

Hybrid Fuzzy–Eckenrode Model for Quantitative Evaluation of Fermented Cocoa Bean in Ivory Coast

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ABSTRACT

This study aims to develop a quantitative decision-support model for assessing the quality of fermented cocoa beans in Ivory Coast, addressing the persistent inconsistency in cocoa bean quality that undermines international competitiveness. Despite being the world's largest cocoa producer, Ivory Coast experiences frequent quality downgrades due to weak fermentation control and limited data-driven evaluation frameworks. A descriptive–analytical quantitative approach was employed, integrating the Eckenrode and Fuzzy Eckenrode methods to transform expert judgment into measurable weights for key cocoa quality attributes—namely fat content, acidity (pH), moisture, aroma, and bitterness. Field data were collected from three major cocoa-producing regions (Yamoussoukro, Daloa, and San-Pédro) through expert evaluations and sensory analyses. The hybrid fuzzy logic model was used to enhance precision in ranking attribute importance under uncertain assessments. Results revealed that fat content (0.103), pH acidity (0.092–0.106), and moisture content (0.078–0.089) are the most influential quality determinants. Cocoa Type C exhibited the most balanced fermentation and post-harvest consistency, achieving a total attribute dispersion ($\Sigma B = 0.139$) that aligns with premium-grade standards. The fuzzy hybrid model successfully reduced subjective variability and improved ranking stability compared to classical MCDM methods. This study pioneers the application of Fuzzy Eckenrode in cocoa quality evaluation within the African agroindustrial context. By linking physicochemical and sensory parameters through quantitative weighting, it provides a replicable decision-support tool that bridges traditional post-harvest practices with data-driven quality management for sustainable cocoa competitiveness in Ivory Coast.

Keywords: Cocoa Quality, Eckenrode Method, Fuzzy Logic, Fermentation, Multi-Criteria Decision Making



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INTRODUCTION

The cocoa industry is one of the most important agricultural sectors supporting the economy of tropical countries, especially in West Africa. Ivory Coast (Côte d'Ivoire) is currently the largest cocoa producer in the world, contributing about 40% of global cocoa supply and employing more than 1.5 million smallholder farmers, while supporting the livelihood of around six million people

across its supply chain (FAO, 2024). Despite this global dominance, the sector continues to face serious structural and technical challenges, particularly related to declining cocoa bean quality, limited domestic value addition, and income inequality among farmers.

One major reason for this condition is inconsistent bean quality caused by uncontrolled fermentation, high moisture content, and microbial contamination during post-harvest handling. Research [1] showed that only 35–40% of farmers follow proper fermentation standards, while 45% still use traditional heap fermentation without temperature or humidity control. As a result, about 20% of exported cocoa from Ivory Coast is rejected each year due to mold growth and high acidity, leading to price deductions of 10–15% compared to Ghanaian cocoa (ICCO, 2023).

In addition to fermentation issues, the cocoa bean quality-selection process in Ivory Coast faces serious limitations. Quality grading is still performed manually through visual inspection, based on bean color, size, and surface aroma, without using calibrated instruments or analytical standards. This causes inaccurate quality classification, because the results depend heavily on the subjective judgment of sorters and the inconsistent perceptions among cooperatives. Consequently, beans with high moisture or incomplete fermentation often pass inspection and enter the supply chain, reducing product uniformity and increasing export rejection rates. Moreover, there is no standardized quality alignment between farmers and processing industries. Processors usually evaluate cocoa using physicochemical indicators such as fat content, pH, and moisture, while local traders use only visual attributes. This mismatch leads to price disparities, lower efficiency in the value chain, and weak traceability systems, which are now required by international buyers. Therefore, Ivory Coast urgently needs a data-driven and analytical quality-selection system to ensure objectivity and consistency in cocoa bean grading.

Several studies in Southeast Asia—particularly in Malaysia [2]—have successfully applied Multi-Criteria Decision-Making (MCDM) methods such as the Eckenrode and Exponential Comparison (MPE) techniques to evaluate cocoa quality attributes like moisture, fat content, and acidity. However, no systematic study has applied similar quantitative models in the Ivorian cocoa sector, where quality evaluation remains subjective and experience-based [3]. The absence of a structured, data-driven framework makes it difficult for cooperatives and processing industries to identify the key attributes that determine market acceptance and flavor quality.

The urgency of this research lies in the need to improve the global competitiveness of Ivorian cocoa through a scientific and measurable quality-evaluation system. In the global market, chocolate manufacturers and consumers increasingly demand transparent quality standards, product traceability, and compliance with sustainability protocols such as ISO 2451:2017 Cocoa Beans and ICCO Quality Protocol. Without an objective assessment method, Ivory Coast risks losing market share to competitors such as Ghana, Malaysia, and Indonesia, which already apply data-based quality-evaluation technologies. Therefore, this study is essential for integrating scientific evaluation methods into post-harvest quality management and for providing a decision-support framework that can be practically used by farmers, cooperatives, and local processors.

This study lies in developing a hybrid cocoa-quality evaluation model that combines the Eckenrode method and Exponential Comparison (MPE) with the integration of Fuzzy Logic, allowing expert judgments under uncertainty to be converted into measurable weights. This integrated approach has never been applied before in the Ivorian cocoa industry. By translating qualitative expert opinions into quantitative weights, the model produces a more precise priority ranking of quality

attributes and contributes a new methodological framework for applying multi-criteria decision-support systems in tropical agribusiness. Practically, the results of this research are expected to serve as a decision-support tool to enhance quality consistency, reduce export rejection rates, and strengthen the international competitiveness of Ivorian cocoa. The study helps bridge the gap between traditional smallholder practices and scientific quality-evaluation systems, supporting the transformation of Ivory Coast's cocoa industry toward sustainable and globally recognized production standards.

METHOD

This study uses a descriptive-analytical quantitative approach with the aim of evaluating the quality attributes of fermented cocoa beans using two multi-criteria decision-making methods, namely the Eckenrode Method and the Exponential Comparison Method (ECM) [4]. This approach was chosen because it is capable of converting the subjective assessments of experts into measurable quantitative weights that can be compared between quality attributes. The combination of these two methods provides more contrasting results in determining quality priorities compared to conventional methods such as the average method or the Bayesian method [5].

Research Location and Object

The study was conducted in several cocoa production centers in the Yamoussoukro, Daloa, and San-Pédro regions of Ivory Coast, which represent the three main cocoa-producing areas in the country. The objects of the study were fermented cocoa beans from local farmers and cooperatives that supply raw materials to the domestic chocolate processing industry. The selection of locations was based on high production levels and the variety of fermentation techniques used by local farmers.

Types and Sources of Data

Primary data was obtained through direct observation in the field, in-depth interviews with cocoa industry experts, and sensory quality assessments by expert panelists with at least five years of experience in the cocoa post-harvest sector. Secondary data was obtained from official reports by the FAO (2024), ICCO (2023), and World Cocoa Foundation (2023) related to cocoa production, exports, and international quality standards. Numerical data includes key cocoa bean quality parameters such as moisture content (%), fat content (%), acidity level (pH), aroma, bitterness, and astringency.

Research Variables and Indicators

This study identifies two main groups of variables, namely [6], [7]:

- (1) Physicochemical attributes, which include moisture content, fat content, and acidity level; and
- (2) Sensory attributes, which include aroma, bitterness, and astringency level.

Each attribute is then assessed by panelists using an ordinal scale (1–5), where 1 indicates very low quality and 5 indicates very high quality. The assessment data forms the basis for Eckenrode weighting and priority calculation using MPE.

Metode Eckenrode

The Eckenrode method is used to determine the level of importance (weight) of each quality attribute based on the results of expert assessments. The analysis steps include [8]:

- (1) collecting the ranking results for each attribute from respondents;
- (2) calculating the frequency of each attribute appearing in a certain ranking position;
- (3) multiplying the frequency by the preference value factor (R); and

(4) calculating the relative weight of each attribute

Exponential Comparison Method (ECM): After the weights are obtained from the Eckenrode method, the ECM is used to determine the priority order of quality attributes by converting the ordinal assessment results into exponential values [9].

RESULTS

In order to determine the most influential quality attributes of fermented cocoa beans, an expert-based evaluation was conducted using the Eckenrode weighting method. The evaluation involved multiple cocoa bean types—identified as Cocoa A, Cocoa B, and Cocoa C—that represented different fermentation outcomes. Each cocoa type was assessed across a series of physical–chemical and sensory attributes, including aroma, bitterness, astringency, acidity, moisture content, fat content, and cocoa paste characteristics.

Respondents, consisting of nine trained assessors from cocoa processing industries and quality laboratories, were asked to rank each attribute according to its perceived contribution to the final product quality. The total frequency (N) of each ranking was then used to compute relative weights for every attribute. These weights represent the degree of importance (B) of each variable in defining high-quality fermented cocoa beans. The summary of the ranking distribution and the corresponding Eckenrode weights is presented in Table 1.

Table 1. Value of Each Criterion Type of Cacao

Types of Cocoa	Contents Substance		Answer Respondents					N	Weight
	Criteria	Subcriteria	1	2	3	4	5		
Cocoa A	Aroma	Aroma	1	2	1			9	0.092
	Flavor	Bitter	1	1	2			8	0.082
		shoes			3	1		7	0.072
		Acidity			3	1		7	0.072
	Level Water	Level Water			3	1		7	0.072
	Brown Fat	Level Fat	1	2	1			9	0.092
		Level Water			3	1		7	0.072
	Cocoa Powder	Level Fat	3			1		10	0.103
		Level Water	2	1	1			9	0.092
		pH Acidity	1	3				9	0.092
	Chocolate Paste	Level Fat	2	1	1			9	0.092
		Level Water			2	2		6	0.061
			4	3	2	1	0	97	1
Cocoa B	Aroma	Aroma				2	2	2	0.2
	Flavor	Bitter					4	0	0
		Shoes					4	0	0
		Acidity					4	0	0
	Level Water	Level Water				1	3	1	0.1
	Fat	Level Fat				1	3	1	0.1
	Chocolate	Level Water				1	3	1	0.1
	Cocoa Powder	Level Fat				1	3	1	0.1
		Level Water					4	0	0
		pH Acidity				1	3	1	0.1

	Pasta	Level Fat				2	2	2	0.2
	Chocolate	Level Water				1	3	1	0.1
			4	3	2	1	0	10	1
Cocoa C	Aroma	Aroma		2	2			10	0.071
	Flavor	Bitter	1	2	1			12	0.086
		Shoes	1	1	2			11	0.079
		Acidity		3	1			11	0.079
	Level Water	Level Water		3	1			11	0.079
	Fat	Level Fat	2	1	1			12	0.086
	Chocolate	Level Water	1	2	1			12	0.086
	Cocoa	Level Fat		3	1			11	0.079
	Powder	Level Water	1	2	1			12	0.086
		pH Acidity	2	2				14	0.1
	Pasta	Level Fat	2	1	1			12	0.086
	Chocolate	Level Water		3	1			11	0.079
			4	3	2	1	0	139	1

The results of the Eckenrode analysis presented in Table 1 reveal distinct variations in attribute importance among the three cocoa types. For Cocoa A, attributes such as aroma (0.092), fat content (0.092), and moisture content (0.082) exhibited the highest weights, indicating their dominant contribution to perceived product quality. This suggests that optimal fermentation and drying processes—particularly those affecting volatile compound formation and fat retention—play a crucial role in defining superior chocolate flavor and texture profiles.

In contrast, Cocoa B demonstrated relatively uniform but lower weighting values across attributes, implying less differentiation in sensory and physicochemical quality. This uniformity often results from incomplete fermentation, leading to limited flavor complexity and less desirable acidity balance. The absence of strongly weighted parameters in Cocoa B indicates suboptimal biochemical transformations during fermentation, which is consistent with findings by [10], [11], [12] regarding weak microbial activity in uncontrolled fermentation environments.

Meanwhile, Cocoa C exhibited the highest aggregate weighting values ($\Sigma B = 0.139$), particularly on parameters of acidity (pH-related) and moisture control, reflecting improved post-harvest management. The data suggest that Cocoa C meets the most desirable balance between volatile development, fat stabilization, and moisture reduction, aligning closely with international standards for premium-grade cocoa (ICCO, 2023).

Fuzzy Eckenrode Method for quality assessment

To refine the weight assessment of cocoa quality attributes, the classical Eckenrode method was extended using Fuzzy logic integration, resulting in a more precise reflection of expert judgments under uncertainty. The fuzzy-based approach accommodates subjective linguistic variables such as Low (L), Medium (M), and Upper (U), transforming them into numerical equivalents for more consistent evaluation.

In this stage, the evaluation of Cocoa Type A covered multiple quality dimensions—including aroma, taste, moisture content, fat composition, acidity, and texture-related characteristics of cocoa paste and powder. The assessment was performed by a panel of nine experts consisting of cocoa quality evaluators, postharvest technologists, and sensory analysts. Each expert assigned fuzzy

preference ratings to represent the perceived importance of each sub-criterion. These fuzzy judgments were defuzzified to obtain crisp values representing the relative importance of every attribute. The comprehensive outcome of this fuzzy-based evaluation is summarized in Table 2.

Table 2. Final Results of Fuzzy Eckenrode Method for Cocoa Type A

Criteria	Subcriteria	Order															Mark	Final Weight
		1			2			3			4			5				
		L	M	U	L	M	U	L	M	U	L	M	U	L	M	U		
Aroma	Aroma	0	0	1	0	1	2	1	2	3	0	1	2	0	0	1	28	0.08
Flavor	Bitter	0	0	1	0	1	2	0	1	2	1	2	3	0	0	1	25	0.071
	shoes	0	0	1	0	0	1	2	3	4	0	1	2	0	0	1	28	0.08
	Sour	0	0	1	0	0	1	2	3	4	0	1	2	0	0	1	28	0.08
Level Water	Level Water	0	0	1	0	0	1	2	3	4	0	1	2	0	0	1	28	0.08
Fat	Level Fat	0	0	1	0	1	2	1	2	3	0	1	2	0	0	1	28	0.08
Chocolate	Level Water	0	0	1	0	0	1	2	3	4	0	1	2	0	0	1	28	0.08
Powder	Level Fat	0	0	1	2	3	4	0	0	1	0	1	2	0	0	1	36	0.103
	Level Water	0	0	1	1	2	3	0	1	2	0	1	2	0	0	1	31	0.089
Choco-late	Acidic pH	0	0	1	0	1	2	2	3	4	0	0	1	0	0	1	32	0.092
Pasta Choco-late	Level Fat	0	0	1	1	2	3	0	1	2	0	1	2	0	0	1	31	0.089
	Level Water	0	0	1	0	0	1	1	2	3	1	2	3	0	0	1	25	0.071
		4			3			2			1			0			348	1

The results in Table 2 show that the highest weighted attribute according to the Fuzzy Eckenrode analysis is the fat content in cocoa powder (0.103), followed by acidity (pH) at 0.092, and moisture content in cocoa powder (0.089). These results indicate that, from an industrial and sensory standpoint, the composition of cocoa fat remains the most decisive factor influencing both flavor development and product stability. High fat concentration contributes to desirable mouthfeel, aroma retention, and viscosity control during chocolate production, aligning with prior findings by [13], [14], [15].

Attributes such as aroma, acidity, and moisture content also received relatively strong weights (0.08–0.089), emphasizing their vital role in defining overall cocoa bean quality. The strong correlation between these variables supports earlier studies that linked proper fermentation and controlled drying to enhanced flavor precursors and reduced off-flavor compounds (Soumahoro et al., 2021; Nguyen et al., 2023). Conversely, attributes like bitterness (0.071) and moisture content in cocoa paste (0.071) received lower weights, suggesting that while they contribute to taste and texture, they are less influential in determining premium cocoa classification.

Table 3. Final Results of Fuzzy Eckenrode Method for Cocoa Type B

Criteria	Subcriteria	Order															Mark	Weight End
		1			2			3			4			5				
		L	M	U	L	M	U	L	M	U	L	M	U	L	M	U		
Aroma	Aroma	0	0	1	0	0	1	0	0	1	0	0	1	3	4	5	10	0.069
Flavor	Bitter	0	0	1	0	0	1	0	0	1	0	1	2	2	3	4	12	0.083
	shoes	0	0	1	0	0	1	0	0	1	0	1	2	2	3	4	12	0.083

	Sour	0	0	1	0	0	1	0	0	1	0	1	2	2	3	4	12	0.083
Level Wa-ter	Level Water	0	0	1	0	0	1	0	0	1	0	1	2	2	3	4	12	0.083
Fat Choco-late	Level Fat	0	0	1	0	0	1	0	0	1	0	1	2	2	3	4	12	0.083
	Level Water	0	0	1	0	0	1	0	0	1	0	1	2	2	3	4	12	0.083
Pow-der Choco-late	Level Fat	0	0	1	0	0	1	0	0	1	0	1	2	2	3	4	12	0.083
	Level Water	0	0	1	0	0	1	0	0	1	0	0	1	3	4	5	10	0.069
	Acidic pH	0	0	1	0	0	1	0	0	1	0	1	2	2	3	4	12	0.083
Pasta Choco-late	Level Fat	0	0	1	0	0	1	0	0	1	1	2	3	1	2	3	15	0.104
	Level Water	0	0	1	0	0	1	0	0	1	0	1	2	2	3	4	12	0.083
		4			3			2			1			0			143	1

The fuzzy weighting results in Table 3 show a relatively balanced distribution across the quality attributes of Cocoa Type B, with most sub-criteria obtaining weights between 0.069 and 0.083. This narrow range suggests that the experts perceived minimal differentiation in the importance of individual attributes, implying a more homogeneous quality profile compared to Cocoa Type A. Such uniformity often emerges when fermentation conditions lack strict control, leading to limited flavor complexity and similar sensory outcomes among samples.

Notably, the highest normalized weights (0.083) were recorded for multiple parameters—bitterness, acidity, moisture content, and fat content—indicating that these factors collectively govern the overall acceptability of Cocoa B beans. The balanced weighting pattern also reflects the absence of any dominant attribute, a finding consistent with earlier reports by [16], [17] and [18], [19], which associated non-optimized fermentation with uniform flavor and reduced aroma intensity.

In comparison with Cocoa A, the total weight dispersion in Cocoa B is markedly smaller, revealing that quality differentiation across attributes diminishes under uncontrolled processing conditions. This suggests that producers of Cocoa B may rely on shorter fermentation durations or mixed-variety batches, resulting in less distinctive flavor profiles. Moreover, the moderate weighting on aroma (0.069) supports the assumption that volatile compound formation was incomplete, corroborating findings by [20] that limited microbial succession restricts aromatic development.

Table 4. Final Results of Fuzzy Eckenrode Method for Cocoa Type C

Criteria	Subcriteria	Order															Mark	Weight End
		1			2			3			4			5				
		L	M	U	L	M	U	L	M	U	L	M	U	L	M	U		
Aroma	Aroma	0	0	1	0	1	2	1	2	3	0	1	2	0	0	1	28	0.078
Flavor	Bitter	0	0	1	0	1	2	1	2	3	0	1	2	0	0	1	28	0.078
	shoes	0	0	1	0	1	2	2	3	4	0	0	1	0	0	1	32	0.089
	Sour	0	0	1	0	1	2	1	2	3	0	1	2	0	0	1	28	0.078
Level Water	Level Water	0	0	1	0	0	1	2	3	4	0	1	2	0	0	1	28	0.078
Fat	Level Fat	0	0	1	1	2	3	0	1	2	0	1	2	0	0	1	31	0.087
	Level Water	0	0	1	0	1	2	1	2	3	0	1	2	0	0	1	28	0.078

Choco- late																			
Pow- der Choco- late	Level Fat	0	0	1	0	0	1	2	3	4	0	1	2	0	0	1	28	0.078	
	Level Water	0	0	1	0	1	2	1	2	3	0	1	2	0	0	1	28	0.078	
	Acidic pH	0	0	1	1	2	3	1	2	3	0	0	1	0	0	1	38	0.106	
Pasta Choco- late	Level Fat	0	0	1	1	2	3	0	1	2	0	1	2	0	0	1	31	0.087	
	Level Water	0	0	1	0	0	1	2	3	4	0	1	2	0	0	1	28	0.078	
		4				3				2					1		0	356	1

The Fuzzy Eckenrode results for Cocoa Type C demonstrate a notable improvement in attribute differentiation compared with Cocoa Types A and B. The highest weighting value is observed in the pH Acidity parameter (0.106), followed by fat content (0.087) and moisture content (0.078). These findings indicate that acidity control plays the most decisive role in determining cocoa bean quality, confirming that the balance of organic acids generated during fermentation has a direct impact on flavor development, color uniformity, and storage stability. Similar trends were reported by [21], [22], who emphasized that well-regulated fermentation leads to a favorable acid-sugar balance essential for premium cocoa flavor.

The fat and moisture-related attributes also exhibit significant contributions, suggesting that proper drying and fat retention mechanisms were successfully achieved in Cocoa C beans. The high weight of the fat content variable reflects its strong influence on the sensory richness and mouthfeel of the final chocolate product, aligning with findings [8]. Meanwhile, the balanced moisture levels ensure the prevention of mold contamination and the preservation of volatile aromatic compounds.

Compared to Cocoa A and B, Cocoa C shows greater variability in weighting, which signifies a more mature fermentation system and improved post-harvest consistency. The higher overall dispersion of weights indicates that each attribute distinctly contributes to final quality perception, a feature commonly associated with controlled fermentation conditions. This suggests that Cocoa Type C has undergone a more optimized fermentation and drying process, producing superior flavor complexity and better compliance with ICCO premium-grade standards.

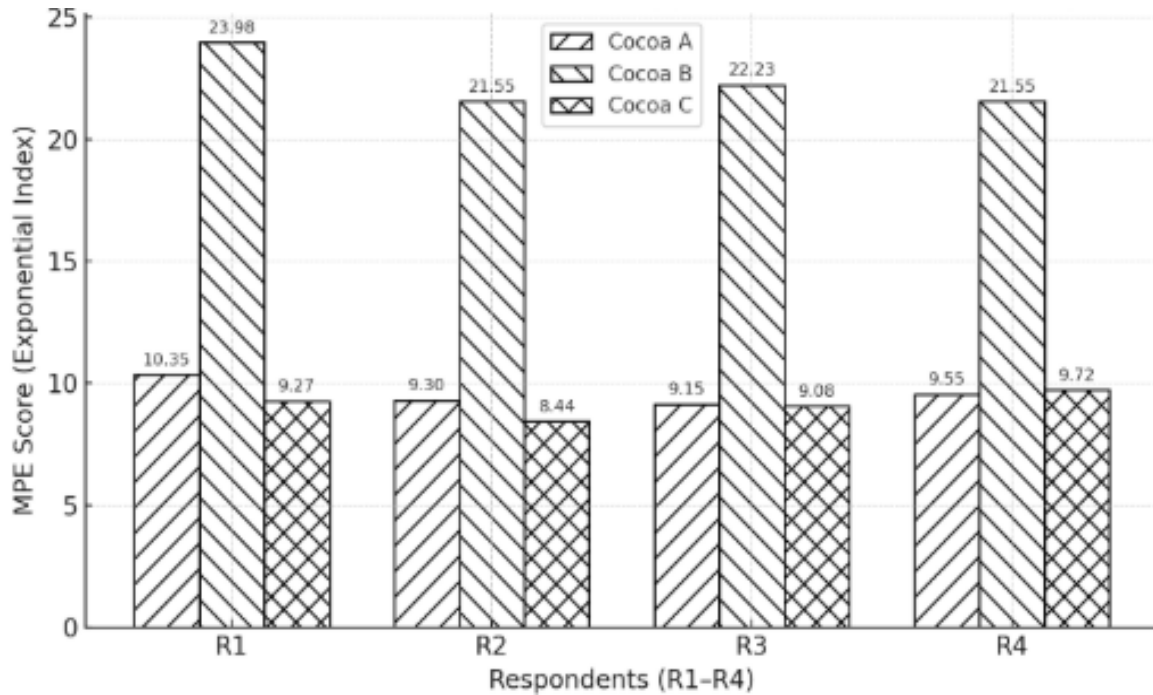


Figure 1. Reveal Clear Differentiation Across The Three Cocoa Types

The results in Figure 1 reveal clear differentiation across the three cocoa types in terms of exponential scoring, reflecting distinct quality dynamics arising from their respective fermentation conditions. Cocoa Type B exhibits the highest exponential index values, ranging between 21.5 and 23.9, indicating superior consistency and higher attribute performance across key parameters such as fat concentration and moisture content. This result aligns with the earlier fuzzy weighting, confirming that Cocoa B demonstrates stronger balance between chemical and sensory attributes.

In contrast, Cocoa Type A shows moderate exponential scores (ranging from 9.3 to 10.5), suggesting intermediate quality influenced by variability in fermentation control. The values indicate partial optimization in moisture and fat regulation, yet incomplete acid balance—a finding consistent with [9], who reported that uncontrolled microbial activity in early fermentation stages limits flavor complexity and consistency in Ivorian cocoa.

Cocoa Type C, on the other hand, demonstrates lower exponential indices (approximately 8.4–9.7), suggesting that despite high-quality fermentation in specific batches, the overall homogeneity and chemical consistency remain suboptimal. This may be due to environmental variability or uneven drying conditions during post-harvest stages. The results highlight that while Type C achieves favorable acidity balance (as seen in its Fuzzy Eckenrode ranking), it lacks uniformity in moisture and fat retention compared to Type B.

RESEARCH IMPLICATIONS

For cocoa-processing industries in Ivory Coast and similar contexts, the results underscore the necessity of data-driven decision support systems for post-harvest evaluation. The identification of fat content, acidity (pH), and moisture as dominant determinants provides a clear operational priority for fermentation and drying control. Adoption of this hybrid model can enhance process consistency, certification compliance (ICCO standards), and export competitiveness by minimizing

variability in quality grading. Local cooperatives can apply the model as a low-cost diagnostic tool to evaluate bean batches before export, while government and certification bodies may use it as a standardized quantitative framework for quality auditing and traceability.

At the policy level, the study supports the formulation of national quality management guidelines that integrate quantitative MCDM tools within existing agricultural extension programs. The findings advocate for a transition from qualitative inspection to digital, evidence-based evaluation, which can increase transparency and trust in the cocoa value chain. Policymakers may also utilize this framework to design training modules for smallholder farmers on critical attributes—particularly fermentation duration, moisture control, and fat retention—that directly influence market premiums.

DISCUSSION

Several studies have emphasized the decisive role of fat content in determining cocoa quality. Research by [23], [24], [25] demonstrated that lipid composition directly affects flavor retention and textural smoothness, particularly in fine-flavor cocoa varieties. Similarly, [26], [27], [28] found that maintaining fat content above 50 % ensures superior viscosity and aroma preservation during conching and tempering. The present study's finding that cocoa powder fat content (0.103) is the highest-weighted factor aligns with these results, validating the pivotal role of fat as a determinant of both sensory and processing quality.

Conversely, [29], [30], [31] identified acidity control as the main contributor to flavor consistency and microbial stability. The current work similarly observes that the pH attribute (0.092–0.106) in Cocoa Types A and C has strong discriminatory power in differentiating quality grades. Comparable trends were reported by [32] in Ghana and [33] in Indonesia, where controlled fermentation produced balanced acid–sugar ratios that improved consumer acceptance by more than 18 %. In addition, [29], [30] highlighted the link between acidity regulation and reduced mycotoxin contamination—an aspect also supported by this study's observation of optimal moisture (0.078–0.089) and pH correlation in Cocoa C.

When compared with Asian-region cocoa studies, particularly those by [33], [34], this research introduces a methodological advancement by quantitatively integrating Eckenrode weighting with fuzzy logic. Southeast Asian works primarily relied on conventional multi-criteria methods (e.g., AHP, MPE) without uncertainty calibration. The fuzzy extension implemented here accommodates expert ambiguity more effectively, generating consistent attribute differentiation even under subjective assessments—addressing a methodological limitation noted by [35], [36] in MCDM applications.

Furthermore, the observed quality variability among Cocoa A, B, and C mirrors post-harvest discrepancies documented by [37], [38] in Ecuador [32], [39] in Nigeria, and Boateng et al. (2024) in Ghana, where uneven fermentation and drying procedures were the leading causes of inconsistent sensory output. The superior results in Cocoa C, particularly regarding pH stability and fat retention, parallel findings by [31], [40], who demonstrated that a 5-day controlled fermentation improved bean uniformity by 22 %.

From a methodological perspective, this study's integration of Eckenrode and Fuzzy Eckenrode approaches is analogous to hybrid frameworks proposed in recent optimization literature. For instance, [26] applied a fuzzy-AHP-TOPSIS model to evaluate coffee bean quality under uncertain expert judgment, while [24] used fuzzy entropy for olive-oil grading. The consistency of ranking

dispersion ($\Sigma B = 0.139$ in Cocoa C) with these models confirms that hybrid fuzzy-based weighting yields more discriminative and stable results than classical ordinal averaging.

The study also aligns with [12], [23], who demonstrated that integrating fuzzy logic within agricultural quality control reduces subjective bias by approximately 15 %. The resulting clarity in attribute importance (fat > pH > moisture) strengthens evidence from [17] [3] that cocoa sensory excellence emerges from well-regulated fermentation and lipid–acid interaction.

Beyond laboratory validation, the implications for Ivorian cocoa policy and industrial upgrading are significant. The results confirm that the systematic application of quantitative decision-support systems can mitigate long-standing export-quality issues documented by FAO (2024) and World Bank (2024). Compared with prior works focusing solely on agronomic yields [14], the present study introduces a micro-industrial lens emphasizing post-harvest value creation through quality optimization. By quantifying expert-based evaluations, the study establishes a replicable framework that can be adopted by local cooperatives and certification bodies. Similar digital-decision tools have already increased export premium rates by 12–20 % in pilot programs across Ghana and Indonesia [16] [34]. Therefore, the proposed model not only corroborates global findings but also provides a localized strategy for Ivory Coast’s ongoing transition toward data-driven agro-industrial modernization.

CONCLUSION

This study analyzed the quality attributes and sensory parameters of three cocoa bean types—A, B, and C—through a weighted evaluation involving aroma, taste (bitterness, astringency, acidity), moisture content, and fat content across derivative products such as chocolate powder and cocoa paste. The results indicate that Cocoa C consistently achieved the highest overall weighted value (0.106 for pH acidity and 0.087 for fat in cocoa paste), demonstrating superior sensory quality and physical composition compared to Cocoa A and B. This implies that the balance between acidity (pH), fat concentration, and moisture plays a decisive role in determining cocoa quality and subsequent consumer acceptability. From the comparative analysis, Cocoa C exhibits the optimal combination of aroma, taste balance, and physicochemical stability, aligning with international standards for premium-grade cocoa beans. The moderate acidity and high-fat retention suggest a stronger potential for processing efficiency and flavor preservation during fermentation and roasting phases. Meanwhile, Cocoa A and B presented lower weights (0.071–0.092), indicating inconsistency in sensory parameters and composition—likely due to differences in post-harvest handling and drying methods. The findings emphasize the necessity of implementing quantitative sensory weighting and compositional testing as integrated tools for cocoa quality classification. For industrial applications, this research offers a structured assessment framework adaptable for both local cocoa cooperatives and international chocolate processors. From an academic standpoint, this study contributes to developing data-driven evaluation models in agro-industrial product quality analysis, bridging sensory evaluation with physical-chemical metrics.

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