* (2018), which indicates differences in water use effectiveness across various production systems. To address these challenges, this study investigates how irrigation frequency affects cocoa bean quality in Ghana's Western, Central, and Eastern Regions. By measuring bean count, moisture content, and purity under different irrigation schedules (morning, evening, and every two days), the research provides empirical data to inform irrigation strategies that balance productivity and quality. These findings are essential for policymakers, agronomists, and cocoa producers aiming to modernise production systems in line with climate adaptation strategies and global market standards.

Material and Methods

Study area

The study was conducted in three major cocoa-producing regions of Ghana: the Central Region (CR), the Eastern Region (ER), and the Western Region (WR). The experiment at Western Region was done on a 8 ha cocoa farm at the Daboase District located at latitudes 5° 5' 31.74"N and longitudes 1° 45' 17.49" W. The cocoa farm in the Eastern Region is located at Latitude 5.9811733N and Longitude 1.105495W, situated in the Camp Junction Community in the Oda District. The cocoa type is hybrid and the farm size is 31.2 ha. Also, in the Central Region, the farm is situated at Latitude 5.7506183N and Longitude 1.3399933W. It is located in the Kwame Tatra Community in the Foso District. The cocoa type is hybrid and the farm size is 10 ha.

Study design

This study adopted a field-based experimental design to evaluate the effect of different irrigation frequencies on cocoa bean quality parameters. Three healthy cocoa trees from each irrigation treatment, watering every morning, every evening, and every two days, were selected for pod harvesting. All trees were subjected to similar agronomic and environmental conditions except for the irrigation schedule. The selection ensured consistency and minimised confounding variables.

Data collection and processing

Cocoa pods were harvested from each selected tree and recorded according to their irrigation treatment group. The harvested pods were broken manually, and the beans were subjected to standard fermentation and drying procedures to ensure uniformity before quality evaluation. From each irrigation frequency category, three bean samples were randomly selected and packed in labelled sampling bags for laboratory analysis. Each sample weighed at least 100 g and was used for bean count, moisture content, and cut test assessments.

Quality parameters

Moisture content analysis (M.C.) %

The equipment used was an Aquaboy Moisture Meter, and the procedure included insertion of the cup electrode of the moisture meter into the beans. Three readings (MC1, MC2, MC3) for each sample were taken, and the average moisture content (AMC) was calculated using the formula:

$$M.C.\% = \frac{M.C_1 + M.C_2 + M.C_3}{3} \quad (1)$$

Bean count analysis

The equipment used was the Coco-scale. The procedure used included measuring 100g of beans from each sample bag and counting the number of beans (BC1, BC2, BC3). The total bean count (TBC) and average bean count were calculated using the formula:

$$\text{Bean Count} = \frac{BC_1 + BC_2 + BC_3}{3} \quad (2)$$

Uniformity test

Coco-scale and visual inspection were used for this test. For each weighed sample, unusual beans were picked out and the count recorded as UB1, UB2, and UB3. The unusual beans were calculated as follows:

$$\text{Total Unusual Beans (TUB)} = UB_1 + UB_2 + UB_3. \quad (3)$$

Cut test analysis

Samples were divided into three portions using a knife and were placed into three sampling bags labelled A, B, and C, treating each bag as a separate lot. From bag A, 100 beans were randomly picked and cut lengthwise to expose the nib. The cut surfaces were carefully examined and all defective beans were identified, including those affected by mould, slaty, germination, insect damage, decay, and flatness, and categorized. The total defective beans were calculated for mould, slaty, and other defects (germinated + insect-damaged + decayed & flat). Finally, the percentage purity was determined using the formula:

$$\frac{\text{Purity}}{\text{Total Beans}} \times 100 = \frac{\text{Total beans} - \text{Total Defective beans}}{\text{Total Beans}} \times 100 \quad (4)$$

Statistical analysis

Data collected was subjected to both one-way analysis of variance (ANOVA) procedure using GenStat software to investigate whether there were statistical differences in the parameters studied. Comparison of means will be done using the Tukey Test at a probability level of 0.05.

Results and Discussion

Irrigation frequency on bean counts, moisture content, and purity levels of cocoa yields across three regions

The analysis of this study demonstrates that irrigation frequency significantly influences cocoa bean count and purity levels, with region-specific responses observed across Ghana's major cocoa-producing zones. In the Western Region (WR), bean count varied

significantly with irrigation frequency ($p < 0.001$) (Table 1). Morning irrigation resulted in the highest mean bean count (125.7), followed by the two-day interval (106.3), with evening irrigation producing the lowest count (92.0). Moisture content did not differ significantly among treatments ($p = 0.110$), with values ranging from 7.03% to 7.26%. Purity percentage, however, was significantly affected ($p = 0.001$): morning irrigation had the highest purity (97.77%), evening was slightly lower (96.20%), and the two-day interval recorded the lowest purity (89.53%).

In the Central Region (CR), irrigation frequency also significantly affected bean count ($p < 0.001$). Evening irrigation yielded the highest count (113), followed by the two-day interval (102), while morning irrigation had the lowest (93). Moisture content did not show significant differences ($p = 0.125$), with all treatments hovering around 7.0–7.2%. Purity percentage was not significantly affected ($p = 0.724$) and remained consistent across treatments, averaging approximately 89%.

In the Eastern Region (ER), the highest bean count was recorded under the two-day irrigation interval (122), with evening and morning irrigation producing 107 and 93 beans, respectively ($p < 0.001$). Moisture content increased significantly with less frequent irrigation ($p = 0.003$), ranging from 6.8% (morning) to 7.2% (two-day interval). Purity percentage also varied significantly ($p = 0.004$); morning irrigation resulted in the highest purity (94.77%), while two-day interval irrigation had the lowest (88.20%).

Table 1. Effect of irrigation frequency on bean counts, moisture content, and purity levels of cocoa yields across three regions.

Regions	Irrigation Frequency	Bean count	Moisture content (%)	Purity percentage (%)
WR	Morning	125.7±1.52 c	7.26± 0.20 a	97.77±0.50 b
	Evening	92.0±2.00 a	7.03±0.05 a	96.20±2.53 b
	Two days	106.3±1.52b	7.03±0.05 a	89.53±0.68 a
	P-value	<.001	0.110	0.001
CR	Morning	93±1.0 a	7.1±0.1 ab	89.80±0.85 a
	Evening	113±2.0 c	7.2±0.1 b	89.43±0.80 a
	Two days	102±1.0 b	7.0±0.1 a	89.13±1.25 a
	P-value	<.001	0.125	0.724
ER	Morning	93±1.0 a	6.8±0.1a	94.77±2.20 b
	Evening	107±3.0 b	7.0±0.0 b	90.23± 0.50 b
	Two days	122±1.0 c	7.2± 0.1 c	88.20±1.01 a
	P-value	<.001	0.003	0.004

Effect of irrigation frequency on bean counts, moisture content, and purity levels of cocoa yields across all regions

Figure 1 shows the effects of irrigation frequency, 0 hours, 12 hours, and 24 hours, on (a) bean count, (b) moisture content, and (c) purity percentage across all regions. As presented in Figure 9a, bean count increased significantly with irrigation frequency. While no significant difference was observed between 0 hours and 12 hours, bean count rose notably at 24 hours, reaching a mean close to 113, compared to approximately 106 at the lower frequencies. However, in Figure

1a, moisture content remained statistically similar across all treatments. The average values fluctuated narrowly around 7.1%, showing that irrigation frequency did not significantly affect bean moisture content. Purity percentage (Figure 1c) decreased significantly as irrigation frequency increased. The highest purity (~95.5%) occurred at 0 hours, followed by 12 hours, and the lowest purity was recorded at 24 hours. These differences were statistically significant, as indicated by different letter groupings.

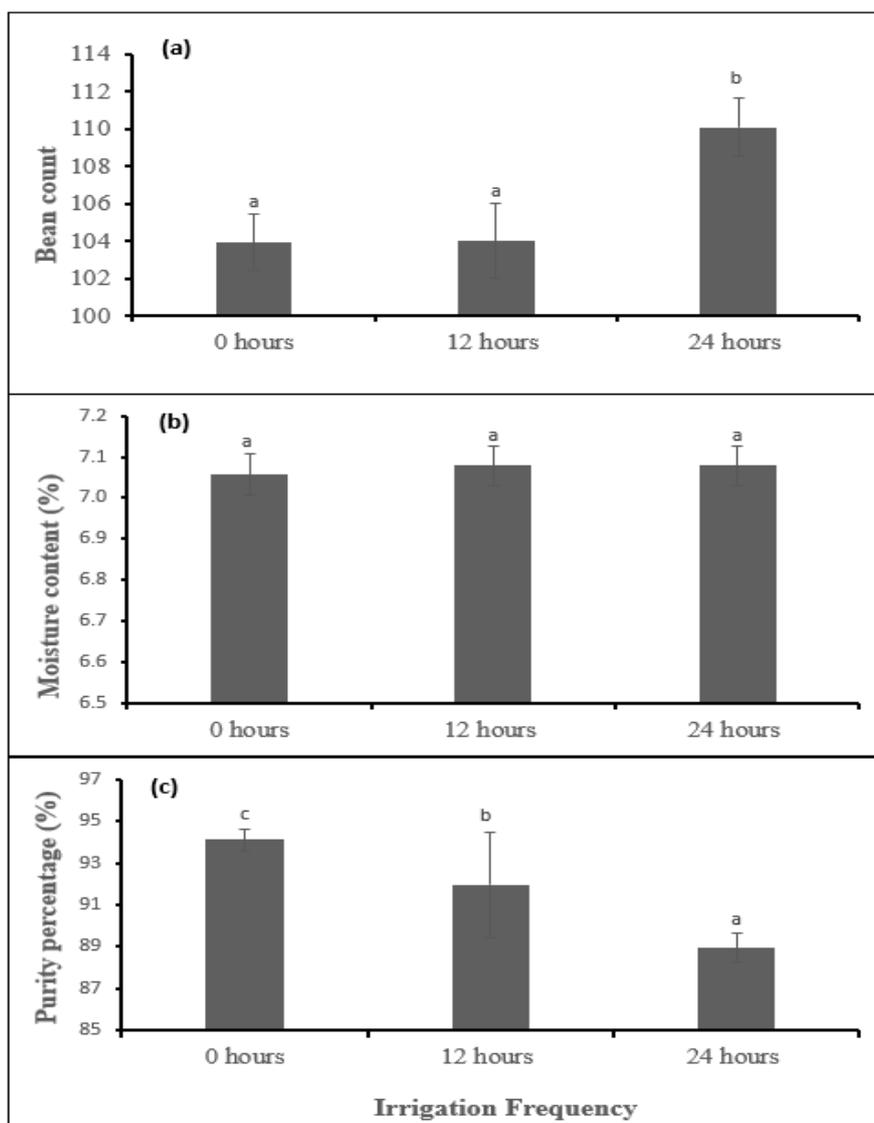


Fig. 1. Effect of irrigation frequency on bean counts, moisture content, and purity levels of cocoa yields across all regions.

Regions on bean counts, moisture content, and purity levels of cocoa yields

Figure 2 presents the effects of region (Western, Central, and Eastern) on (a) bean count, (b) moisture content, and (c) purity

percentage in cocoa yields. From Figure 2a, Western and Eastern regions showed similarly high bean counts. The Central region had the lowest bean count, significantly different from the other two

regions. There were no statistically significant differences in moisture content across the three regions. In Figure 2c, the Western Region recorded the highest purity percentage, significantly higher than both the

Central and Eastern Regions. The Central region had the lowest purity, while the Eastern Region showed a moderate value in between.

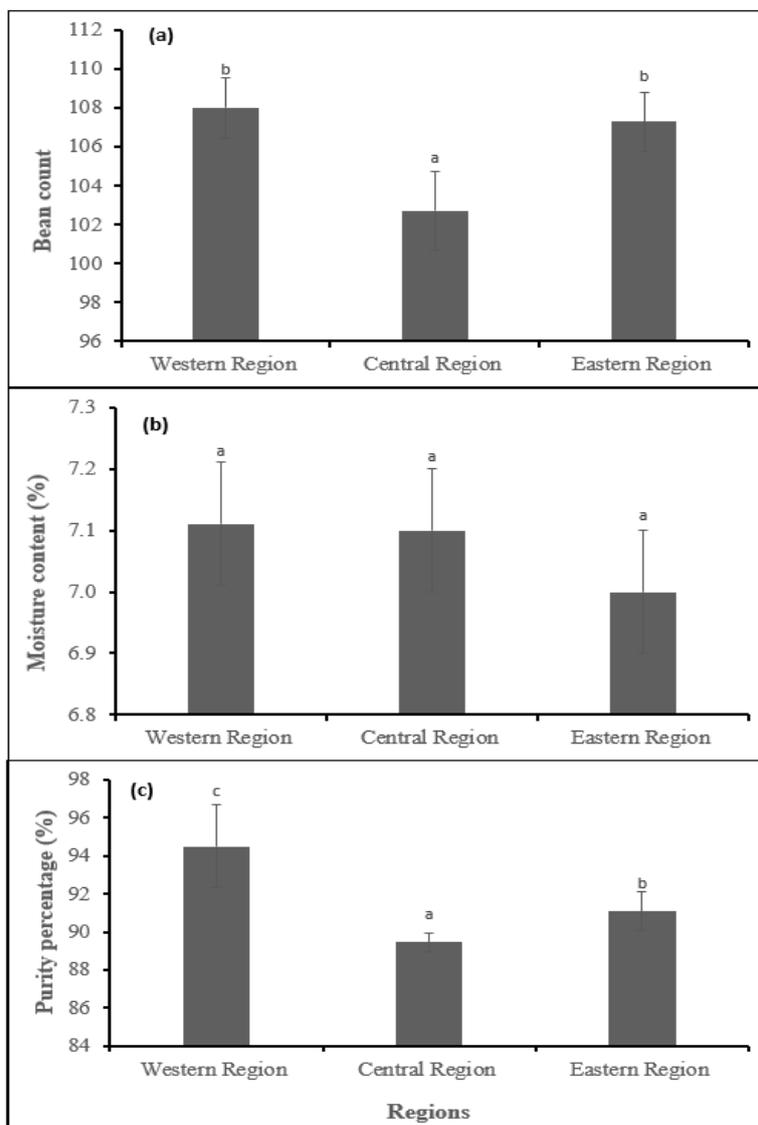


Fig. 2. Effect of regions on bean counts, moisture content, and purity levels of cocoa yields.

Irrigation frequency on bean counts, moisture content, and purity levels of cocoa yields across three regions

The significant differences in bean count across regions and irrigation schedules underscore how local environmental conditions and irrigation timing interact to influence cocoa productivity. In WR, the good performance under morning irrigation suggests that aligning water application with early-day physiological activity may improve nutrient uptake and pod development. Morning hours coincide with peak stomatal conductance, which enhances water use efficiency, an interpretation supported by findings from [Hucheon *et al.* \(1973\)](#), who

observed that properly timed irrigation improved cocoa yield during dry seasons in Trinidad. In CR, the pattern was reversed, with evening irrigation producing the highest bean counts. This could reflect regional differences in temperature and soil moisture dynamics. Evening irrigation may reduce evaporative losses in CR's conditions, allowing more water to infiltrate and be available for root uptake overnight. Similarly, [Ayegboyin and Akinrinde \(2016\)](#) emphasised the variability in cocoa's irrigation needs across Ghana, pointing to the role of microclimate and soil characteristics in determining optimal watering schedules.

In ER, the highest bean count from the two-day interval suggests that less frequent watering may be beneficial, possibly by promoting deeper root systems or avoiding over-saturation. This supports Hucheon *et al.*'s (1973) observation that longer irrigation intervals can enhance productivity in years with moderate drought by reducing vegetative overgrowth and focusing resources on reproductive development. Moisture content remained largely unaffected by irrigation in WR and CR, indicating that post-harvest drying practices were effective at maintaining optimal bean moisture regardless of field treatment. However, in the ER, irrigation frequency had a measurable impact on moisture levels. This could be due to local humidity or slower drying rates when water was applied closer to harvest. Ndukwu *et al.* (2011) also found that while field conditions matter, post-harvest processes like fermentation and drying are the primary determinants of final bean moisture content.

Purity percentage showed a consistent advantage for morning irrigation in WR and ER, likely due to more uniform pod development and reduced disease pressure. Beans from these treatments were cleaner and more uniform, suggesting that early-day watering supports better physiological balance during critical stages of pod development (Islam *et al.*, 2023). Opoku-Ameyaw *et al.* (2011) highlighted the link between consistent irrigation during pod filling and the reduction of defects such as mould, underscoring the role of water timing in quality control.

Effect of irrigation frequency on cocoa yield and quality parameters

The results from Figure 1 suggest a clear trade-off between cocoa yield quantity and bean quality under varying irrigation frequencies. The significant increase in bean count at the 24-hour irrigation interval indicates that more frequent watering can enhance pod development, likely due to improved nutrient uptake and sustained physiological activity in the plant (Saleh *et al.*, 2018; Souza *et al.*, 2020). This finding aligns with Läderach *et al.* (2013), who observed that consistent soil moisture availability supports higher cocoa yields, especially during dry spells when moisture stress limits pod growth.

However, the decline in purity percentage with increasing irrigation highlights a quality problem. The highest purity was observed in beans that received no irrigation, while the lowest occurred under the 24-hour irrigation regime. Over-irrigation may encourage excessive vegetative growth or create damp field conditions that promote fungal infections, mould growth, or delayed pod maturation, all of which can reduce bean

cleanliness and uniformity. This interpretation is supported by Opoku-Ameyaw *et al.* (2011), who emphasised the importance of avoiding waterlogging in cocoa fields to maintain bean quality and limit contamination during pod development and post-harvest handling. However, moisture content remained stable across irrigation levels. This suggests that post-harvest drying and fermentation practices were effective at regulating final moisture content in beans, regardless of field treatment. Haruna *et al.* (2025) also reported that, although field conditions influence bean characteristics, final moisture is primarily determined by post-harvest processing.

Cocoa yield and quality parameters as affected by regions

The regional differences observed in Figure 2 highlight how environmental and agronomic conditions can influence cocoa yield and quality. The higher bean counts in the Western and Eastern regions compared to the Central region may be attributed to favourable agro-ecological factors such as richer soils, better rainfall patterns, and more established cocoa farming systems. According to Osei (2017) and Asante *et al.* (2022), the Western Region is Ghana's most productive cocoa zone due to its optimal temperature and rainfall, which support vigorous tree growth and pod development. The lack of significant differences in moisture content across regions suggests that post-harvest drying practices are relatively uniform or standardised across locations. This echoes findings by Haruna *et al.* (2025), who noted that final moisture in beans is typically shaped more by post-harvest handling than by field location.

The Western Region's significantly higher purity could be due to better harvest hygiene, more efficient fermentation and drying processes, or even the presence of local knowledge and infrastructure to support quality cocoa handling (Ackah and Dompey, 2021). In contrast, the Central region, with the lowest purity, may face constraints such as poor drying facilities, higher pest pressure, or less consistent quality control during processing. In earlier studies, these factors have been linked to bean contamination and inconsistency (Opoku-Ameyaw *et al.*, 2011). According to the Ghana Cocoa Report (2024), regional disparities in infrastructure, knowledge, and agro-climatic conditions play a substantial role in shaping yield and the quality of cocoa beans.

Conclusion

This study provides critical insights into how irrigation frequency influences cocoa bean quality across Ghana's major cocoa-producing regions. The findings show that

the irrigation schedule significantly affects two key parameters: bean count and purity percentage, while having minimal impact on moisture content, which remained within acceptable post-harvest standards due to consistent drying practices. In the Western Region, morning irrigation resulted in the highest bean count and purity, likely due to alignment with peak plant physiological activity. In contrast, the Central Region favoured evening irrigation, possibly due to lower evaporative losses during cooler periods. In the Eastern Region, a two-day interval yielded the highest bean count, suggesting that moderate irrigation intervals may encourage better pod development without oversaturation. These results demonstrate that optimal irrigation strategies are region-specific, depending on local agro-climatic conditions and farm management practices.

A key finding is the inverse relationship between irrigation frequency and bean purity. As irrigation became more frequent, purity levels decreased across all regions, likely due to increased susceptibility to fungal contamination or reduced uniformity in pod maturation. This highlights a trade-off between maximizing yield through frequent irrigation and maintaining high-quality standards. In practice, cocoa producers must navigate this balance to meet both quantity and quality targets, especially for export markets with stringent quality requirements. The broader implications of this research support the integration of precision irrigation strategies into climate-resilient cocoa production systems. With increasing pressure on freshwater resources and anticipated climate shifts, efficient irrigation not only sustains yields but also ensures quality control. The study underscores the need for regional irrigation guidelines tailored to specific environmental contexts, rather than one-size-fits-all recommendations. By filling the knowledge gap on quantitative relationships between irrigation frequency and cocoa bean quality, this study contributes to ongoing policy and research efforts aimed at modernising Ghana's cocoa sector. It encourages the adoption of smart water use practices and strengthens the case for investing in infrastructure and extension services that promote evidence-based irrigation management.

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Author Contributions

All authors contributed to the study conception. Design for the article: FKN, LKSA, ROD, JDOS; Literature search and data analysis: FKN, ROD, FK, CN; Writing - original draft: FKN, LKSA, ROD, FK; and all authors commented on previous versions of the manuscript; Review and editing: FKN, LKSA, JDOS, CN. All authors read and approved the final manuscript.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Conflicts of interest: The authors declare no conflicts of interest related to this publication.

Ethical: The current study did not include any human or animal subjects. Thus, this study is not subject to an ethics review committee and does not require any informed consent.

Competing Interests: The authors have no relevant financial or non-financial interests to disclose.

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