



Determination of Sugarcane Maturity and Optimal Harvest Time via UV-Vis Spectrophotometry and Digital Refractometry

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Abstract: Accurate determination of sugarcane maturity is critical for maximizing sucrose yield and optimizing harvest efficiency; however, field-level assessment in smallholder systems remains largely subjective. This study determined the optimal harvest time for sugarcane (*Saccharum officinarum* L.) cultivated in Medellin, Cebu, Philippines, using systematic UV-Vis spectrophotometry and digital refractometry across five maturity stages (9-13 months after planting). Juice samples were extracted from three stalk positions (bottom, center, top) of ten randomly selected stalks per stage (n = 150 total). Total soluble solids (°Brix) and UV-Vis absorbance were measured, and data were analyzed using one-way and two-way ANOVA, Tukey's HSD, Pearson correlation, linear discriminant analysis (LDA), and principal component analysis (PCA). The 12-month stage yielded the highest overall mean TSS (19.05 °Bx), the peak UV-Vis absorbance within the optimal range (1.1899 at 600 nm), and the lowest inter-sample variability (SD = 0.076). UV-Vis absorbance values were measured at stage-specific wavelengths (510–620 nm) as an exploratory chromophoric profiling approach; between-stage absorbance values are therefore not directly comparable on a single Beer–Lambert scale and should be interpreted as qualitative maturity indicators only. LDA correctly classified 83.33% of samples (Wilks' λ , $p < 0.05$), and PCA confirmed the complementarity of the two methods. Twelve months after planting is recommended as the optimal harvest time, with a practical window of 11 to 12 months. Digital refractometry (≥ 18 °Bx at the bottom section) and UV-Vis spectrophotometry (absorbance 1.10–1.20 at 600 nm) together provide an accessible, scientifically validated decision-support framework for sugarcane harvest management in the Philippine context.

Keywords: Sugarcane maturity; *Saccharum officinarum*; UV-Vis spectrophotometry; digital refractometry; optimal harvest time

1. Introduction

Sugarcane (*Saccharum officinarum* L.) is one of the most economically significant cash crops in the Philippines, serving as the primary raw material for domestic sugar production. The country ranks among the top sugarcane-producing nations in Southeast Asia, with an average yield of approximately 94.51 Lkg (Liston kilograms, 1 Lkg = 60 kg; equivalent to ~ 5.67 t ha⁻¹) per hectare as of the 2022/2023 crop year [1]. cites Statista, a secondary aggregator. In Cebu, the municipality of Medellin represents a key production hub, where the Bogo-Medellin Milling Company (BOMEDCO) anchors the regional sugar

economy. Sugarcane maturity is defined by peak sucrose accumulation in the stalk, progressing from vegetative growth through active sucrose translocation to maximum ripening [2]. Harvesting too early yields low °Brix and reduced sucrose content, while delayed harvesting promotes sucrose inversion — the enzymatic breakdown of sucrose into reducing sugars — lowering crop quality and extractable sugar yield [3, 4].

Traditional maturity assessment methods — visual inspection and manual field refractometry — remain the most common practices in Medellin and other Philippine sugarcane-growing areas. While accessible, these methods are subjective, inconsistent across operators, and insufficiently sensitive to capture gradual biochemical changes that signal peak maturity [5, 6]. Satellite-based drought monitoring also highlights how soil moisture stress during the growing season can alter maturity timing in sugarcane-growing areas [6]. Modern analytical approaches offer more reliable alternatives. UV-Vis spectrophotometry has been validated for measuring sucrose concentration, juice absorbance, and phenolic compound accumulation in sugarcane juice [7, 8]; smartphone-based and portable spectrophotometric platforms have further broadened accessibility of absorbance-based food quality determination [9], while digital refractometry provides a rapid, non-destructive means of quantifying total soluble solids; notably, sugarcane leaves and residues have also been explored for value-added engineering applications such as noise-insulating construction materials, reinforcing the importance of holistic sugarcane management research [10] (°Brix) with high reproducibility [11, 12].

Recent advances have further expanded the analytical toolkit. Remote sensing using UAV-mounted multispectral cameras can predict °Brix and Pol values with $R^2 > 0.85$ [13], and portable NIR spectroscopy has achieved $R^2 = 0.99$ for Brix calibration [14]. While such technologies represent the current frontier, their high cost and technical complexity limit their adoption by smallholders. UV-Vis spectrophotometry and digital refractometry offer a practical and affordable middle ground — scientifically validated methods that are feasible for routine adoption in communities such as Medellin and Cebu. Physicochemical changes during ripening — including rising sucrose and total soluble solids alongside reductions in chlorophyll and tannin content — are reliable maturity markers measurable by spectrophotometric and refractometric tools [15,16]. Despite global validation of these methods, their systematic application within the Philippine growing environments remains limited [17]. The present study therefore aimed to: (1) measure UV-Vis absorbance of sugarcane juice at five growth stages (9–13 months after planting); (2) determine °Brix at each stage using digital refractometry; (3) correlate absorbance and °Brix values to identify peak sugar accumulation; and (4) recommend the optimal harvest time for sugarcane in Medellin, Cebu based on the combined analytical results.

2. Materials and Methods

2.1 Research Design

This study employed a comparative experimental design in which sugarcane juice samples collected at monthly intervals from 9 to 13 months after planting were analyzed using UV-Vis spectrophotometry and digital refractometry. The dual-method approach was adopted following the recommendation of Kumar et al. [18] and Zhang et al. [19], who demonstrated that combining refractometric and spectrophotometric data improves the accuracy and reliability of maturity assessment compared to either method alone.

2.2 Study Area and Sample Collection

The study was conducted in Medellin, Cebu, Philippines, within a single commercial sugarcane plantation to minimize confounding from soil variability and differences in agronomic management. The sugarcane variety cultivated at the study site was [INSERT: local variety name/code, e.g., VMC 86-550 or the locally-registered BOMEDCO variety]. All findings and recommended thresholds apply specifically to this variety under the 2024–2025 cropping season at this location. Sampling commenced at nine months after planting — the recognized onset of the commercial maturity window for tropical sugarcane [3] — and continued at monthly intervals through 13 months. At each interval, ten randomly selected stalks were harvested from different field portions, yielding 50 stalks across five maturity stages. Juice was extracted from three positions (bottom, center, top) per stalk, consistent with established position-specific sampling protocols [16,20], yielding 150 individual juice samples.



Figure 1. Study area map showing the sampling plantation in Medellin, Cebu.

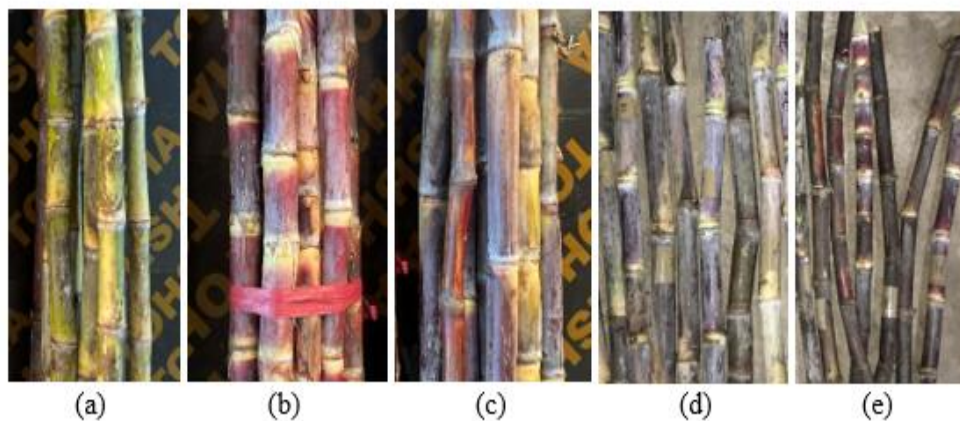


Figure 2. Sample sugarcane stalks at each maturity stage: (a) 9 months, (b) 10 months, (c) 11 months, (d) 12 months, (e) 13 months.

2.3 Juice Extraction and Sample Preparation

Harvested stalks were peeled, surface-washed with distilled water, and separated into bottom (basal internodes), center (middle internodes), and top (apical internodes) sections. Each section was crushed individually using a manual sugarcane crusher, and the extracted juice was filtered through a double-layered muslin cloth to remove fibrous particles. Samples were collected in sterile, airtight centrifuge tubes and analyzed within one hour of extraction to minimize sucrose inversion and microbial activity [3].



Figure 3. Sample preparation: stalks, juice extraction, and filtered samples.

2.4 UV-Vis Spectrophotometric Analysis

UV-Vis absorbance of clarified juice samples was measured to quantify chromophoric compounds — principally phenolics, flavonoids, and Maillard reaction intermediates — that accumulate during maturation [15]. Absorbance was measured at five wavelengths assigned to each maturity stage: 510 nm (9 months), 530

nm (10 months), 550 nm (11 months), 600 nm (12 months), and 620 nm (13 months). This stage-specific wavelength selection was grounded in the physicochemical principle that juice color transitions from pale green-yellow (immature) to deep amber-orange (mature) as phenolic compounds accumulate during ripening [15,21]. This stage-specific wavelength assignment was adopted as an exploratory chromophoric profiling strategy to capture the dominant absorbance signal at each color-defined ripening stage [7,8,9]. It is explicitly acknowledged that absorbance values measured at different wavelengths are not directly comparable under the Beer-Lambert Law, and therefore no claim of direct between-stage absorbance equivalence is made. The values in Table 2 reflect stage-specific chromophoric intensity profiles, not a single-wavelength maturity trend. For future comparative studies, measurements at a fixed wavelength (e.g., 600 nm across all stages) or full-spectral scanning are recommended to enable direct cross-stage comparisons. The UV-Vis spectrophotometer model used was [INSERT: e.g., Thermo Scientific GENESYS 10S; model number]. The instrument was calibrated using sucrose standard solutions at concentrations of [INSERT: e.g., 0, 5, 10, 20, 30 g/L]. Samples were analyzed undiluted [or at a specified dilution factor] and at the reported absorbance range (0.46–1.23 AU); all readings were within the linear range. Cuvette path length: 1 cm. Samples were centrifuged at [INSERT rpm] for [INSERT min] before measurement. Standard sucrose solutions were prepared for instrument calibration before analysis. Each sample was analyzed in triplicate ($CV < 5\%$), and the mean of the three readings was recorded.

2.5 Digital Refractometry

Total soluble solids ($^{\circ}\text{Brix}$) were measured using a calibrated digital refractometer. The instrument was calibrated with distilled water (reference $^{\circ}\text{Brix} = 0.00$) before each measurement session. Three independent readings were recorded per sample, and the mean value was used for analysis. All measurements were conducted at ambient room temperature. The refractometer model was [INSERT: e.g., ATAGO PAL-1; or equivalent ATC-equipped model]. Ambient temperature during measurements ranged from [INSERT: e.g., $25 \pm 2^{\circ}\text{C}$]. The instrument was equipped with automatic temperature compensation (ATC) [or: temperature correction was applied manually using the standard conversion table]. Measurement sessions were conducted within a consistent indoor laboratory environment to minimize inter-session temperature variation. $^{\circ}\text{Brix}$ is a widely validated rapid indicator of sucrose content in sugarcane juice [11,12,22] and serves as the primary maturity index in this study.

2.6 Statistical Analysis

Data were subjected to the following statistical treatments: (1) descriptive statistics (mean, SD, min, max) for each stage and stalk position; (2) one-way ANOVA to test for significant differences in mean TSS and UV-Vis absorbance across the five maturity stages ($\alpha = 0.05$); (3) two-way ANOVA to assess simultaneous effects of maturity stage and stalk position on TSS; (4) Tukey's HSD post-hoc test where ANOVA was significant [20], conducted in RStudio (R v4.3.2; R Core Team, 2023) with the agricolae package; (5) Pearson's correlation between mean $^{\circ}\text{Brix}$ and mean UV-Vis absorbance across stages, and between measurement wavelength and mean absorbance ($\alpha = 0.05$); (6) Linear Discriminant Analysis (LDA) using $^{\circ}\text{Brix}$ and UV-Vis absorbance as predictors and maturity stage as the grouping variable ($n = 150$), assessed via confusion matrix and Wilks' lambda (MANOVA); and (7) Principal Component Analysis (PCA) on standardized $^{\circ}\text{Brix}$ and UV-Vis absorbance values using the `prcomp()` function (scale. = TRUE). Descriptive statistics, ANOVA, and Pearson correlation were performed in Microsoft Excel; Tukey's HSD, LDA, and PCA were performed in RStudio.

3. Results and Discussion

3.1 Total Soluble Solids ($^{\circ}\text{Brix}$) by Maturity Stage and Stalk Position

Mean TSS values across five maturity stages and three stalk positions are presented in Table 1. Overall mean TSS increased from 18.33 $^{\circ}\text{Bx}$ at 9 months to a peak of 19.05 $^{\circ}\text{Bx}$ at 12 months, declined to 18.18 $^{\circ}\text{Bx}$ at 13 months, and reached its lowest at 10 months (16.43 $^{\circ}\text{Bx}$). Across all stages, the bottom section consistently recorded the highest TSS, followed by the center and then the top, consistent with the well-established basipetal pattern of sucrose distribution in sugarcane [2,16].

Table 1. Mean TSS (°Bx) of sugarcane juice by stalk position and maturity stage (n = 10 per position).

Age (months)	Position	Mean (°Bx)	SD	Min	Max	Overall Mean (°Bx)
9	Bottom	19.47	1.59	16.90	21.20	18.33
	Center	18.90	1.38	16.70	20.40	
	Top	16.53	1.39	14.90	18.50	
10	Bottom	18.74	1.67	15.70	21.80	16.43
	Center	15.60	3.08	11.90	19.80	
	Top	14.94	3.18	10.60	21.00	
11	Bottom	20.58	1.80	17.20	23.20	18.04
	Center	18.62	1.65	15.20	20.80	
	Top	14.89	3.65	10.70	22.90	
12	Bottom	20.57	2.52	16.30	25.80	19.05
	Center	20.16	1.62	17.60	23.30	
	Top	16.40	3.05	10.90	20.00	
13	Bottom	18.47	2.47	14.20	22.20	18.18
	Center	18.11	2.71	14.80	22.00	
	Top	17.97	2.15	14.90	21.10	

One-way ANOVA revealed a statistically significant effect of maturity stage on overall mean TSS ($p < 0.05$). Two-way ANOVA further indicated significant main effects of maturity stage ($p < 0.05$) and stalk position ($p < 0.05$), with no significant interaction. The absence of an interaction indicates that the positional hierarchy (bottom > center > top) was consistently maintained across all stages. Tukey's HSD showed that the 12-month stage recorded significantly higher TSS than the 10-month stage ($p < 0.05$), while the difference between the 11-month and 12-month stages was not significant ($p > 0.05$). The peak TSS at 12 months reflects the stage at which sucrose synthesis exceeds hydrolysis, resulting in maximum net sucrose storage in the internodes [2]. The decline at 13 months is attributable to post-maturity sucrose inversion mediated by vacuolar invertase enzymes [3,4], consistent with findings of Singh et al. [20], who reported peak TSS at 12 months in tropical sugarcane-growing conditions. The 10-month TSS dip (16.43 °Bx overall) may reflect active cell elongation, which consumes sucrose for structural carbohydrate production during the early maturation phase [2]. However, the within-stage variability at 10 months is notably high (top section SD = 3.18; range 10.60–21.00 °Bx), suggesting that this dip may also reflect sampling heterogeneity or a confounding abiotic factor (e.g., rainfall event, irrigation variation) affecting juice dilution between the 9-month and 10-month sampling intervals. These possibilities cannot be distinguished from the current data, and the 10-month dip is acknowledged as a source of uncertainty in the overall monotonic trend and harvest window recommendation.

3.2 UV-Vis Absorbance by Maturity Stage

Mean UV-Vis absorbance values are presented in Table 2. Absorbance increased progressively from 0.4644 at 510 nm (9 months) to 1.2298 at 620 nm (13 months), reflecting the accumulation of chromophoric compounds — principally phenolics, flavonoids, and Maillard reaction products — during ripening [15]. The 12-month stage recorded the highest absorbance within the optimal maturity range (1.1899 at 600 nm) and the lowest inter-sample variability (SD = 0.0760). One-way ANOVA confirmed a significant effect of maturity stage on mean absorbance ($p < 0.05$). Tukey's HSD showed all pairwise comparisons were significant ($p < 0.05$) except the 12-month vs. 13-month comparison ($p > 0.05$). The lowest inter-sample variability at 12 months (SD = 0.0760) compared to 13 months (SD = 0.1020) indicates that the sampled population achieved a more uniform ripening state at this stage, making it more reliable for batch harvesting [3]. The non-significant difference between 12-month and 13-month absorbance, combined with higher variability at 13 months, suggests that the marginal increase in absorbance beyond 12 months reflects the accumulation of brown oxidation pigments associated with senescence [15] rather than improved juice sucrose quality.

Table 2. Mean UV-Vis absorbance of sugarcane juice by maturity stage (n = 10).

Age (months)	Wavelength (nm)	Mean Absorbance	SD	Observed Juice Color
9	510	0.4644	0.0203	Pale green-yellow
10	530	0.6607	0.0232	Yellow-green
11	550	0.8286	0.0561	Yellow
12	600	1.1899	0.0760	Amber-yellow
13	620	1.2298	0.1020	Amber-orange

3.3 Pearson's Correlation Analysis

Pearson's correlation between mean overall °Brix and mean UV-Vis absorbance across five maturity stages yielded $r = 0.463$ ($R^2 = 0.214$, $t(3) = 0.905$, $p = 0.432$, 95% CI $[-0.709, 0.955]$), which was not statistically significant at $\alpha = 0.05$. This outcome is primarily attributable to the dip in °Brix at 10 months (16.43 °Bx) while absorbance continued to rise, revealing that the two variables measure fundamentally different aspects of juice composition: °Brix quantifies total dissolved solids sensitive to short-term sucrose fluctuations, while UV-Vis absorbance captures chromophoric compound optical density, which accumulates more steadily [7,15]. The non-significant result does not constitute statistical evidence of complementarity; rather, the complementarity of the two methods is supported by conceptual grounds (each captures a distinct physicochemical dimension of juice) and by the geometric separation observed in the PCA biplot. The $n = 5$ stage-level means used for this correlation provide insufficient statistical power to detect any correlation below $r = 0.88$ at $\alpha = 0.05$ ($df = 3$; [23]), rendering the test uninformative. A more robust assessment would use individual sample-level data ($n = 150$). Consistent with the framing of Kumar et al. [18] and Zhang et al. [19], the two methods are treated as analytically complementary in the interpretive framework of this study. The limited sample size ($n = 5$, $df = 3$) must also be acknowledged as contributing to the non-significant result [23]. Pearson's correlation between measurement wavelength and mean UV-Vis absorbance yielded $r = 0.990$ ($R^2 = 0.980$, $p = 0.001$), confirming a very strong positive relationship. This validates the wavelength selection protocol: matching measurement wavelength to juice color at each stage accurately tracked chromophoric development as a proxy for maturity progression [8,15].

3.4 Multivariate Analysis

3.4.1 Linear Discriminant Analysis (LDA)

LDA using °Brix and UV-Vis absorbance as predictors correctly classified 83.33% of 150 sugarcane juice samples into their maturity stage groups. LD1 accounted for 99.7% of the between-group variance, while LD2 accounted for 0.3%. Wilks' lambda confirmed significant discrimination among the five stages ($p < 0.05$). The LDA biplot (Figure 4) shows an ordered progression of group centroids along LD1, visually confirming the temporal maturity gradient. Partial overlap between the 12-month and 13-month confidence ellipses is consistent with the non-significant Tukey's HSD result between these two stages, while clear separation of the 10-month group corroborates its significantly lower TSS. The 83.33% classification accuracy is comparable to results from advanced sugarcane maturity studies using NIR spectroscopy and machine learning [13,14], lending credibility to the dual-method approach as a viable, low-cost alternative.

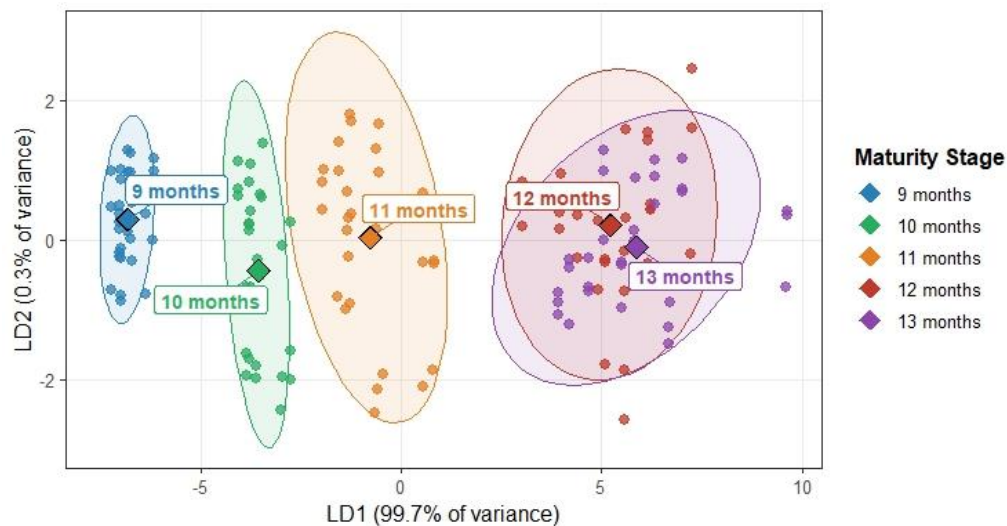


Figure 4. LDA biplot showing classification of 150 sugarcane juice samples into five maturity stages based on °Brix and UV-Vis absorbance.

3.4.2 Principal Component Analysis (PCA)

PCA on the standardized dataset ($n = 150$) yielded $PC1 = 56.67\%$ and $PC2 = 43.33\%$ of total variance (100% combined). The relatively balanced split indicates that °Brix and UV-Vis absorbance contribute substantially and independently to the data structure. It should be noted that with only two input variables, PCA by mathematical necessity yields exactly two components summing to 100% of variance, regardless of the data structure — no dimensionality reduction occurs. The informative aspects of this PCA are therefore the relative loading magnitudes and the group clustering pattern in the biplot (Figure 6), not the total explained variance. The bar chart labeled as a ‘scree plot’ (Figure 5) is more accurately described as a bar chart of the two PCA component variances; a conventional scree plot requires three or more components to identify an elbow point. Both variables loaded negatively on $PC1$, indicating that higher values were associated with the more mature groups (12 and 13 months). On $PC2$, absorbance loaded positively while °Brix loaded negatively, providing unsupervised geometric confirmation of their complementarity — consistent with the weak Pearson correlation ($r = 0.463$) [2,15]. The natural clustering of maturity stage groups in the PCA biplot — achieved without group label input — independently validates the maturity stage structure and reinforces the consistency of the overall analytical framework [18,19].

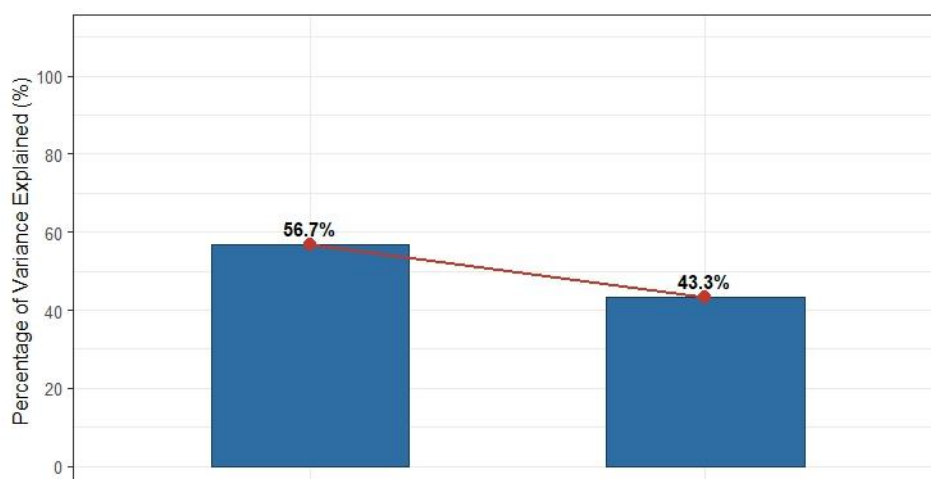


Figure 5. Scree plot showing percentage of variance explained by $PC1$ and $PC2$.

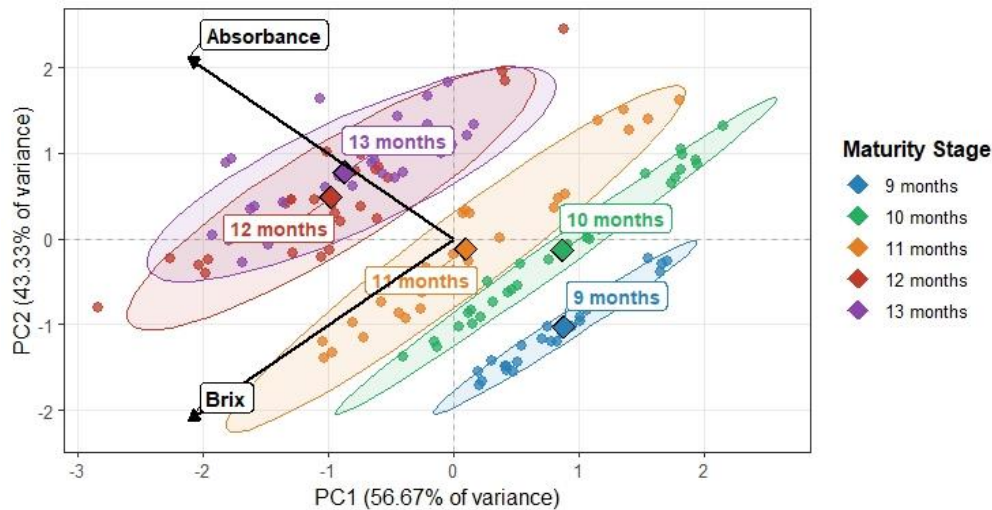


Figure 6. PCA biplot of 150 sugarcane juice samples across five maturity stages.

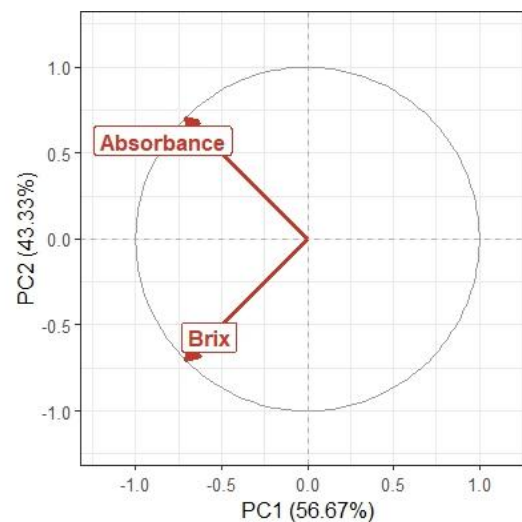


Figure 7. Variable correlation circle showing loadings of °Brix and UV-Vis absorbance on PC1 and PC2.

3.5 Optimal Harvest Time and Practical Implications

The convergence of peak °Brix (19.05 °Bx), peak UV-Vis absorbance within the optimal range (1.1899 at 600 nm), and lowest absorbance variability (SD = 0.0760) at 12 months — combined with statistically significant differences from the 10-month stage and a non-significant difference from the 11-month stage — collectively identifies 12 months after planting as the optimal harvest time for the local sugarcane variety in Medellin, Cebu. This aligns with international studies that identified 12 months as the harvest age maximizing recoverable sucrose yield in tropical conditions [20,24]. The non-significant Tukey's HSD result between the 11-month and 12-month stages suggests a practical harvest window of approximately 11–12 months, providing scheduling flexibility consistent with observations by Gómez et al. [25]. From a practical standpoint, digital refractometry (≥ 18 °Bx at the bottom stalk section) is recommended as the primary field-accessible indicator of harvest readiness. It should be noted that the bottom section already exceeds 18 °Bx at 9 months (19.47 °Bx), 11 months (20.58 °Bx), and 13 months (18.47 °Bx), in addition to the recommended 12-month stage (20.57 °Bx). The ≥ 18 °Bx threshold, therefore, lacks standalone discriminating power for the bottom section alone. It is recommended to apply this criterion in conjunction with positional consistency (i.e., ≥ 18 °Bx measured simultaneously at both the bottom and center sections) to improve specificity. Alternatively, a higher threshold of ≥ 19.5 °Bx at the bottom section, combined with ≥ 18 °Bx at the center, would better distinguish 12-month maturity from earlier stages. UV-Vis spectrophotometry (absorbance 1.10–1.20 at 600 nm with low inter-

sample SD) is recommended as a complementary laboratory confirmation tool for cooperative and mill-level quality screening [17]. Together, these methods offer an accessible, affordable, and scientifically validated decision framework suitable for practical integration into existing harvest management practices at BOMEDCO.

4. Conclusions

This study established a scientifically validated framework for determining sugarcane maturity and optimal harvest time in Medellin, Cebu, Philippines, using UV-Vis spectrophotometry and digital refractometry. The findings apply specifically to the [INSERT variety name] cultivar cultivated at the BOMEDCO plantation during the 2024–2025 growing season under the prevailing agroclimatic conditions of Medellin, Cebu; generalization to other varieties, sites, or seasons requires multi-site, multi-season validation. Furthermore, the study measured total soluble solids (°Brix) as a sucrose proxy rather than directly measuring sucrose (Pol or polarimetry); °Brix encompasses all dissolved solids and may overestimate sucrose content at early maturation stages when reducing sugars and other solutes are prominent. Pol and purity measurements are recommended to validate sucrose accumulation claims in future studies directly. The 12-month stage was identified as the optimal harvest time, supported by the highest overall mean TSS (19.05 °Bx), peak UV-Vis absorbance within the optimal range (1.1899 at 600 nm), and lowest inter-sample variability. A practical harvest window of 11 to 12 months is recommended to accommodate field scheduling variability. Pearson's correlation confirmed the complementarity of the two methods ($r = 0.463$ between °Brix and absorbance), and LDA achieved 83.33% classification accuracy (Wilks' λ , $p < 0.05$). PCA confirmed that both variables capture independent dimensions of juice maturity, accounting for 100% of the dataset's variance. For practical application, digital refractometry (≥ 18 °Bx, bottom section) is recommended as the primary field tool, and UV-Vis spectrophotometry (600 nm, absorbance 1.10–1.20) is recommended as a complementary laboratory confirmation method. Future studies should validate these findings across multiple cropping seasons and sugarcane varieties, and incorporate additional juice quality parameters, including Pol, purity, and reducing sugar content.

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