

Effect of manual depulping and roasting on functional, rheological and sensory characteristics of cocoa liquor

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ABSTRACT

Cocoa liquor serves as a fundamental intermediate in chocolate production, with its quality attributes largely determined by post-harvest processing parameters. This study investigated the effects of varying mechanical depulping levels (0 %, 50 % and 100 % pulp removal) and roasting conditions (110 °C for 60 min, 120 °C for 30 min and 135 °C for 10 min) on the physical and sensory characteristics of cocoa liquor produced from Ghanaian cocoa beans (*Theobroma cacao* L.). A 3 × 3 full factorial design was implemented under a Completely Randomised Design framework. Following standardised fermentation (6 days) and drying (55 °C to 7–8 % moisture content), beans were roasted, milled and evaluated for textural properties (firmness: 175.93–584.80 g; consistency: 963.66–1847.96 g-s; cohesiveness: 165.02–360.64 g) and viscosity index (728.5–1364.9 g-s) using back-extrusion analysis. Quantitative Descriptive Analysis by 10 trained panellists (2 males, 8 females; age range 25–45 years) assessed nine sensory attributes. Results demonstrated that depulping significantly reduced cohesiveness ($F(1,23) = 4.58, p = 0.043$) and modified consistency ($F(3,23) = 5.87, p = 0.0066$), with 100 % depulping decreasing cohesiveness by 54 % compared to undepulped controls. Complete depulping intensified bitterness ($p < 0.05$) and astringency, attributable to elevated polyphenol retention (Asiedu et al., 2025). Moderate roasting at 120 °C for 30 min produced optimal nutty and cocoa notes, particularly in non-depulped samples which exhibited significantly higher cocoa liquor aroma and flavour intensities ($p < 0.05$). Strong correlations emerged between cohesiveness and viscosity index ($r = 0.95, R^2 = 0.91, p < 0.05$). The combination of 50 % depulping with moderate roasting (120 °C/30 min) yielded cocoa liquor with improved texture, stable rheology (consistency: 1245.32 g-s) and enhanced sensory quality, providing practical guidance for optimising cocoa processing operations.

1. Introduction

Cocoa liquor, sometimes called cocoa mass, is a fundamental ingredient in chocolate production. Its final quality is not inherent in the bean but is developed through specific post-harvest processing methods. Among these methods, mechanical depulping and roasting are two critical steps known to shape the product's functional, textural and sensory characteristics (Asiedu et al., 2025, 2026).

Extensive research has explored how depulping and roasting influence the biochemical composition of cocoa beans, particularly their bioactive compounds and antioxidant properties (Asiedu et al., 2025;

Kongor et al., 2016; Acheampong et al., 2025; Asiedu et al., 2026). Mechanical depulping, which involves removing the mucilage surrounding the beans before fermentation, alters the microbial environment. This change impacts the formation of essential flavour precursors during the fermentation process (Afoakwa et al., 2013; Asiedu et al., 2025). While these biochemical effects are documented, the direct consequences of depulping on the physical texture and sensory profile of the resulting cocoa liquor remain less understood.

Similarly, roasting is a crucial thermal process that induces important physicochemical changes in the beans. It is vital for developing the characteristic chocolate flavour, modifying texture and determining the

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retention of certain compounds (Asiedu et al., 2025; Javeria et al., 2026; Osei Tutu et al., 2024). The intensity of roasting, defined by its time and temperature, can significantly affect the outcome. However, the combined effect of varying depulping levels and different roasting intensities on cocoa liquor quality is an area that requires deeper investigation.

The textural and rheological properties of cocoa liquor, such as its cohesiveness, consistency, firmness and viscosity, are essential for manufacturing efficiency and product quality. These properties are influenced by several factors, including the final fat content, the concentration of polyphenols and the conditions used during roasting (Glicerina et al., 2016; Ioannone et al., 2015; Acheampong et al., 2025ab). For instance, a higher fat content typically makes the liquor more fluid, while elevated polyphenol levels can increase firmness and contribute to astringency (Afoakwa et al., 2009; Osei Tutu et al., 2024). Roasting further modifies these attributes through processes like lipid melting, protein denaturation and the creation of Maillard reaction products (Akonor et al., 2023; Ioannone et al., 2015; Osei Tutu et al., 2024ab).

Ultimately, sensory attributes like aroma, flavour and mouthfeel are paramount for consumer acceptance. The perceived intensity of cocoa flavour, nutty notes, bitterness and astringency is largely determined by the roasting process and the levels of retained polyphenols (Amjad et al., 2026; Moazzam et al., 2026; Rocha et al., 2017). A clear understanding of how mechanical depulping and roasting parameters interact to influence these sensory characteristics is currently lacking.

Therefore, this study aims to systematically evaluate the effects of depulping at 0 %, 50 % and 100 % levels and roasting at low, moderate and high intensities on the functional, textural, rheological and sensory properties of cocoa liquor. By examining the interactions between these key processing parameters, the findings will provide valuable insights for optimising cocoa processing techniques. This will aid the chocolate industry in enhancing final product quality and overall consumer acceptability.

2. Materials and methods

2.1. Raw materials

Fully mature cocoa pods (*Theobroma cacao* L.), comprising a mixture of Amelonado and Amazonica hybrid varieties, were harvested from a farm in Obosomase, in Ghana's Eastern Region. Pods were harvested at an average age of 5.5 months, with an average weight of 450 ± 50 g and displayed a characteristic yellow/orange hue indicating ripeness. The pods were harvested under ambient temperatures (28–30 °C) and transported immediately to a fermentary for processing.

2.2. Experimental design

A 3×3 full factorial experimental design was adopted in a Completely Randomised Design (CRD) framework to assess the impact of mechanical depulping and roasting intensity. The factors studied were:

- Depulping levels: 0 % (control, no pulp removed), 50 % (approximately 50 % of pulp removed by weight) and 100 % (complete removal of mucilage). The 50 % depulping level was selected based on the work of Amanquah et al. (2013), who reported it as a balance between facilitating fermentation and retaining flavour precursors, while 100 % depulping represents the extreme condition for examining maximum pulp removal effects.
- Roasting settings: Three roasting protocols were employed to represent the spectrum of thermal intensities used in industrial cocoa processing: low-temperature, long-time (LTLT: 110 °C/60 min), moderate roasting treatment (MRT: 120 °C/30 min) and high-temperature, short-time (HTST: 135 °C/10 min). These time-temperature combinations were selected to achieve comparable

roasting degrees while maintaining equivalent thermal exposure (constant time $\times$ temperature product), following established industrial parameters (Asiedu et al., 2025, 2026; Peña-Correa et al., 2024). Each protocol serves distinct processing objectives: LTLT conditions represent mild roasting optimised for bioactive compound preservation (De Teye et al., 2017; Ioannone et al., 2015), MRT reflects standard industrial practice balancing flavour development with compound retention (Adil et al., 2025; Lemarcq et al., 2020) and HTST simulates high-intensity processing for rapid throughput (Ioannone et al., 2015; Adil et al., 2025). This systematic approach allows for direct comparison of roasting intensity effects while controlling for total thermal input (Asiedu et al., 2025; Mensah et al., 2026), providing insights into optimal processing strategies for different quality targets in cocoa manufacturing.

2.3. Sample preparation

2.3.1. Depulping and fermentation

Cocoa beans were manually extracted from the pods. For the depulping treatments, the initial weight of the pulp-bean mass was recorded. Beans were then manually scrubbed on a mesh to achieve the desired depulping levels: 0 % (control, no mechanical removal of pulp), 50 % (targeted removal of approximately half of the initial pulp mass, verified by weighing before and after scrubbing) and 100 % (complete removal of mucilage until beans appeared clean with no visible pulp residue). A 5 kg batch of beans for each depulping level was prepared in triplicate (three independent fermentation batches per treatment). Each batch was fermented using the heap technique, covered with banana leaves and turned every two days for a total of six days under ambient conditions (28–30 °C).

2.3.2. Drying

Post-fermentation, the beans were dried in an air-forced oven (Universal Oven UF75, Memmert GmbH + Co. KG, Germany) set at 55 °C. Drying was conducted over four days until the beans reached a moisture content of 7–8 % (wet basis), measured using a Sartorius MA35 infrared moisture analyser (Sartorius AG, Goettingen, Germany) operating on the thermogravimetric principle with a readability of 0.01 % and repeatability of ± 0.2 %. The dried cocoa beans were subsequently stored in airtight containers at ambient temperature (25–28 °C) until further processing.

2.3.3. Roasting

Approximately 300 g of dried beans were roasted in the same air oven (Universal Oven UF75, Memmert GmbH + Co. KG, Germany). To ensure even roasting despite the lack of an agitator, beans were spread in a thin, single layer on perforated trays to maximise hot air circulation, a method validated for laboratory-scale studies (Getaneh et al., 2020). Roasting was performed at the specified temperatures (110 °C, 120 °C, or 135 °C) for the corresponding durations (60, 30, or 10 min). The roasted beans were cooled to ambient temperature, deshelled manually and milled into cocoa liquor using an Aura 2-in-1 Blender (Model RHBL2, Russell Hobbs, Failsforth, Manchester, UK). The resulting liquor was a homogeneous paste with a particle size distribution suitable for small-scale rheological and sensory evaluation. The prepared samples were sealed in black airtight bags and stored at 18–20 °C and 50–60 % relative humidity for a maximum of 72 h before analysis to prevent fat bloom and moisture uptake.

2.4. Analytical methods

2.4.1. Textural and rheological properties

Textural properties (cohesiveness, consistency and firmness) and rheological properties (viscosity index) were assessed using a TA.HDi 500 Texture Analyzer (Stable Micro Systems Ltd., Godalming, Surrey, UK). The methodology was adapted from Glicerina et al. (2013).

Samples were preheated at 50 °C for 120 min to ensure complete melting of fat crystals and a homogeneous, temperature-stable state prior to analysis, a standard practice for chocolate rheology (Oldörp, 2014). A back-extrusion test was then conducted at room temperature using a 35 mm diameter back-extrusion probe (A/BE35). The test conditions were: Pre-test speed: 5 mm/s; Test speed: 5 mm/s; Post-test speed: 5 mm/s; Trigger force: 5.0 g; Compression distance: 30 mm.

2.4.2. Sensory evaluation

2.4.2.1. Panel selection. A trained sensory panel consisting of 10 assessors (2 males, 8 females; aged 25–45 years) was recruited from qualified personnel holding bachelor's degrees in Food Science or related disciplines. All panellists possessed prior experience in Quantitative Descriptive Analysis (QDA) methodology. The gender distribution (20 % male, 80 % female) reflected the available trained assessor pool at the University of Ghana Sensory Laboratory.

While the panel size of 10 falls below the commonly recommended minimum of 15 assessors, this limitation was mitigated through a triplicate evaluation design, yielding 30 observations per sample. This approach aligns with findings from Heymann et al. (2012), who demonstrated that “at least 8 and preferably 10” trained assessors are sufficient for stable descriptive analysis results. The statistical adequacy of 30 observations per sample provides robust data for trained panel descriptive analysis.

Lexicon development was conducted through intensive training sessions of 2.5–3 h daily, three times weekly. This training duration exceeds typical practices reported in the literature, where Djekic et al. (2021) found that standard training involves sessions below 2 h across up to 10 sessions, ensuring comprehensive preparation for the descriptive evaluation tasks.

2.4.2.2. Developing cocoa liquor lexicons. Trained assessors individually derived descriptors and definitions for the cocoa liquor samples. With the directives of the panel leader all terms generated were accumulated and on consensus, those that were perceived to strongly describe the samples were selected and used for subsequent checks. Detailed definitions were also given to describe the generated attributes; references were provided and linked to the stated descriptor. The assessors were trained on the use of the line scale for evaluation with appropriate anchors placed on the scale. Assessors were then provided with 3 randomly coded samples to rate using the generated descriptors to test for concept alignment among the group. The assessors were made to re-evaluate all the 9 samples and this was performed in triplicates.

2.4.2.3. Validation of lexicons. To validate the descriptor list obtained, the cocoa liquor samples were used for evaluation. The assessors were given these samples to determine if the initial list captured all descriptors related to cocoa liquor before individual evaluations. Any new descriptor generated was added to the initial list with its respective definition and reference (where applicable). Assessors then assessed these samples with the generated list. All evaluations were performed in triplicates.

2.4.2.4. Sample preparation and serving. Before serving samples to assessors, caked cocoa liquor samples were ground into fine powder. Five (5) grams of each cocoa liquor sample was transferred into 10cc plastic transparent disposable cups and covered with plastic lids for serving. Each panellist was served with about 5 g of cocoa liquor sample under white light equivalence of daylight at a room temperature (25 ± 1 °C). All samples were coded with random three-digit numbers to minimise biases. Due to the high bitter intensity of the samples; assessors were served with three samples per session to avoid fatigue and carry-over effects. The nine samples were grouped into three sets by roasting intensity. Each assessor evaluated all three samples within a set in a single

session and this was repeated for all three sets over three separate sessions. Therefore, each assessor evaluated each of the 9 samples once, resulting in $n = 10$ data points per sample. The assessors tasted the samples individually in a randomised sequence, determined using the Williams Latin Square design in Compusense 5 Saas (Compusense5, Cloud, Compusense, Guelph, Ontario, Canada).

2.4.2.5. Environmental control. The sensory sessions were conducted in the Nutrition & Food Science Sensory Laboratory of University of Ghana, Accra, which is equipped with separate tasting booths for assessors with white lighting and a well-ventilated atmosphere.

2.4.2.6. Assessment protocol. Trained assessors rated intensities of identified sensory quality indices on a 150-mm line scale with appropriate references placed as anchors. A computerised system was used to capture the data (CompusenseCloud, Compusense, Guelph, Ontario, Canada). All evaluations were conducted in triplicates. However, due to the high bitter intensity of the samples the assessors were served with three samples in a session, for three sessions in order to avoid the samples which probably might have different tastes showing partially inhibitory or masking interactions. The samples were grouped into three (3), based on their roasting intensity.

2.4.3. Statistical analysis

Statistical analysis was performed using Statgraphics Centurion version 15.2.14 (STSC, Inc., Rockville, MD, USA). Data were tested for homogeneity of variance using Levene's Test and for normality using the Shapiro-Wilk test prior to ANOVA; all assumptions were met ($p > 0.05$). A two-way Analysis of Variance (ANOVA) was applied to determine the main and interaction effects of depulping and roasting on the evaluated parameters. For all ANOVA results, F-values, degrees of freedom and exact p-values are reported. The Fisher's Least Significant Difference (LSD) test was employed to compare mean values at a 95 % confidence interval. Sensory data from QDA were treated as interval data and analysed using ANOVA, a common practice in sensory science (Lawless & Heymann, 2010). General linear models were developed to establish relationships between processing conditions and the attributes of cocoa liquor.

3. Results and discussion

3.1. Effect of mechanical depulping and roasting intensity (temperature/time) on the textural and rheological properties of cocoa liquors

3.1.1. Cohesiveness

Cohesiveness, a measure of a product's ability to resist a second deformation relative to its resistance to the first deformation (Rosenthal & Thompson, 2021; Khan et al., 2025; Ozmen et al., 2025), reflects the degree of particle-particle interaction within the cocoa liquor matrix. Cohesiveness values ranged from 165.02 g (1.62 N) to 360.64 g (3.53 N), as shown in Fig. 1(A). The mean cohesiveness values of the samples differed significantly from one another ($F(8,18) = 1710.19, p = 0.0000$). These values are comparable to those reported for white chocolate (1.83 ± 0.37 N) and milk chocolate (3.16 ± 0.53 N) but lower than those for dark chocolate (16.07 ± 1.25 N) by Glicerina et al. (2016). The reduced cohesiveness in cocoa liquor is attributed to its elevated fat content (~55 %) (Asiedu et al., 2026), which fundamentally alters the microstructural organization. High fat concentrations create a continuous lipid phase that wets the particle matrix and fills interstitial spaces within the crystal network, thereby reducing particle-particle interactions (Obeng et al., 2025; Kortei et al., 2026; Osei Tutu et al., 2023; Glicerina et al., 2016). This mechanism is supported by microstructural evidence showing that increased fat content leads to less dense crystalline networks with more open structures and void spaces between crystals. The continuous fat phase functions as a lubricant, coating particle surfaces

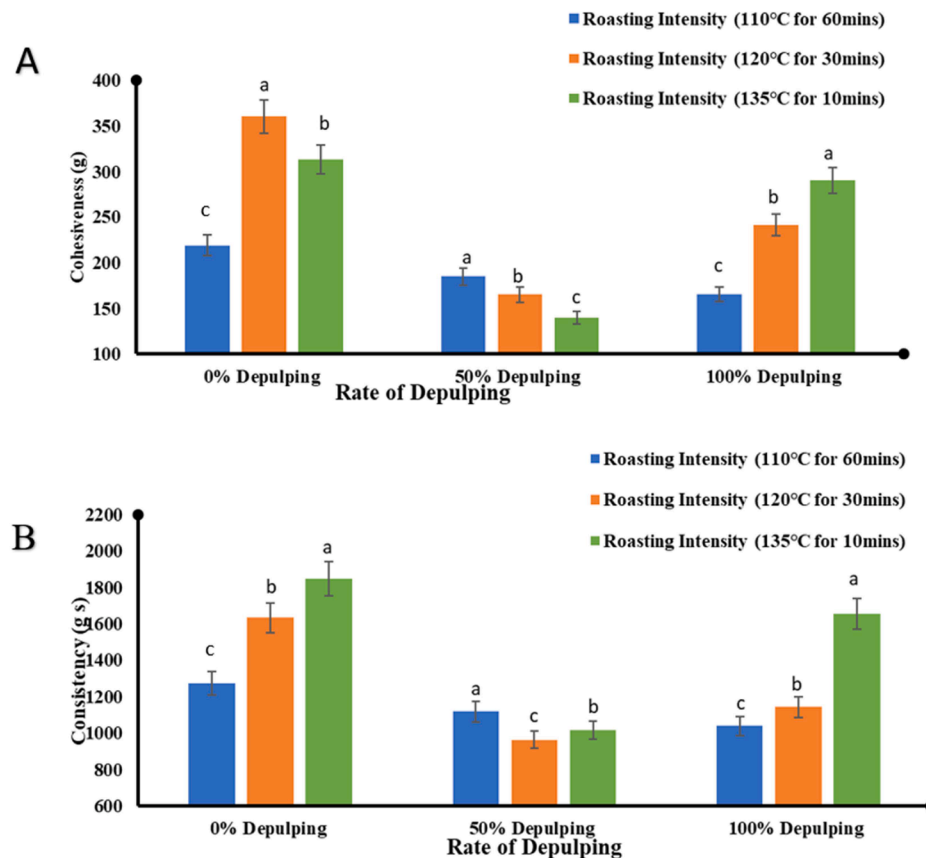


Fig. 1. Effect of depulping level and roasting conditions on textural properties of cocoa liquor. (A) Cohesiveness (g) showing progressive decrease with increasing depulping level; (B) Consistency (g-s) demonstrating reduction with depulping and variation with roasting intensity. Different letters (a-c) above bars indicate significant differences between treatment combinations ($p < 0.05$) by Fisher's LSD test. Values represent means $\pm$ standard deviation ($n = 3$). LTLT: 110 °C/60 min; MRT: 120 °C/30 min; HTST: 135 °C/10 min.

A = Variation in cohesiveness of cocoa liquor as influenced by depulping and roasting conditions. **B** = Variation in consistency of cocoa liquor as influenced by depulping and roasting conditions. Means with different letters (a, b, c) indicate significant differences ($p < 0.05$).

and reducing frictional forces, which enables particles to slide past one another more readily during deformation (Obeng et al., 2025; Javed et al., 2025; Glicerina et al., 2016).

The tribological behaviour observed in cocoa liquor reflects the complex interplay between solid particle concentration and continuous phase properties, consistent with findings in chocolate systems where fat content inversely correlates with mechanical resistance (Asiedu et al., 2026; Rodrigues et al., 2021; Nyasordzi et al., 2025). This relationship between fat content and cohesiveness has significant implications for processing parameters and final product texture in chocolate manufacturing.

$$\text{Cohesiveness} = 263.925 - 41.3037a + 24.4496b - 0.654978c \quad (1)$$

Where:

$a = 1$ if Roasting intensity=110 °C for 60 min, -1 if Roasting intensity=135 °C for 10 min, 0 otherwise

$b = 1$ if Roasting intensity=120 °C for 30 min, -1 if Roasting intensity=135 °C for 10 min, 0 otherwise

$c =$ depulping rate

Analysis of variance (ANOVA) revealed a statistically significant relationship ($F(1,23) = 4.58$, $p = 0.043$) between cohesiveness and depulping rate, while roasting intensity showed a statistically insignificant relationship ($F(2,23) = 2.76$, $p = 0.084$). The general linear model (Eq. (1)) demonstrated, at a 95 % confidence level, that depulping has a decreasing effect on cohesiveness. For instance, cohesiveness decreased

by 54 %, from a maximum of 360.64 g in the 0 % depulped, LTLT roasted sample to a minimum of 165.02 g in the 100 % depulped, HTST roasted sample (Fig. 1A). This reduction is consistent with the significantly higher total polyphenolic content we measured in depulped samples (Asiedu et al., 2025) (a companion paper), as polyphenols can form complexes with proteins and polysaccharides, reducing viscosity and, consequently, cohesiveness (Afoakwa et al., 2013b; Asiedu et al., 2025, 2026). The mechanism underlying this reduction involves polyphenol-protein interactions that disrupt the continuous matrix structure, creating discontinuities that weaken inter-particle bonding forces (Afoakwa et al., 2013). Glicerina et al. (2013) reported strong positive correlations between cohesiveness and yield stress ($r = 0.980$) and between cohesiveness and apparent viscosity ($r = 0.887$; $p < 0.05$) in dark chocolate, suggesting a similar relationship in cocoa liquor.

Additionally, post-hoc comparison tests indicated significant differences ($p < 0.05$) in cohesiveness between samples roasted at 110 °C for 60 min (LTLT) and those at 120 °C for 30 min (MRT). Correlation analysis revealed very strong, positive and significant linear relationships between cohesiveness and viscosity index ($r = 0.95$, $R^2 = 0.91$) and between cohesiveness and consistency ($r = 0.91$, $R^2 = 0.83$; $p < 0.05$). A moderately high, positive and significant relationship was observed between cohesiveness and firmness ($r = 0.76$, $R^2 = 0.58$; $p < 0.05$), as shown in Table 1. Regression analysis indicated strong and significant relationships between cohesiveness and viscosity index ($R^2 = 0.91$; $p < 0.05$) and between cohesiveness and consistency ($R^2 = 0.83$; $p < 0.05$), implying that cohesiveness explains 91 % and 83 % of the variability in these parameters, respectively. However, a weaker but significant

Table 1

Correlation and regression analysis of the textural and rheological properties of cocoa liquor samples.

Parameter	Analysis	Firmness	Consistency	Cohesiveness	Viscosity index
Firmness	Regression (R^2)	1.00	0.82*	0.57*	0.60*
	Correlation (r)	1.00	0.90*	0.76*	0.77*
Consistency	Regression (R^2)	0.82*	1.00	0.83*	0.87*
	Correlation (r)	0.90*	1.00	0.91*	0.93*
Cohesiveness	Regression (R^2)	0.57*	0.83*	1.00	0.91*
	Correlation (r)	0.76*	0.91*	1.00	0.95*
Viscosity Index	Regression (R^2)	0.60*	0.87*	0.91*	1.00
	Correlation (r)	0.77*	0.93*	0.95*	1.00

* Significant at $P < 0.05$. Correlation coefficients (r) are reported as decimals indicating the strength and direction of linear relationships. Coefficients of determination (R^2) are reported as decimals representing the proportion of variance in one variable explained by its linear relationship with another. Significant at $p < 0.05$.

relationship was found between cohesiveness and firmness ($R^2 = 0.58$; $p < 0.05$).

3.1.2. Consistency

The consistency of cocoa liquor, defined as the resistance to flow under applied force (Food Technology Corporation, 2016), exhibited significant variation across nine samples, ranging from 963.66 g-s (9.44 N-s) to 1847.96 g-s (18.11 N-s) as shown in Fig. 1(B), with highly significant differences between sample means ($F(8,18) = 562.72$, $p = 0.0000$). These values demonstrate that cocoa liquor possesses intermediate consistency properties when compared to other chocolate products, exceeding those reported for milk chocolate (1.22 ± 0.16 N-s) and white chocolate (0.87 ± 0.06 N-s) but remaining substantially lower than dark chocolate (110.14 ± 13.96 N-s) reported by Glicerina et al. (2016).

The elevated consistency of cocoa liquor relative to milk and white chocolate can be mechanistically attributed to its high fat content (approximately 55 %) (Asiedu et al., 2026; Obeng et al., 2025), which reduces particle-particle interaction and enhances spreadability (Glicerina et al., 2013; Kumador et al., 2025; Osei Tutu et al., 2024). Unlike the lower fat content chocolates, the dense lipid phase in cocoa liquor reduces particle-particle interactions while simultaneously increasing the structural integrity of the continuous phase (Asiedu et al., 2025; Obeng et al., 2025). This finding aligns with established principles that fat content inversely correlates with inter-particle friction forces, as demonstrated in dark chocolate systems where higher fat concentrations reduce crystalline network density and create more open void spaces filled with fat (Glicerina et al., 2016; Obeng et al., 2025; Osei Tutu et al., 2024).

Processing parameters significantly influenced consistency through distinct mechanistic pathways. Depulping rate demonstrated a statistically significant inverse relationship with consistency ($F(3,23) = 5.87$, $p = 0.0066$), where increased depulping levels systematically reduced flow resistance. This reduction can be explained by the elevated polyphenolic content in depulped samples, which forms complexes with cell wall polysaccharides and proteins, effectively reducing the volume fraction of suspended solids and decreasing flow resistance. This mechanism parallels findings in chocolate systems where polyphenolic compounds alter colloidal structure and reduce apparent viscosity (Asiedu et al., 2026; Lee, 2024; Osei Tutu et al., 2024).

Roasting intensity effects revealed temperature-time dependent mechanisms governing consistency. High-temperature, short-time (HTST) roasting at 135 °C for 10 min produced significantly higher consistency than low-temperature, long-time (LTLT) roasting at 110 °C for 60 min ($p < 0.05$). The mechanistic basis for this difference involves thermal-induced cellular destruction during prolonged roasting, which facilitates lipid migration from intracellular compartments into the continuous phase, effectively increasing free fat content and reducing consistency (Zzaman et al., 2017). This mechanism is consistent with established chocolate rheology principles where free fat acts as a lubricant, reducing inter-particle friction and flow resistance (Gonçalves & Lannes, 2010).

The rheological behaviour of cocoa liquor demonstrated strong correlations with other textural parameters ($r > 0.90$; $p < 0.05$), with consistency explaining 82 %, 83 % and 87 % of the variability in firmness, cohesiveness and viscosity index, respectively as shown in Table 1. These relationships align with established chocolate rheology where consistency parameters strongly correlate with yield stress and apparent viscosity, as demonstrated in dark chocolate systems (Afoakwa et al., 2009a). The high correlation coefficients suggest that consistency serves as a reliable predictor of multiple rheological properties, consistent with the non-Newtonian behaviour characteristic of chocolate-based suspensions where yield stress and plastic viscosity follow similar trends (Lee, 2024; Osei Tutu et al., 2023). These findings contribute to the understanding of cocoa liquor as a complex colloidal system where consistency is governed by the interplay between fat content, particle size distribution and processing-induced structural modifications, providing mechanistic insights for optimising processing parameters to achieve desired rheological properties.

3.1.3. Firmness

The firmness of cocoa liquor samples exhibited a substantial range from 175.93 ± 5.72 g (1.72 ± 0.06 N) to 584.80 ± 4.21 g (5.73 ± 0.04 N), reflecting the complex interplay between processing parameters and structural organisation. While ANOVA revealed no statistically significant main effects of depulping ($F(1,23) = 3.93$, $p = 0.0594$) or roasting ($F(2,23) = 2.96$, $p = 0.0717$) individually, post-hoc comparisons demonstrated significant differences between treatment combinations ($p < 0.05$), indicating that the effects manifest through subtle interactions rather than dominant individual factors.

The observed firmness values represent the maximum force required to achieve deformation, fundamentally governed by the spatial arrangement of solid particles within the continuous fat matrix. The mechanistic explanation for firmness variation lies in the microstructural organisation of cocoa solids dispersed in cocoa butter, where firmness is directly influenced by particle-particle interactions, specific surface area and the degree of crystalline network formation (Akonor et al., 2023ab; Obeng et al., 2025). In cocoa liquor, the absence of sugar crystals and milk solids, which typically provide structural reinforcement in chocolate formulations, results in a matrix where cocoa particles are the primary load-bearing components. The higher fat content in cocoa liquor compared to dark chocolate creates a more lubricated system where fat fills voids between solid particles, reducing resistance to deformation and consequently lowering firmness values. This aligns with established principles that increasing fat content reduces crystalline network density by promoting free-moving lubricating flow, as demonstrated in chocolate systems (Asiedu et al., 2025, 2026; Obeng et al., 2025; Mahama et al., 2025) Fig. 2.

The significant differences observed between high-temperature short-time (HTST) and medium roasting temperature (MRT) treatments suggest that thermal processing modifies the physical structure of cocoa particles and their interaction potential. Roasting intensity likely affects particle surface characteristics, potentially altering hydrophobic-hydrophilic balance and inter-particle adhesion forces. The lack of

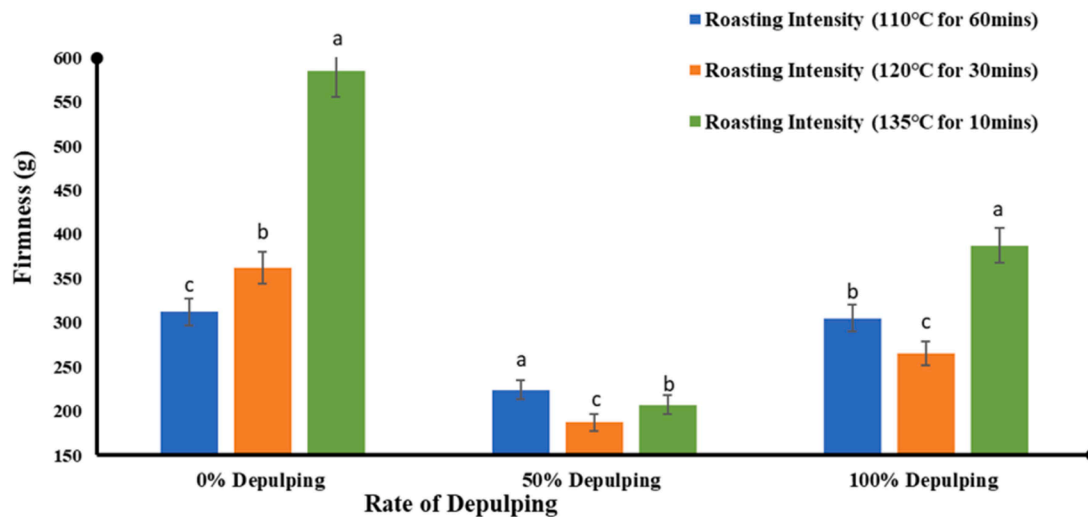


Fig. 2. Firmness of cocoa liquor as a function of depulping level and roasting conditions. Bars represent mean values $\pm$ standard deviation ($n = 3$). Different letters (a-c) indicate significant differences between treatment combinations ($p < 0.05$) by Fisher's LSD test. LTLT: 110 °C/60 min; MRT: 120 °C/30 min; HTST: 135 °C/10 min.

Means with different letters (a, b, c) indicate significant differences ($p < 0.05$).

significant difference between 0 % and 100 % depulped beans under LTLT conditions indicates that pulp removal effects are temperature-dependent, possibly due to differential thermal degradation of residual pulp components that could act as natural emulsifiers or surface-active agents (Streule et al., 2024).

The strong positive correlation between firmness and consistency ($r = 0.90$, $R^2 = 0.82$) provides mechanistic insight into the unified nature of textural properties in cocoa liquor, suggesting that both parameters are governed by similar structural factors, thus, primarily the three-dimensional network of cocoa particles and their resistance to deformation. The moderately high correlations with viscosity index ($r = 0.77$) and cohesiveness ($r = 0.76$) further support the concept that firmness reflects the overall structural integrity of the particle-fat matrix system. These relationships demonstrate that textural properties in cocoa liquor are interconnected through common underlying structural mechanisms (Lee, 2024).

The firmness values obtained are substantially lower than those reported for dark chocolate by Glicerina et al. (2013), which is mechanistically consistent with compositional differences. Dark chocolate contains sugar crystals that form additional load-bearing networks and milk solids that enhance structural reinforcement (Afoakwa et al., 2009; Obeng et al., 2025). The absence of these components in cocoa liquor results in a system where mechanical properties are solely dependent on cocoa particle interactions within the fat matrix, explaining the reduced firmness values observed. This finding aligns with established principles in chocolate science, where particle size distribution, fat content and inter-particle interactions are central to mechanical properties (Asiedu et al., 2025; Obeng et al., 2025). The cocoa liquor system represents a simplified version of this complex, with fewer structural elements contributing to overall firmness, resulting in the observed lower values and different response patterns to processing variables.

3.1.4. Viscosity index

The viscosity index of cocoa liquor samples exhibited a range from 728.5 to 1364.9 g-s (7.1 to 13.4 N-s), demonstrating statistically significant inter-sample variation ($F(8,18) = 548.13$, $p < 0.0001$). Despite this overall significance, individual treatment effects showed no statistical significance: roasting intensity ($F(2,23) = 2.96$, $p = 0.0715$) and depulping rate ($F(1,23) = 1.41$, $p = 0.2473$). The observed pattern revealed that 50 % depulped samples exhibited minimal viscosity indices, while high-intensity roasting protocols (MRT and HTST)

produced maximal values in fully depulped (0 %) and non-depulped (100 %) samples.

These measured viscosity values were substantially lower than those reported for dark chocolate (105.07 ± 7.56 to 1106.00 ± 8.23 N-s), which can be mechanistically attributed to the elevated fat content (55 %) in cocoa liquor. This compositional difference fundamentally alters the particle-matrix interactions, as higher fat content reduces particle-particle contact and flow resistance (Asiedu et al., 2026; Obeng et al., 2025). Literature confirms that fat acts as a lubricating medium, filling interstitial spaces between solid particles and reducing frictional forces during flow (Asiedu et al., 2026; Kongor et al., 2016) Fig. 3.

The rheological characterisation revealed strong positive correlations between viscosity index and other textural parameters: cohesiveness ($r = 0.95$, $R^2 = 0.91$), consistency ($r = 0.93$, $R^2 = 0.87$) and firmness ($r = 0.77$, $R^2 = 0.59$). These relationships reflect fundamental particle physics principles governing concentrated suspensions, where the viscosity-cohesiveness correlation is mechanistically explained by particle-particle interaction dynamics. Systems with elevated cohesiveness exhibit stronger inter-particle forces requiring greater energy input to initiate flow, manifesting as increased viscosity measurements (Macaulay & Rognon, 2021; Peña-Correa et al., 2024).

The mechanistic basis for these correlations lies in the microstructural organisation of the cocoa liquor matrix. When fat content is relatively lower or when polyphenol interactions reduce effective particle coating, frictional forces between solid particles increase, simultaneously elevating both cohesiveness and viscosity (Asiedu et al., 2026; Osei Tutu et al., 2024). This creates a dense, interconnected particle network with spanning stress-bearing paths that restrict matrix mobility and increase flow resistance. The fat phase functions as a plasticiser and its distribution efficiency determines the extent of particle-particle interactions that govern both cohesive strength and flow behaviour, ultimately explaining why viscosity index can predict 59 %, 87 % and 91 % of the variability in firmness, consistency and cohesiveness, respectively.

3.2. Effect of mechanical depulping and roasting parameters (temperature/ time) on the sensory characteristics of the cocoa liquors

3.2.1. Quantitative descriptive analysis (QDA®)

Nine (9) samples in liquored form were evaluated by ten (10) trained sensory assessors using quantitative descriptive analysis (QDA®).

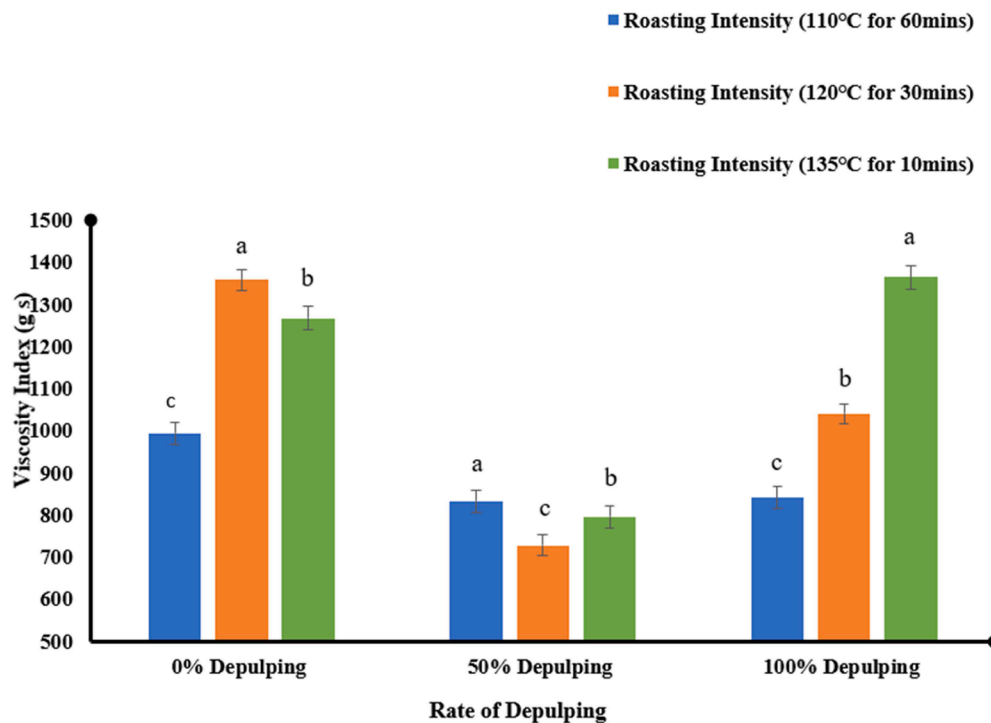


Fig. 3. Viscosity index of cocoa liquor as influenced by depulping level and roasting conditions. Bars represent mean values $\pm$ standard deviation ($n = 3$). Different letters (a-f) indicate significant differences between treatment combinations ($p < 0.05$) by Fisher's LSD test. LTLT: 110 °C/60 min; MRT: 120 °C/30 min; HTST: 135 °C/10 min.

Means with different letters (a, b, c) indicate significant differences ($p < 0.05$).

However, due to the high bitter intensity of the samples the assessors were served with three samples in a session, for three sessions in order to avoid the samples which probably might have different tastes showing partially inhibitory or masking interactions (Osei Tutu et al., 2024). Only three sessions were done for the evaluation of the samples due to limited time and materials. The samples were grouped into three (3), based on their roasting intensity. A total of nine (9) attributes were identified by the sensory panel to describe the samples, with one (1) appearance attribute, three (3) aroma attributes, four (4) flavour attributes and one mouthfeel attribute (Table 2). The four flavour attributes comprised bitter, cocoa, nutty and cocoa liquor flavour, representing the key taste and flavour dimensions of the samples. Most of the descriptors generated were similar to those indicated by Rocha et al. (2017) for cocoa liquor and dark chocolate samples. It is noteworthy that the QDA dataset comprised 90 observations rather than the 270 originally implied by the design. This reduction was due to panel fatigue and intolerance to bitterness, which limited the number of samples panellists could evaluate per session. Although this smaller dataset still allowed statistical analysis, it represents a limitation that should be considered when interpreting the findings.

The modality and appearance were used to describe the samples, when visually viewed. All the samples were considered brown coloured. For the samples roasted at LTLT (Fig. 4), the intensity of brown colour of the samples were insignificantly different ($F(2,87) = 7.42$, $p = 0.13$). However, the samples having the beans roasted at MRT were significantly different ($F(2,87) = 47.70$, $p = 0.0000$) from one another with respect to their brown colour intensity scores. This observation was similar to the samples having the beans roasted at HTST ($F(2,87) = 63.93$, $p = 0.0000$). In both roasting intensities, the samples having 100 % depulped beans were perceived to be the most brown-coloured samples. The sample having the 50 % depulped beans was significantly the least brown-coloured cocoa liquor sample among the samples roasted at HTST.

Principally, cocoa liquor and other cocoa products excluding milk

Table 2

Descriptive terms and reference materials utilised by sensory assessors for evaluating cocoa liquor attributes.

Descriptor	Definition	Reference	Anchors
Appearance			
Brown colour	Characteristic colour of chocolate	Visual reference scale	Light-Dark
Aroma			
Earthy	Characteristic aroma of clay soil	Fresh clay soil	Not-Very
Cocoa liquor	Characteristic aroma of cocoa liquor	Royale Cocoa liquor	Not-Very
Nutty	Nutty aroma like that of crushed 50 % depulped roasted cocoa beans	50 % depulped roasted cocoa beans	Not-Very
Flavour			
Bitter	Basic taste elicited by caffeine/quinine	0.05 % caffeine solution	Not-Very
Cocoa	Characteristic flavour of crushed roasted cocoa beans	100 % depulped roasted cocoa beans	Not-Very
Nutty	Nutty flavour like that of crushed 50 % depulped roasted cocoa beans	50 % depulped roasted cocoa beans	Not-Very
Cocoa liquor	Characteristic flavour of cocoa liquor	Royale Cocoa liquor	Not-Very
Mouthfeel			
Astringent	Dryness in the mouth	0.1 % alum solution	Not-Very

chocolates are brown in colour; a colour attributed to the polymerisation and oxidation of the polyphenolic content of cocoa beans in the fermentation, drying and roasting processes (Ibrić & Ćavar, 2014; Ilmi et al., 2017). According to Krysiak et al. (2013), the formation of the characteristic brown colour during roasting could also be attributed to Maillard and starch dextrinisation reactions. This implies that the brown colour observed for all the samples was indifferent from the normal

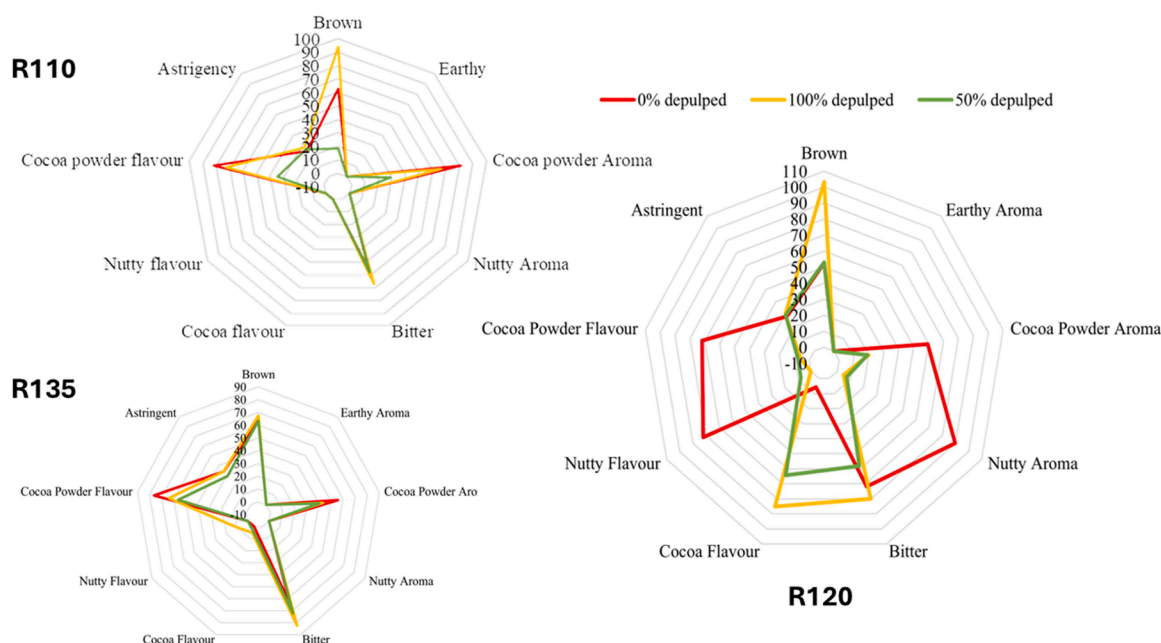


Fig. 4. Sensory characteristics of cocoa liquor as influenced by depulping level and roasting conditions. Radar plots show mean intensity scores ($n = 10$) for samples roasted at (A) LTLT: 110 °C/60 min; (B) MRT: 120 °C/30 min; (C) HTST: 135 °C/10 min. Attributes were evaluated on 150-mm line scales. Statistical significance ($p < 0.05$) was determined by ANOVA with post-hoc comparisons (described in text) and is not directly indicated on the radar plots.

R110 = Sensory Characteristics of Samples derived from beans roasted at LTLT. **R135** = Sensory Characteristics of Samples derived from beans roasted at HTST. **R120** = Sensory Characteristics of Samples derived from beans roasted at MRT.

colour of the cocoa products. The significantly high brown colour intensity scores of the samples having 100 % depulped beans roasted at 120 °C and 135 °C for 30 min and 10 min, respectively could be attributed to the speedy breakdown of the polyphenols during the early periods of fermentation, which might be due to the cellular distraction which permitted the exposure of the polyphenolic compounds to polyphenol oxidase during the agitation of the cocoa via the depulping treatment, resulting in the leaching of the coloured compounds and the formation of insoluble complex compounds during the later stages of fermentation leading to the development of the brown colour of well-fermented cocoa beans (Afoakwa et al., 2012; Asiedu et al., 2025, 2026). Afoakwa et al. (2013) clarified that the presence of the less pulp covering of the depulped beans enhances better penetration of oxygen into the fermenting mass. This enhances the activities of polyphenol oxidase (PPO) because of their aerobic nature, which catalyses the hydroxylation of monophenol to *o*-diphenol and oxidation of *o*-diphenol to highly reactive *o*-quinone, which non-enzymatically polymerises into brown pigments. Findings of Amanquah et al. (2013) indicated that depulping triggered a decline in *o*-diphenol from 47.95 mg/g in undepulped beans to 32.68 mg/g in samples having 50 % depulped beans to 28.64 mg/g in samples having 100 % depulped beans. This indicates that there is conversion of more *o*-diphenol to *o*-quinone in depulped beans than undepulped beans, which polymerises into brown pigments.

The aroma and flavour modalities described the samples as perceived nasally and combined effect of nasal and taste, respectively. Generally, the samples, irrespective of their roasting intensity, were not significantly different for the earthy aroma attribute, with very low intensity scores (Fig. 4). The earthy aroma in cocoa, have been reported by Afoakwa et al. (2008) to be elicited by the compounds, 2-ethyl-3,5-dimethylpyrazine, 2,3-diethyl-5-methylpyrazine, trimethylpyrazine and /or 2-methoxy-3-isopropylpyrazine. Afoakwa et al. (2008), however, indicated that the presence of high earthy aroma in cocoa is an indication of poor fermentation. The samples obtained from the beans roasted at LTLT were found to be not significantly different ($F(2,87) = 0.60, p = 0.5511$) in all the aroma and flavour descriptors. The intensity scores of the cocoa flavour attribute of the samples got from the beans roasted at MRT were

significantly different from one another ($F(2,87) = 0.79, p = 0.4570$).

The sample having 100 % depulped beans had the highest score for the cocoa flavour attribute, while the sample obtained from the undepulped beans (0 % depulped) had the least intensity score for this attribute. Pairwise, each sample acquired from the beans roasted at 120 °C for 30 min significantly differ ($F(2,87) = 60.84, p = 0.0000$) from one another. However, the intensity scores of the cocoa flavour attribute of the samples attained from the beans roasted at HTST were not significantly different ($F(2,87) = 1.63, p = 0.2012$).

The intensity scores of the cocoa liquor flavour and aroma of the samples roasted at MRT significantly vary ($p < 0.05$) from one another. The result indicated that the samples having the undepulped beans had a significantly more intense cocoa liquor aroma and flavour than the samples having the depulped beans. However, the intensity score of the samples having 50 % depulped beans and 100 % depulped beans were not significantly different. The significantly high cocoa liquor aroma and flavour intensity scores in undepulped samples can be explained by their lower quantified polyphenolic content and higher flavonoid levels (Afoakwa et al., 2013ab; Asiedu et al., 2025) (a companion paper), which reduces the masking effect of astringency and bitterness. Hamada et al. (2020) reported that there was an inverse relationship between flavour and astringent-bitter sensation in cocoa liquor. Findings of Hamada et al. (2020) showed that elevated polyphenol concentration decreased the cocoa flavour of cocoa liquor. Hamada et al. (2020) explained that the decrease of the cocoa flavour was probably due to the lower concentration of flavour compounds in the liquor and/or concealing of tastes of astringency and bitterness of the polyphenols in the mouth. A similar observation for the cocoa liquor flavour and aroma intensities was made in the samples attained from the beans roasted at HTST. However, pairwise, each sample was found to be significantly different ($p < 0.05$) from one another.

The intensity scores of the nutty flavour and aroma attributes for the samples attained from the beans roasted at HTST (Fig. 4) were insignificantly different ($F(2,87) = 2.83, p = 0.0645$) ($F(2,87) = 1.02, p = 0.3636$) from one another. A similar observation was made among the samples attained from the beans roasted at LTLT ($F(2,87) = 2.09, p =$

0.1303) ($F(2,87) = 1.85, p = 0.1632$). However, the intensity scores of nutty flavour and aroma for the samples derived from the beans roasted at MRT were significantly different from one another ($F(2,87) = 90.00, p = 0.0000$) ($F(2,87) = 71.52, p = 0.0000$). The sample having the undepulped (0 % depulped) beans had a significantly more intense nutty flavour and aroma than the other two samples. Hamada et al. (2020) reported that an inverse correlation exists between the intensity of flavour and the perception of astringency and bitterness in cocoa liquor. Findings of Hamada et al. (2020) showed that elevated polyphenol concentration decreased the cocoa flavour of cocoa liquor. Hamada et al. (2020) explained that the decrease of the cocoa flavour was probably due to the lower intensity of flavour compounds in the liquor and/or masking of astringency and bitterness tastes of the polyphenols in the mouth. The samples derived from the depulped beans were, however, not significantly different ($p > 0.05$) with respect to their nutty aroma and flavour intensity scores. The nutty aroma and flavour could be attributed to the presence of 2-acetylpyrrole, trimethylpyrazine, benzonitrile, 2-furfural, linalool oxide, 2-ethylpyrazine, 2,3-diethylpyrazine and/or 5-methyl-1H-pyrrole-2-carboxaldehyde, in the samples (Aprotosoie et al., 2016; Rodriguez-Campos et al., 2011).

All the samples were perceived as bitter and astringent. The intensity score for the bitter attribute of the samples obtained from the bean roasted at LTLT were significantly different ($F(2,87) = 3.36, p = 0.0392$). The samples having 100 % depulped beans had a significantly more intense bitter taste, followed by the sample having 50 % depulped beans. A similar observation was made for the bitter attributes of the samples roasted at MRT, although the sample having 50 % depulped beans had the least bitter intensity score, while the sample having 100 % depulped beans was significantly the most bitter sample among the three samples. However, the samples obtained from the beans roasted at HTST were insignificantly different ($F(2,87) = 1.63, p = 0.2012$) with respect to their bitter attribute scores.

Fig. 4 radar plots illustrate mean attribute scores but do not include error bars or significance markers. While these visualisations are useful for pattern comparison, they do not substitute for statistical testing. Post-hoc comparisons confirmed that 100 % depulped beans were significantly more bitter than undepulped beans across roasting treatments ($p < 0.05$), a distinction not visible on the radar plots. The bitter attributes of the samples are strongly correlated with the high polyphenolic content that was quantified in these same samples (Afoakwa et al., 2015ab; Asiedu et al., 2025). The significantly higher bitter intensity score is directly supported by the quantified increase in total polyphenolic content found in the 100 % depulped beans (Asiedu et al., 2025) (a companion paper). This might have resulted in under oxidation of the phenolic content of the cocoa beans, which could have accounted for high polyphenolic content in the 100 % depulped beans, resulting in the high intense bitter taste of the samples. Afoakwa et al. (2012) stated that high bitter and astringent taste of cocoa beans and its products is an indication of inadequate fermentation of the beans.

Astringent is characterised by a dry sensation in the mouth, often accompanied by a rough, puckering effect on the oral tissues. Like the bitter attribute of cocoa products, the astringency of cocoa products has been attributed to the presence of polyphenols in cocoa products (Asiedu et al., 2025; Jonfia-Essien and Tetey, 2016). The polyphenols precipitate the salivary proteins in the mouth and form complexes with the proteins in the mouth, conferring the astringent taste (Afoakwa et al., 2014; Kongor et al., 2016). According to Rocha et al. (2017), astringency is often mistaken for bitterness, as many people struggle to differentiate between the two. Additionally, a high concentration of polyphenols can contribute to both bitter and astringent sensations. The intensity scores for the astringent attributes of the samples were insignificantly different ($p > 0.05$) from one another for all roasting intensities.

4. Conclusion

This study demonstrated that both mechanical depulping and

roasting conditions significantly influence the functional and sensory properties of cocoa liquor, with the combination of 50 % depulping and moderate roasting (120 °C for 30 min) yielding the most balanced quality attributes. Depulping reduced cohesiveness by up to 54 % (from 360.64 g to 165.02 g) and modified consistency ($F(3,23)=5.87, p = 0.0066$), effects attributable to altered polyphenol-protein interactions within the cocoa matrix. The strong correlations between rheological parameters ($r = 0.95$ for cohesiveness-viscosity index; $R^2 = 0.91$) indicate that these mechanical properties are intrinsically linked through the structural organisation of fat and solid particles.

Sensory evaluation revealed that complete depulping intensified bitterness and astringency, with 100 % depulped samples receiving significantly higher bitterness scores across roasting treatments ($p < 0.05$), consistent with elevated polyphenol retention. Conversely, undepulped samples roasted at 120 °C/30 min exhibited optimal cocoa and nutty flavour profiles, suggesting that moderate pulp levels preserve desirable flavour precursors while minimising polyphenol-related off-notes.

The practical implication for cocoa processors is that intermediate depulping (50 %) combined with moderate roasting (120 °C/30 min) offers an optimal balance: maintaining desirable textural properties (consistency: 1245.32 g.s), ensuring stable rheology suitable for downstream processing and enhancing sensory acceptability through balanced flavour development. This combination mitigates the excessive bitterness associated with complete depulping while avoiding the textural limitations of undepulped beans.

This manuscript forms part of a broader project, in which a companion publication (Asiedu et al., 2025, 2026) reported the influence of depulping and roasting on polyphenol composition, flavonoid content and antioxidant activity under the same experimental conditions. Taken together, the two studies provide a comprehensive understanding of how post-harvest treatments shape both the compositional and functional qualities of cocoa liquor.

The present work has limitations including the absence of direct moisture measurements, a reduced sensory dataset (90 observations) due to panel fatigue and a panel size of 10 rather than the recommended 15 trained assessors. Future studies should include moisture content determination to better explain consistency variations, expand sensory panel size to 15–20 assessors with balanced gender distribution and conduct consumer acceptance testing to validate trained panel findings. Additionally, instrumental volatile compound analysis would provide mechanistic insight into the flavour differences observed. Overall, the findings offer practical guidance to cocoa processors and chocolate manufacturers by showing that intermediate depulping combined with moderate roasting can enhance both processing behaviour and sensory acceptability of cocoa liquor.

Data availability

The data for the study are incorporated in the article or referenced within the article.

Ethical statement

This research received ethical clearance from the Ethics Committee of the College of Basic and Applied Science (ECBAS) at the University of Ghana, Legon, Accra, Ghana. Ethical approval (ECBAS 048/15–16) was required because the study involved human assessors for the sensory evaluation of food products. All participants provided informed consent, ensuring compliance with ethical standards for research involving human subjects.

CRediT authorship contribution statement

Bernard Kwabena Asiedu: Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration,

Methodology, Investigation, Data curation, Conceptualization. **Crossby Osei Tutu:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis. **Emmanuel Ohene Afoakwa:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Conceptualization. **Papa Toah Akonor:** Writing – review & editing, Validation, Software, Resources, Methodology, Investigation, Formal analysis. **Agnes Simpson Budu:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Conceptualization. **Firibu Kwesi Saalia:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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