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IMPACT OF FERMENTATION PROCESS, DRYING METHODS IN DIFFERENT MONTHS ON PHYSICO-CHEMICAL CHARACTERISTICS OF COCOA BEANS

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ABSTRACT

Cocoa (*Theobroma cacao* L.) is a globally important commodity and its quality is largely determined by post-harvest practices, particularly fermentation and drying. A field study was conducted at farmer field with an aim to evaluate the effect of fermentation methods (spontaneous *vs.* starter culture) and drying techniques (sun, solar, and poly dryer) in different months (Jan – June) on the physico-chemical attributes of cocoa beans. Key quality parameters assessed included fermentation time (days), drying time (hours), titratable acidity (m.eq. NaOH/g), and phenolic content (mg/g). Results revealed that starter culture fermentation consistently increased phenolic content while reducing the titratable acidity compared to spontaneous fermentation. Drying methods significantly influenced bean composition, sun drying resulted in increased drying time while lowered titrable acidity and phenol retention whereas solar and poly dryer systems better preserved biochemical quality. Seasonal variation was also evident, with beans harvested in April and May exhibiting higher phenolic content, while those from January and February showed lower values. Interactive effects (fermentation × drying × month) highlighted that optimal quality was achieved with starter culture fermentation combined with poly dryer drying during dry months. The findings underscore the need for standardization of fermentation and drying protocols tailored to seasonal conditions to ensure consistent cocoa quality, enhance market competitiveness, and support the growing cocoa sector in India.

***Key words*: Cocoa, Fermentation, Sun drying, Solar drying, poly drying, quality**

Introduction

Cocoa (*Theobroma cacao L.*), often referred to as "Food of the Gods," is a globally important commodity crop, serving as the raw material for chocolate production. Its origin traces back to the western Amazon region, from where it spread widely across equatorial zones. The primary determinants of cocoa quality lie in its post-harvest handling, particularly fermentation and drying. Freshly harvested beans are bitter, astringent and lacking in the characteristic flavour and aroma of chocolate. Fermentation initiates critical biochemical transformations mediated by yeasts, lactic acid bacteria and acetic acid bacteria, leading to the formation of colour, aroma and flavour precursors. Following fermentation, drying reduces the moisture content to about 7–7.5%, prevents mould growth and stabilizes beans for storage, while also enhancing flavour development. Traditional sun drying is widely practiced but depends heavily on favourable weather and exposes beans to contamination, whereas artificial drying offers controlled conditions but may negatively impact flavour if not carefully managed. Recent trends show a decline in bean quality due to farmers fast-tracking post-harvest operations for quicker returns, often through incomplete fermentation or improper drying. Such practices result in beans with poor flavour, excessive acidity and reduced market value. Given the rising importance of cocoa in India, particularly in Andhra Pradesh, there is an urgent need to standardize fermentation and drying protocols to ensure consistent bean quality. This study evaluates different fermentation and drying methods, along with their durations, to assess their impact on the physical, chemical characters of cocoa beans, with the ultimate goal of enhancing quality and ensuring competitiveness in domestic and global markets.

Materials and Methods

A study was conducted from January to June 2025 at farmer's field in Venkataramannagudem, West Godavari district of A.P with an aim to study the effect of different fermentation process, drying methods in different months (seasons) on physico-chemical characters of cocoa. In this study a total of 36 treatments were carried out during the experimental period, with 6 treatments each month and two replications. About 3 kg of fresh beans were taken in each bamboo basket and subjected to two fermentation methods, spontaneous fermentation and fermentation with starter culture. In starter culture fermentation 10g of dry yeast (*Sachharomyces cervevisiae*) per each kg of fresh beans was activated by taking dried yeast (10 g/kg wet beans) and was rehydrated in 100 ml of warm water (35-40°C) and allowed it to sit undisturbed for 10-15 min. The yeast was mixed into 3kg of wet cocoa (1% concentration) beans in starter culture method of fermentation. The observations on fermentation time (days), drying time (hours), titrable acidity (m.eq.NaOH/g) and phenols (mg/g) were recorded during the study.

Fermentation time (Days)

The starting point of fermentation was recorded immediately after the beans were loaded into the fermentation unit. The process was monitored daily at regular intervals. Fermentation was considered complete when the pulp removal was nearly complete and internal cotyledon colour changed uniformly from purple to brown, indicating death of the embryo and diffusion of oxidation products.

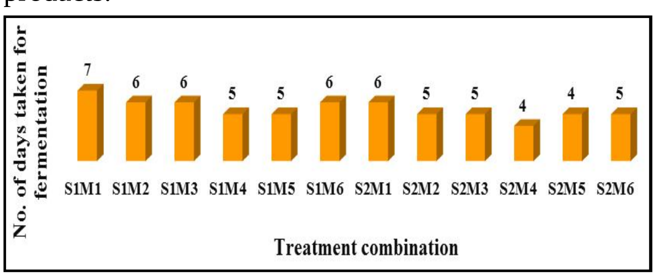

Fig. 1: Effect of fermentation methods during different months.

Drying time (Hours)

The ratio of the removed moisture is defined as drying rate kg/m^2 of dry weight of material per unit time. The amount of moisture evaporated is decided and then the rate of drying is determined.

It is calculated by the following formula:

R =dm/dq

$$= \frac{\text{Amount of moisture removed}}{\text{time taken (h)} \times \text{Bean dry weight of the sample}}$$

The drying rate is computed by taking into account initial and final moisture content of the cocoa beans.

Titrable Acidity (m.eq.NaOH/g)

The titrable acidity (lactic acid and acetic acid) of the cocoa bean powder was determined by the method of Friedrich (2001) under colorimetric acidity titration as follows. The solid samples were mixed with equal portions of deionized distilled water and swirled in blender at 100 rpm within a 2min centrifugation at 2500 rpm at room temperature. To the 10 ml of the supernatant sample solution on a clean Erlenmeyer flask, 5 drops of 1% phenolphthalein indicator solution were added with a magnetic stir bar and stirred. Then 0.1N NaOH was titrated against the sample solution to the end point of pH 8.2 until a faint but definite pink colour was obtained and it was found to be stable between 5 and 10 seconds.

$$\text{Titrable acidity (\%)} = \frac{V \times N \times \text{m.eq.wt} \times 100}{1000 \times Vs}$$

Where,

V is volume (ml) of NaOH solution used for titration

N is normality of NaOH solution

m.eq.wt is milli equivalent weights of acids (lactic acid = 90; acetic acid = 60)

Vs = sample volume (10 ml).

Phenol content (mg/g)

The total phenol content of cocoa beans was estimated by using Folin cio-calteau reagent as determined by Sadasivam and Manickam, 2005. The sample of the dried bean about 0.5 g was weighed and crushed with the pestle and mortar with 1/ 10 of the volume of 80 % ethanol. The centrifugation was performed at 10000 rpm for 25 min and the supernatant was collected. The residues were again centrifuged with 80 percent ethanol five times, supernatants were combined and allowed to dry off. The residue was dissolved in 5 ml of distilled water and various aliquots of 0.2 to 2 ml of the same are pipette out into test tubes. The tubes were filled to 3 ml of water and 0.5 ml of Folin cio-calteau reagent. After 3 minutes, 2 ml of 20

Table 1: Effect of fermentation process, drying techniques employed in different months on drying time.

S×D Mean Table

	D_1	D_2	D_3	Means of S
S_1	90.75	62.00	86.67	**79.81**
S_2	91.25	62.00	86.67	**79.97**
Means of D	**91.00**	**62.00**	**86.67**	

D×M Mean Table

	M_1	M_2	M_3	M_4	M_5	M_6	Means of D
D_1	109.75	99.25	77.75	70.00	69.5	119.75	**91.00**
D_2	72.00	72.00	60.00	48.00	60.00	60.00	**62.00**
D_3	96.00	96.00	80.00	72.00	80.00	96.00	**86.67**
Means of M	**92.58**	**89.08**	**72.58**	**63.33**	**69.83**	**91.92**	

S×M Mean Table

	M_1	M_2	M_3	M_4	M_5	M_6	Means of S
S_1	92.50	89.00	72.50	63.17	69.67	92.00	**79.81**
S_2	92.67	89.17	72.67	63.50	70.00	91.83	**79.97**
Means of M	**92.58**	**89.08**	**72.58**	**63.33**	**69.83**	**91.92**	

	SEm±	CD at 5%		SEm±	CD at 5%
S	0.073	NS	S×D	0.127	NS
D	0.090	0.258	S×M	0.180	NS
M	0.127	0.365	D×M	0.220	0.632
S×D×M	0.312	NS			

per cent sodium carbonate was pour in each test tube and thoroughly mixed. Then the tubes were placed into boiling water for one minute and and left them to cool. The absorbance of the solution at 650 nm was recorded against blank, after its cooling. Different concentrations

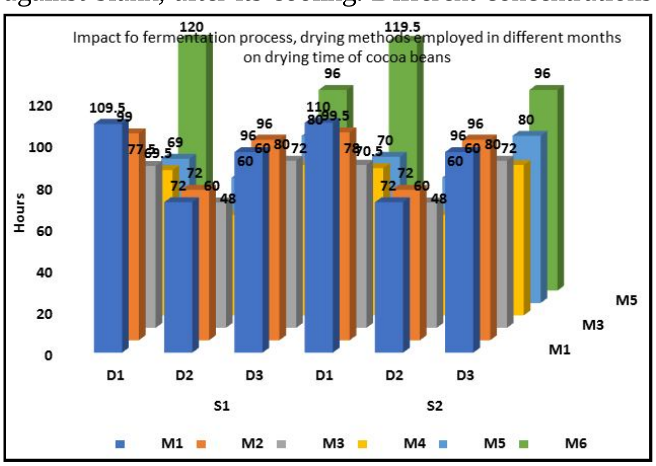

Fig. 2: Interaction effect of fermentation and drying methods employed in different methods on drying period of cocoa beans.

Fermentation	Drying techniques	Months	
S_1- Spontaneous fermentation	D_1-Sun drying	M_1-January	M_4-April
S_2- Starter culture fermentation	D_2-Solar drying	M_2-February	M_5-May
	D3-Poly drying	M_3-March	M_6-June
S×M×D	SEm± = 0.312	CD at 5%	NS

of catechol were used to prepare a standard curve in order to determine the concentration of phenols in cocoa sample and was measured as mg / gram.

Results and Discussions

The data pertaining to the effect of fermentation process, drying methods in different methods were presented in Table 1 to 4 and Fig. 1 to 4.

Fermentation time (Days)

In general, cacao fermentation is carried out for 5 to 7 days. Fermentation with starter culture and without starter culture (spontaneous fermentation) was depicted from Fig. 1, indicated that wet beans with starter culture during the months of April and May took less of days for fermentation (4 days) whereas spontaneous fermention during January took more number of days (7 days). Maharani Shinta Dewil (2022) stated that the function of fermenting cocoa beans by adding a starter culture not only guarantees a short and optimal cacao fermentation process but also avoids variability in the degree of fermentation and flavour profile that is usually seen in the case of spontaneous fermentation of cacao beans. The addition of starter culture (*Saccharomyces cerevisiae)* accelerated the increase in the temperature of fermentation. It resulted in a higher final temperature than the one without a starter culture (Marwati *et al.,* 2024).

Drying time (Hours)

The impact of fermentation methods, drying methods in different months on drying time and their interactions on cocoa beans were given in Table 1 and Fig. 2.

It was observed from the Table 1 that the fermentation methods (spontaneous fermentation *vs* fermentation with starter culture) exhibited non-significant difference on drying time. Drying methods (Sun drying, solar drying & poly dryers) showed considerable difference on drying time. Among drying methods, the beans dried in solar dryer (D_2) took least drying time (62.00 hrs) followed by poly dryer (D_3) (86.67 hrs) whereas beans dried under sun (D_1) took more drying time (91.00hrs). The findings are in tune with the results of Puello-Mendez *et al.*, (2017) where the solar greenhouse dryer dried at a faster rate as the enclosed space trapped more heat and resulted in a lower relative humidity condition that increased moisture loss in cocoa beans. Further, in solar dryers with a metal base, beans also absorb heat by conduction from the surface, which is warmed by solar radiation. This process accelerates

Table 2: Variation of titrable acidity in cocoa beans, fermented and dried in different methods.

S×D Mean Table

	D_1	D_2	D_3	Means of S
S_1	2.48	3.39	2.79	**2.89**
S_2	2.51	3.34	2.53	**2.80**
Means of D	**2.50**	**3.37**	**2.66**	

D×M Mean Table

	M_1	M_2	M_3	M_4	M_5	M_6	Means of D
D_1	2.29	2.33	2.46	2.61	2.95	2.34	**2.50**
D_2	3.04	3.23	3.40	3.69	3.74	3.11	**3.37**
D_3	2.48	2.53	2.70	3.00	2.91	2.36	**2.66**
Means of M	**2.60**	**2.70**	**2.85**	**3.10**	**3.20**	**2.60**	

S×M Mean Table

	M_1	M_2	M_3	M_4	M_5	M_6	Means of S
S_1	2.66	2.77	2.90	3.10	3.25	2.66	**2.89**
S_2	2.55	2.63	2.81	3.09	3.16	2.54	**2.80**
Means of M	**2.60**	**2.70**	**2.85**	**3.10**	**3.20**	**2.60**	

	SEm±	CD at 5%		SEm±	CD at 5%
S	0.012	0.035	S×D	0.021	0.060
D	0.015	0.043	S×M	0.030	NS
M	0.021	0.060	D×M	0.037	0.105
S×D×M	0.052	0.148			

moisture removal from the bottom layer of beans before heat is more uniformly distributed through convection (Santander *et al.*, 2025). Months also showed significant impact on drying time of cocoa beans. The less drying time (63.3 hours) was observed during April month (M_4) whereas the beans took more time (92.58 hours) for drying in the month of January(M_1). Similar findings was depicted by Dzelagha *et al.*, (2020) stated that thermal radiation plays a crucial role in solar dryers, where solar energy is converted into heat, which is absorbed directly by the cocoa beans and drying surfaces.

From the Fig. 2, it was noticed that the interaction between fermentation and drying techniques (S×D) and fermentation and months (S×M) showed non-significant effect on drying time of cocoa beans whereas the interaction between drying techniques and months (D×M) impacted the drying of cocoa beans. The beans dried under sun during the month of June (D_1M_6) took more time for drying (119.75), while beans in solar drying during April (D_2M_4) took least time (48 hrs). SxDxM interaction was also non-significant influence on drying time.

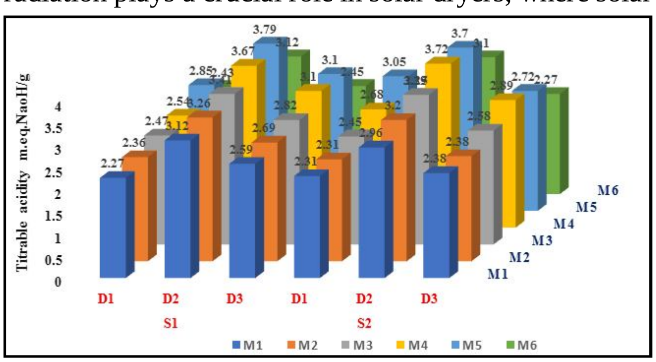

Fig. 3: Effect of titrable acidity in cocoa beans by different fermentation and drying methods.

Fermentation	Drying techniques	Months	
S_1- Spontaneous fermentation	D_1-Sun drying	M_1-January	M_4-April
S_2- Starter culture fermentation	D_2-Solar drying	M_2-February	M_5-May
	D3-Poly drying	M_3-March	M_6-June
S×M×D	SEm± = 0.312	CD at 5%	NS

Titrable acidity (m.eq NaOH/g)

The influence of fermentation methods, drying methods during different months and their interactions showed significant effect on titrable acidity in cocoa beans and the results were presented in Table 2 and Fig. 3.

Fermentation methods differed significantly for titrable acidity (Table2). Titrable acidity (2.89 m.eq NaOH/g) was found highest in beans kept for spontaneous fermentation (S_1) when compared to the beans with starter culture fermentation (S_2) (2.80 m.eq NaOH/g). Similar findings were done by Balcazar Zumaeta *et al.*, (2023) who stated that starter cultures produce more controlled fermentation where inoculated yeasts prevail early in the production of ethanol and limit unregulated growth Acetic acid bacteria. The influence of drying methods on titrable acidity was highly significant. The highest titrable acidity (3.37 m.eq NaOH/g) was recorded in beans of solar drying (D_2), followed by beans dried in poly dryers (D_3) (m.eq NaOH/g). It was noticed that beans dried under sun (D_1) recorded least titrable acidity (m.eq NaOH/g). Guehi *et al.*, (2010) stated that titratable acidity was increased in artificial hot-air drying since the high rate of drying inhibited volatilization of organic acids like acetic acid, whereas sun and mixed drying permitted more gradual losses of organic acids by evaporation, resulting in a lower acidity. Months showed significant effect on titrable acidity. Beans cured during the month of May (M_5), noticed highest titrable acidity (3.20 m.eq NaOH/g) whereas the least titrable acidity (2.60 m.eq NaOH/g) was recorded in beans cured during January (M_1) and June (M_6). According to Adeyemi *et al.*, (2020), the seasonal conditions affected titrable acidity, which was greater during the dry season ranged from 3.47 to 3.70 m.eq KOH/g and lesser during wet season varied from 3.19 to 3.38 m.eq KOH/g. thus the climatic

Table 3: Impact of fermentation process, drying methods in different months on phenol content of cocoa beans.

S×D Mean Table				
	D_1	D_2	D_3	**Means of S**
S_1	60.16	63.31	68.63	**64.03**
S_2	62.05	66.28	71.71	**66.68**
Means of D	**61.10**	**64.79**	**70.17**	

D×M Mean Table							
	M_1	M_2	M_3	M_4	M_5	M_6	**Means of D**
D_1	54.21	57.26	63.55	65.25	66.61	59.75	**61.10**
D_2	59.56	62.27	66.86	69.47	69.37	61.23	**64.79**
D_3	65.00	68.32	73.68	74.20	73.37	66.47	**70.17**
Means of M	**59.59**	**62.61**	**68.03**	**69.64**	**69.78**	**62.48**	

S×M Mean Table							
	M_1	M_2	M_3	M_4	M_5	M_6	**Means of S**
S_1	57.89	62.23	67.57	68.29	68.38	59.84	**64.03**
S_2	61.28	63.00	68.49	70.98	71.19	65.13	**66.68**
Means of M	**59.59**	**62.61**	**68.03**	**69.64**	**69.78**	**62.48**	

	SEm±	CD at 5%		SEm±	CD at 5%
S	0.148	0.425	S×D	0.257	0.737
D	0.182	0.521	S×M		
M	0.257	0.737	D×M		

conditions especially in the dry season retards the degradation of acid that left higher proportions of acidity.

S×D interaction significantly effected the titrable acidity. Beans in spontaneous fermentation dried in solar drier (S_1D_2) were noticed with highest titrable acidity (3.39 m.eq NaOH/g) which was on par with (S_2D_2) (3.34 m.eq NaOH/g) while the least titrable acidity was noticed in (S_1D_1) (2.48 m.eq NaOH/g). Statistically significant difference was observed in interaction of drying methods and different months whereas non-significant results were noticed with interaction of fermentation process (S) and months (M). Beans dried in solar dryers during the month of May (D_2M_5) recorded the maximum titrable acidity (3.74 m.eq NaOH/g) and it was on par with (D_2M_4) (3.69 m.eq NaOH/g). Beans dried under sun during the month of January (D_1M_1) has the least titrable acid value (2.29 m.eq NaOH/g). S×D×M interaction had significant effect on titrable acidity. Beans in spontaneous fermentation dried in solar drier during *i.e* May ($S_1D_2M_5$) recorded highest value of titrable acidity (3.79 m.eq NaOH/g) and the least titrable acidity (2.27 m.eq NaOH/g) was noticed in beans fermented with spontaneously and dried under sun during the month of January ($S_1D_1M_1$).

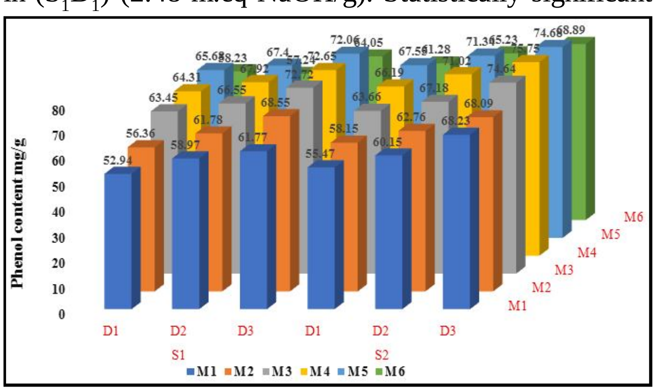

Fig. 4: Variation in phenol content in cocoa beans by different fermentation process, drying methods in different months.

Fermentation	Drying techniques	Months	
S_1- Spontaneous fermentation	D_1-Sun drying	M_1-January	M_4-April
S_2- Starter culture fermentation	D_2-Solar drying	M_2-February	M_5-May
	D3-Poly drying	M_3-March	M_6-June
S×M×D	SEm± = 0.629	CD at 5%	1.805

Phenol content (mg/g)

The effect of fermentation process, drying methods and the process during different months and their interactions on phenol content in cocoa beans are presented in Table 3 and Fig. 4.

Significant differences were noticed in between fermentation process. The beans with starter culture (S_2) had higher phenol content (66.68mg/g) compared to the beans in spontaneous fermentation (S_1) (64.03mg/g). Nugrohoa *et al.*, (2021) stated that controlled oxidation in fermentation has a lower rate of uncontrolled oxidation and variable microbial alteration that preserve phenolic compounds in comparison to spontaneous fermentation with the starter cultures.

Among drying methods significant differences were noticed among the drying treatments. The highest phenol content (70.17 mg/g) was recorded in beans dried in poly dryer (D_3) while the lowest phenol content (61.10 mg/g) was recorded in sun drying (D_1) method. Solar and greenhouse dryers stabilize temperatures and humidity causing protection to cocoa phenols. They do also cause lower oxidation and heat damage to the produce than open- sun drying.

Noticable variations in phenol content were found in fermentation process in different months. Phenol content in the beans was peaked during summer months *i.e.,* April (M_4). & May (M_5) 69.64 mg/g & 69.78 mg/g respectively whereas fermentation during January (M_1) exhibited the lowest phenol content (59.59 mg/g). The increased quantity of phenols in the beans of cocoa grown during the dry season is associated with less water supply, which induces slight stress during the ripening of cocoa fruits. This also encourages the formation and maintenance of the phenolic compounds, but wet conditions further the phenol oxidation enzyme, thus spurring an increase of phenol loss (Niether *et al*., (2018).

S×D interaction exhibited a significant difference on phenol content. Beans in starter culture, dried in poly dryer (S_2D_3) recorded highest phenol content (71.71 mg/g), whereas the least phenolic content was observed in (S_1D_1) (60.16 mg/g). In D×M interaction (D_3M_4) is having highest phenol content (74.2mg/g). Phenol content was lowest in sun dried beans during January (D_1M_1) (54.21 mg/g). S×M interaction significantly effected the phenol content in cocoa beans. Beans in starter culture fermentation during the month of May (S_2M_5) exerted higher phenol content (71.19 mg/g), and it was on par (70.98 mg/g) with (S_2M_4). (S_1M_1) had least phenol content (57.89 mg/g). S×D×M interaction had a significant effect on phenol content. The beans fermented with starter culture and dried in poly dryer during the month of April ($S_2D_3M_4$) recorded highest phenol content (75.75 mg/g) and the least phenol content was observed in ($S_1D_1M_1$) (52.94 mg/g).

Conclusion

The study clearly demonstrated that fermentation methods, drying techniques, and seasonal variations exert a strong influence on the fermentation time, drying time and quality attributes of cocoa beans. It was clearly indicated that addition of starter culture reduced the fermentation time and consistently enhanced phenolic content while lowering titratable acidity compared to spontaneous fermentation, confirming its role in producing more uniform and stable fermentation outcomes. Similarly, drying methods showed marked effects, with sun drying resulted in reduced phenolic retention, while controlled drying systems such as poly dryers and solar dryers preserved higher levels of phenols and influenced acidity differently. Seasonal differences also proved critical, with beans harvested and processed in May and April showing higher phenolic contents, whereas months like January and February recorded lower values, highlighting the importance of climatic conditions in cocoa quality development.

Overall, the significant single and interactive effects of fermentation process, drying techniques and months underscore the need for integrated post-harvest management strategies in cocoa production. The interactions (S×D×M) revealed that optimal combinations, such as starter culture fermentation with poly dryer method of drying during dry months, maximized phenolic content while balancing acidity. These findings emphasize that adopting controlled fermentation process and drying systems, along with consideration of seasonal conditions, can enhance the quality attributes of cocoa beans, ultimately improving their flavour profile, storability, and suitability for chocolate processing.

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