



## Analysis of Cashew Tree Yield Variability at the Tree and Orchard Scales

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### Abstract

This study was conducted across 24 orchards in the Poro region of Côte d'Ivoire to evaluate the influence of tree age and planting density on cashew tree productivity. Morphological characteristics (height, diameter at breast height (DBH), and canopy spread) and cashew nut weight were measured every two days for 162 trees. To examine the relationship between morphology, planting density, and yield, we employed a one-way analysis of variance (ANOVA) and multiple linear regression analysis using the Ordinary Least Squares (OLS) method. The ANOVA results revealed that planting density is a determining factor for yield. High-density plantations (300 trees/ha) promote vertical growth and increase initial yields in young trees. However, this high density limits long-term DBH and canopy development due to increased competition for resources. Conversely, low-density plantations (75 trees/ha) allow for superior development of these morphological traits, resulting in higher productivity in mature trees. Furthermore, the regression analysis confirmed that DBH ( $p = 0.017$ ) and canopy spread ( $p \approx 0.084$ ) are the morphological factors most significantly influencing yield, demonstrating a positive and significant effect. Our findings demonstrate that adequate spacing is essential to maximize long-term yield and ensure the sustainability of cashew plantations. Individual tree productivity is primarily determined by lateral development (DBH and canopy) rather than vertical growth.

**Keywords:** *Anacardium occidentale*, planting density, morphological traits, yield variability, Poro region, Côte d'Ivoire.

### Introduction

Vegetables are gradually acknowledged as crucial for food and nutrition security [22]. However, organic vegetables are increasingly preferable to many consumers as they are shifting their food choice priorities towards food they perceive to be healthier for themselves and the environment. *Cucurbita pepo* is a squash or pumpkin belonging to the *Cucurbitaceae* family and genus *cucurbita* that resembles a gourd, with over 130 genera and up to 800 species [21]. In the agricultural industry, pumpkins are cultivated as vegetables on a large scale, contributing to the agricultural economy. The production and sale of pumpkins, whether for fresh consumption or processing into various products, generate revenue for farmers and the agricultural sector. They are processed into a wide range of food products such as pumpkin soup, pumpkin-based snacks, pumpkin pie filling, etcetera. These processed products contribute to the food industry's revenue and provide employment opportunities in processing and manufacturing plants. The seasonal demand for pumpkins drives retail sales of fresh pumpkins, decorative pumpkins, and pumpkin-related products, contributing to the economy, especially in regions with a vibrant pumpkin culture. In some cultures, pumpkins are an important part of traditional dishes and celebrations, such as pumpkin pie in the USA, or pumpkin lanterns on Halloween. Pumpkin is a natural treasure full of health benefits, from its

Revenue generated from the marketing of cashew nuts is further utilized to fund social ceremonies (such as weddings, funerals, and rituals), acquire consumer goods (including motorcycles and appliances), and invest in housing construction [5].

Overall, the cashew sector supports approximately 2.5 million Ivorians and contributes 7% to the national Gross Domestic Product (GDP) [5].

Despite its socioeconomic importance, the average yield per hectare remains relatively low, estimated at 620 kg/ha, which is significantly below the optimal potential of 1,200 kg/ha for raw cashew nuts (RCN). This yield gap is attributed to several factors, including insufficient agricultural investment, limited knowledge regarding input application, and a lack of proficiency in essential cultural practices, such as pruning. Previous studies have highlighted these challenges, emphasizing that specific agricultural behaviors and technical constraints directly contribute to the low productivity of orchards across the region [7, 8, 9].

Notwithstanding the alarming data on low yields, comprehensive knowledge of tree cropping systems in West Africa remains limited and fragmented. Whether at the micro-scale (individual tree) or the macro-scale (plot or production basin), available data are frequently imprecise, incomplete, or absent

In Côte d'Ivoire, while cashew nuts occupy a strategic position in rural economies—serving as an essential income source for producers in the north and northeast—the crop's potential remains largely under-exploited.

This underperformance is compounded by high yield variability, which remains poorly documented at both the tree and orchard levels. A deeper understanding of this variability is therefore critical to identifying primary limiting factors and developing

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impact of morphological variables (height, canopy diameter, and trunk diameter) on yield per tree. Model validation was based on the fulfillment of normality, homogeneity, and independence assumptions [12]. Data processing and statistical analyses were conducted using Microsoft Excel and RStudio.

**RESULTS**

This section presents the detailed findings from the statistical analyses and field observations conducted in this study. It begins with a descriptive and exploratory analysis of yield variability and morphological parameters, followed by hypothesis testing (ANOVA) and the results of the multiple linear regression modeling regarding the influence of morphological traits on yield.

**Descriptive Analysis**

Descriptive and exploratory data analysis allowed for the characterization of the statistical distribution of yield variables and morphological parameters (height, DBH, and canopy diameter). Table 1: Descriptive statistics of morphological and productive characteristics of cashew trees.

*Table 1: presents the descriptive statistics for the primary morphological characteristics (height, diameter at breast height, and canopy diameter) and yield per tree.*

VARIABLE	MIN.	1ST QU.	MEDIAN	MEAN	3RD QU.	MAX.
DENSITY (TREES/HA)	75	75	150	175	300	300
AGE (YEARS)	5.00	8.75	15.00	16.25	22.50	30.00
TREE_HEIGHT (M)	3.929	5.438	5.889	5.931	6.646	7.341
TREE_DBH (CM)	13.51	18.74	22.48	22.84	24.43	46.04
TREE_CANOPY (M)	4.771	6.591	7.961	7.714	8.327	11.293
YIELD/TREE (KG/TREE)	0.9543	5.0386	9.0886	11.20	11.65	39.33

Regarding morphological parameters, tree height ranged from 3.93 m to 7.34 m, with a mean of 5.93 m. The proximity between the mean and the median indicates relatively homogeneous growth; however, the gap between the extreme values suggests differences in development likely related to tree age or planting density. Furthermore, the DBH, ranging from 13.51 to 46.04 cm (mean = 22.84 cm), and the canopy diameter, varying from 4.77 to 11.29 m (mean = 7.71 m), confirm this trend, revealing a majority of medium-sized trees.

In contrast, yield results indicate high inter-tree variability, fluctuating from 0.95 to 39.33 kg/tree, with a mean of 11.20 kg/tree. Since the median (9.09 kg/tree) is lower than the mean, the distribution is positively skewed, heavily influenced by a few highly productive trees. Consequently, this heterogeneity suggests that productivity depends not only on tree morphology but also on other factors, including genetic variability, micro-environmental conditions, and cultural practices.

Thus, at the individual tree level, productivity appears highly unequal, while at the orchard scale, this intra-plot variability directly influences overall performance and production consistency.

**Univariate Analysis of Variance for Morphological Variables**

Table 4 summarizes the results of the one-way ANOVA conducted to evaluate the combined effects of tree age and planting density on morphological characteristics, specifically Diameter at Breast Height (DBH), canopy diameter (crown spread), and tree height.

*Table 4: Univariate ANOVA for morphological variables.*

VARIABLES	DF	SUM SQ	MEAN SQ	F-STATISTIC	P-VALUE
DBH	11	59164	5379	3.983	0.0126 *
CANOPY	11	3964	360.4	5.757	0.00268 **
HEIGHT	11	1609.4	146.31	2.99	0.0363 *

The results indicate that planting density and age have a significant effect on the trunk diameter growth of cashew trees (F = 3.983; p = 0.0126). Regarding the mean canopy diameter, a highly significant effect was observed (F = 5.757; p = 0.00268), reflecting the sensitivity of crown expansion to variations in density and age. Mean tree height was also significantly influenced by these factors (p < 0.05).

**ANOVA Diagnostic Tests on Residuals**

To ensure the validity of the ANOVA, the underlying assumptions were tested and are summarized in Table 5.

*Table 5: ANOVA validation tests.*

	Variables Shapiro-Wilk (Normality)	Bartlett (Homoscedasticity)	Durbin-Watson (Independence)
DBH	0.6522	0.7476	0.97
Canopy	0.0529	0.1075	0.588
Height	0.8857	0.4956	0.89

The results show that the residuals for DBH, canopy, and height yielded p-values greater than 0.05 for the Shapiro-Wilk, Bartlett, and Durbin-Watson tests. These findings confirm the normality, homogeneity of variances, and independence of the residuals, thereby validating the use of ANOVA for this analysis.

**Multiple Linear Regression: Effects of Morphological Variables on Yield per Tree**

Table 6 presents the results of the multiple linear regression model using the Ordinary Least Squares (OLS) method. This model was developed to assess the influence of height, canopy diameter, and DBH on yield per tree (Log-transformed).

*Table 6: Effects of morphological variables on yield per tree.*

(Intercept)	1.20394	0.43628	2.76	0.00647	**
Height	-0.10500	0.08540	-1.229	0.22072	
Canopy	0.10177	0.06034	1.687	0.05366	.
DBH	0.03044	0.01266	2.405	0.01732	*

Coefficient Estimate Std. Error tvalue Pr(>|t|) Significance

The analysis reveals that DBH and canopy diameter are the primary morphological predictors of yield per tree, showing significant positive effects (p = 0.017 and p ≈ 0.054, respectively). This suggests that more developed radial growth and horizontal architecture favor individual tree production. In contrast, tree height did not have a significant effect on yield (p = 0.221), although a negative trend was observed. Overall, these results indicate that radial vigor (DBH) and horizontal spread (canopy) contribute more to productivity than vertical growth.

**DISCUSSION**

This section interprets the results in light of the initial research hypotheses and existing scientific literature. Graphical and statistical analyses demonstrated that the orchard "type" (defined by age and planting density) significantly influenced yield (following log-transformation) at the 10% significance level. The fundamental assumptions for the ANOVA model, normality of residuals, homogeneity of variances, and the absence of autocorrelation, were validated through their respective diagnostic tests.

These findings provide a robust basis to conclude that the various plot types studied exert distinct impacts on yield.

### **Influence of Density and Age on DBH**

The results indicate that trunk diameter (Diameter at Breast Height, DBH) is significantly influenced by planting density. While high-density configurations may favor vegetative growth in the short term, inter-tree competition for water, nutrients, and solar radiation becomes the primary limiting factor for radial development over the long term. Our observations corroborate the findings of [11], who demonstrated that excessive density triggers tree elongation (etiolation) as individuals compete for light at the expense of secondary (radial) growth.

Conversely, low-density arrangements, such as 75 trees/ha, facilitate superior resource acquisition and utilization by individual trees. This reduced competition fosters accelerated growth rates and results in significantly larger trunk diameters over time. This is in agreement with [12], who argued that wider spacing promotes lateral trunk expansion through optimized allometric growth. In summary, although high-density planting may offer initial advantages in terms of land-use efficiency, adequate spacing is critical for ensuring sustained physiological health and achieving optimal trunk dimensions in cashew orchards.

### **Canopy Development and Planting Density**

Tree age is a determining factor for canopy architecture, as the mean canopy diameter increases over time regardless of planting density. However, this growth is non-uniform; it becomes significantly more pronounced after 10 years, particularly in low-density plots. These results align with the observations of [12], who also highlighted the critical impact of density on canopy geometry and spatial distribution.

Consequently, to optimize long-term canopy expansion, low planting densities are recommended. This conclusion is supported by [13], who stated that the optimal density for maximizing crown development is approximately 100 trees/ha. Beyond this threshold, inter-tree competition for light and space intensifies with age, eventually leading to canopy overlap and reduced individual tree vigor.

### **Vertical Growth and Resource Competition**

Cashew tree height is determined by both planting density and tree age. While high-density configurations may initially induce an appearance of rapid, vigorous vertical growth, an attribute often favored by farmers, our results demonstrate that such density levels are unsustainable for individual tree development over the long term. This initial height gain is often a physiological response to shading, where trees prioritize apical growth to access light.

However, as the orchard matures, below-ground competition for limited soil resources eventually restricts further development. Our observations align with the findings of [14], who showed that while high density stimulates height growth in juvenile trees, a threshold effect emerges over time, diminishing this advantage. In mature cashew orchards with established canopies, subterranean resources, specifically soil moisture and nutrient availability become the critical limiting factors for sustained growth and tree longevity.

### **Morphological Determinants of Yield**

The multiple linear regression analysis evaluated the influence of tree height, canopy diameter, and DBH on individual tree yield. The results demonstrate that both DBH and canopy diameter exert a significant positive effect on yield ( $p=0.017$  and  $p=0.054$ ), respectively, while height had no significant effect ( $p=0.221$ ). These findings suggest that radial vigor and horizontal architecture are stronger contributors to productivity than vertical growth.

This trend is consistent with the findings of [15], who identified trunk diameter and canopy spread as primary indicators of cashew productivity, largely due to their direct relationship with photosynthetic leaf area and the structural capacity to support fruit load. In contrast, the lack of significant correlation with tree height corroborates the conclusions of [16], which suggest that in perennial fruit crops, vertical elongation does not necessarily translate into higher yields and may even indicate resource allocation toward vegetative maintenance rather than reproductive output.

The multiple linear regression analysis evaluated the effect of height, canopy diameter, and DBH on yield per tree. The results show that DBH and canopy diameter exert a positive effect on yield ( $p=0.017$  and  $p=0.054$ , respectively), while height had no significant effect ( $p=0.221$ ). These observations suggest that radial vigor and horizontal architecture contribute more to productivity than vertical growth. This trend is consistent with that of, who showed that trunk diameter and canopy spread are key indicators of fruit tree productivity due to their relationship with photosynthetic leaf area and structural support for fruit. In contrast, tree height showed no significant correlation, corroborating the conclusions that vertical growth does not always correlate with higher production in woody species.

### **Conclusion**

The multiple linear regression and one-way Analysis of Variance (ANOVA) conducted in this study identified the primary factors influencing cashew yield at both the individual tree and orchard scales. Our findings confirm that Diameter at Breast Height (DBH) and canopy diameter are the morphological traits most directly linked to individual productivity. Specifically, DBH exerted a positive and significant effect on yield ( $p=0.017$ ), while the canopy diameter also showed a positive influence, albeit with marginal significance ( $p=0.054$ ). However, the results also revealed substantial yield variability among trees with similar morphologies, suggesting the influence of additional underlying factors. At the orchard level, statistical evidence demonstrated that planting density is a critical determinant of yield. Trees grown at lower densities exhibited superior long-term productivity, as wider spacing facilitates optimal trunk and canopy development by minimizing inter-tree competition for resources. Although high planting densities may initially stimulate vertical growth, they ultimately constrain individual development as competition for water and nutrients intensifies. Consequently, maintaining adequate spacing is essential for maximizing sustainable cashew production.

### **Future Perspectives**

To build upon the findings of this study, we propose integrating additional variables into future research. Subsequent studies should focus on the following key areas:

- **Genotypic Analysis:** Investigating the influence of different cashew genotypes to determine the extent to which genetic variation impacts yield and adaptability.

- Edaphic Factors: Evaluating the role of soil properties including soil type, pH, and nutrient fertility in driving tree growth and overall productivity.
- Climatic Variables: Modeling the effects of rainfall patterns, temperature fluctuations, and humidity levels on morphological development and yield stability.

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