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Comparative evaluation of drying methods on the chemical composition and quality attributes of cocoa beans of high-yielding variety Nethra Centura (VTLCH 5)

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Abstract
Cocoa beans are the seeds derived from the fruit pods of *Theobroma cacao L.*, a perennial tropical tree of high economic significance due to its use in the global chocolate and confectionery industry. Post-harvest processing, especially drying, plays a critical role in determining the final biochemical composition, sensory quality, shelf stability and market value of cocoa beans. The present study evaluated the influence of three drying techniques solar drying, oven drying and artificial mechanical drying on the physicochemical and nutritional characteristics of fermented cocoa beans belonging to the variety VTLCH-5 (Nethra Centura). Key biochemical parameters analysed included pH, titratable acidity, crude protein, phenolic content, flavonoid content, antioxidant capacity, fat level, volatile acidity and free fatty acids. The results revealed notable differences among drying treatments. Solar-dried beans recorded the highest pH value (6.45), indicating a favourable reduction in acidity and potentially milder flavour development. Artificial drying resulted in the highest titratable acidity (0.24 meq/100 g), crude protein (14.00%), phenolic content (0.53 mg/g), and the highest fat content (39.08%), suggesting improved retention of nutritional constituents under controlled drying conditions. Sun-dried beans exhibited lower volatile acidity compared to oven drying, whereas artificially dried beans showed comparatively higher free acidity levels than both oven- and sun-dried samples. Across all treatments, free fatty acid accumulation increased gradually but remained below the critical rancidity threshold of 1.75%, indicating acceptable storage quality. Overall, findings demonstrate that drying technique significantly affects the biochemical integrity, nutritional value and chemical stability of fermented cocoa beans. Artificial drying enhances desirable biochemical attributes such as protein, phenolics and fat, while solar drying supports more balanced acidity levels. These results highlight the importance of selecting appropriate drying strategies to optimize cocoa bean quality for processing and value addition. Further studies involving sensory evaluation, storage stability and economic feasibility may help refine drying recommendations for commercial cocoa production.

Keywords: Quality attributes, cocoa, drying techniques, phenol, antioxidant, titrable acidity, artificial drying techniques

Introduction
Cocoa (*Theobroma cacao* L.) is one of the most economically valuable plantation crops cultivated across humid tropical regions, particularly in West Africa, Southeast Asia, and Latin America. It serves as the primary raw material for chocolate and a wide range of confectionery products and has growing applications in pharmaceutical, nutraceutical, and cosmetic industries due to its rich composition of flavonoids, polyphenols, essential fatty acids, and other bioactive compounds. Cocoa production also plays an important socio-economic role, providing livelihoods for an estimated 40-50 million people worldwide, particularly smallholder farmers who rely on cocoa as their major cash crop (Afoakwa *et al*., 2014) [3]. Therefore, improving cocoa bean quality is essential not only for industrial processing but also for enhancing farmer income and sustaining global market competitiveness.
Post-harvest handling, especially fermentation and drying, plays a crucial role in determining the chemical composition, nutritional value, storage stability, and final flavor profile of

cocoa beans. Fermentation initiates several biochemical reactions that contribute to flavor precursor formation, pigment development, and acidity reduction. However, fermentation alone is insufficient to stabilize the beans; drying is essential to prevent microbial spoilage and extend shelf life by reducing moisture content from around 60% at harvest to below 7%, which is the accepted threshold for safe storage and international trade (Kongor *et al.*, 2016) [18]. The drying stage also influences enzymatic activity, oxidation processes, and volatile compound formation, all of which contribute to the sensory and commercial quality of the final cocoa product.

The choice and management of drying techniques significantly affect the chemical composition, physical properties, and organoleptic quality of cocoa beans. Parameters such as drying temperature, humidity, rate of moisture removal, and airflow can alter concentrations of key compounds, including phenolics, flavonoids, proteins, sugars, and lipids, which are associated with antioxidant activity, nutritional value, and flavor. Suboptimal drying may result in case hardening, smoky or moldy flavors, incomplete fermentation, or excessive acidity, leading to quality deterioration and rejection in export markets (Aprotosoaie *et al.*, 2016) [7].

Several drying systems are commonly used in cocoa-producing regions, including traditional sun drying, oven drying, solar dryer designs, and artificial mechanical dryers. Sun drying remains the most widely adopted method due to its low cost and environmental sustainability; however, it is weather-dependent, slow, and prone to contamination. Artificial drying systems provide better control over drying parameters and reduce processing time, yet improper temperature regulation may degrade heat-sensitive phytochemicals and negatively influence flavor development. In recent years, hybrid drying techniques have emerged as promising alternatives, integrating solar and mechanical components to improve energy efficiency and retention of biochemical constituents.

Studies indicate that drying methods strongly influence the retention of bioactive compounds and fat stability in cocoa beans. For example, Guehi *et al.*, (2010) [7] reported higher phenolic content and antioxidant capacity in sun-dried beans compared to mechanically dried samples. Similarly, Lima *et al.*, (2024) [19] demonstrated that controlled solar-assisted drying systems can enhance drying efficiency while preserving desirable nutritional and sensory attributes. Despite advances in drying technologies, comparative evaluations involving different drying methods across high-yielding cocoa genotypes remain limited.

Given the crucial role of drying in determining cocoa quality and its economic value, there is a need to assess how different drying methods affect the chemical composition and quality attributes of specific cocoa varieties. Therefore, the present study investigates the effects of solar, oven, and artificial drying methods on the biochemical characteristics of fermented cocoa beans of the variety VTLCH-5 (Nethra Centura). The outcomes are expected to support improved post-harvest processing strategies, enhance quality optimization, and strengthen value addition in cocoa value chains. Therefore, this study aims to compare the effects of solar, oven, and artificial drying methods on the chemical composition and quality attributes of fermented cocoa beans, providing insights into the most suitable drying approach for optimizing cocoa bean quality and post-harvest value.

Materials and Methods

- **Sample Collection and Preparation:** Ripe cocoa pod of variety VILCH5 were harvested from the high-density plantation system plot maintained at ICAR-Central Plantation Crops Research Institute, Vittal. The beans were separated from the pod after breaking it open using a wooden tool. The wet fresh bean were fermented in a perforated basket for seven days. After the completion of the fermentation, samples were taken for drying in different drying methods (Fig.1.). They were dried as follows,
- **Drying Methods:** Three drying techniques were evaluated

1. **Solar tunnel dryer:** The fermented cocoa beans were dried in a solar tunnel dryer for five days with daily turns of the beans. The bean moisture was reduced to 6% (Fig.2.).
2. **Dryer:** The fermented cocoa beans were dried for 30h in a heat pump dryer at 55 ˚C. The final moisture content of the bean was reduced to 6% (Fig.3.).
3. **Hot air oven:** The fermented beans were dried in a hot air oven at 55˚C for 21h. The bean moisture reduced to 6% (Fig.4.). The dried beans were cooled to room temperature, packed in airtight polyethylene bags, and stored.

Preparation of Cocoa Bean Powder

The cocoa beans were first subjected to manual shelling to separate the outer husk from the inner nibs. After complete restored removal of the shells, the nibs were collected and transferred into a clean mortar. Using a pestle, the nibs were carefully ground with steady pressure until affine, uniform powder was obtained. This powdered cocoa was then stored in a clean, dry container and used for further analytical procedure (Fig.5.).

- **Determination of Moisture Content:** Moisture content was determined by oven drying 5 g of ground cocoa sample at 105 °C for 24 hoursuntil constant weight (AOAC, 2019).
- **Chemical Composition Analysis:** pH, titratable acidity, crude protein, crude fat, total phenolics, flavonoids, and antioxidant activity were analyzed using standard AOAC and colorimetric methods (Singleton *et al.*, 1999; Chang *et al.*,2002; Brand-Williams *et al.*, 1995) [5, 11, 9].
- **Statistical Analysis:** All experiments were conducted in triplicate. Data were analyzed using one-way ANOVA and Turkey's post-hoc test (p<0.05) in SPSS version 26.0.

Results and Discussion

The comparative results of the chemical composition and antioxidant properties of cocoa beans subjected to different drying methods are presented in Table 1.

Effect of Drying Methods on Chemical Composition: Table 1 displays the pH values of cocoa beans processed using three different drying techniques. A notable variation in pH was detected among the methods. Beans subjected to solar drying showed the highest pH (6.45), which was significantly higher than those produced by the other two drying approaches. This variation can be explained by multiple factors, including the temperature and duration of drying, ambient humidity, airflow characteristics, and the rate at which moisture moves from the inner bean tissues to the surface, as highlighted by Tagro *et al.* (2010) [23]. The solar drying method ensures slower moisture removal and extended contact with open air, encouraging the evaporation of volatile acids and leading to a rise in pH. Similar findings were reported by Jinap *et al.*, (1994a) [16], who observed that sun drying enhances the loss of acidic compounds, thereby increasing the pH of cocoa beans. Solar drying resulted in higher pH and compared to oven and artificial drying, suggesting a milder drying effect that preserved organic acids and prevented excessive fermentation. Similar findings were reported by Adeyeye *et al.* (2020) [2], who noted improved flavor precursors in sun-dried cocoa.

Table 1 depict the effect of various drying techniques on the titratable acidity of cocoa beans. Among the different methods, oven-dried beans recorded a comparatively higher titratable acidity value (0.24 meq/100 g), which was significantly greater than those obtained from the other drying processes. The increased acidity in fermented cocoa beans can be linked to the build-up of acetic acid, which forms when ethanol is oxidized by acetic acid bacteria in the presence of oxygen during fermentation. On the other hand, beans dried under sun or mixed drying exhibited lower acidity due to the slower and milder drying conditions that enable the steady evaporation of acetic acid. In contrast, faster artificial drying methods may hinder acid diffusion, reducing the efficiency of acid removal during moisture loss.

Effect of drying methods on crude protein content of Cocoa Beans: Fresh cocoa beans generally contain about 11.71% crude protein, but this level decreases after drying because of protein denaturation and Maillard reactions caused by heat. The degree of protein reduction varies depending on the drying technique. Open-sun and cabinet drying methods preserved relatively higher protein contents (around 10.4%), while solar drying, which exposes beans to higher internal temperatures, resulted in a more noticeable decline (around 7.77%). These observations suggest that gentle drying processes operating at moderate and controlled temperatures are more effective in maintaining protein levels. While sun drying helps conserve protein due to its mild heat, it is slower and increases the risk of microbial contamination. Conversely, oven drying provides better regulation of temperature and duration, but excessive heating can lead to protein degradation (Biehl and Passern, 1982) [8].

Effect of Drying Methods on Bioactive Compounds and Antioxidant Activity: Sun drying, being the most traditional method, often results in substantial degradation of phenolic compounds due to extended exposure to sunlight, oxygen, and fluctuating temperatures. Oven drying, when carried out under moderate and controlled conditions, tends to preserve more phenols; however, excessive heat can still cause significant losses. Studies have shown that oven drying generally yields higher total phenolic content than sun drying (Alean et al., 2016) [16]. Comparatively, convection drying produces significantly higher phenolic retention than traditional sun drying, while low-temperature techniques such as freeze drying are most effective in conserving these compounds (Oracz and Nebesny, 2016) [20]. These findings provide valuable insight into how post-fermentation drying methods affect the chemical composition of cocoa beans. Sun drying helps maintain a greater amount of polyphenols and flavour precursors than artificial drying, though artificial drying achieves faster moisture removal and reduces microbial risks. Nevertheless, the higher temperatures in artificial drying can lead to polyphenol degradation. Among all methods, freeze drying preserved the highest total phenolic and flavonoid contents, demonstrated the strongest antioxidant activity, whereas oven drying resulted in the lowest levels (Camu *et al*., 2008) [10].

In our study it is revealed that flavonoid and antioxidant content was higher recorded in samples dried under and sun and oven drying than mechanical or artificial drying (Table.1). The low-temperature or short-duration drying techniques—such as sun drying or controlled hot-air drying—are more effective in preserving flavonoid compounds, resulting in only slight losses compared to levels after fermentation. In contrast, high-temperature or prolonged drying, particularly through mechanical or oven systems, accelerates oxidative and thermal breakdown, leading to significant reductions in flavonoid content. Among the various methods, freeze drying retains the highest concentrations of flavonoids, followed by sun drying and then oven drying; this pattern corresponds closely with observed antioxidant capacities (Camu *et al.*, 2008) [10].

Research also indicates that flavonoids such as epicatechin and catechin are highly sensitive to heat, and their degradation during drying lowers the antioxidant potential, although this process contributes to flavour formation and ensures bean safety (Sandoval-Rodriguez *et al.*, 2025) [21]. Consistent with these findings, freeze drying was shown to preserve the greatest total phenolic and flavonoid contents and exhibit the strongest antioxidant activity, whereas oven drying resulted in the lowest levels (Hafiz, 2019) [14]. The choice of drying method and its specific conditions significantly affect flavonoid retention. While sun drying is economical, it often leads to higher losses due to uncontrolled exposure to heat, light, and oxygen. Oven drying allows better temperature regulation but still risks thermal degradation, whereas freeze drying achieves superior flavonoid preservation compared to both sun and oven drying methods (Sulaiman *et al*., 2014) [22].

In another study, the results revealed that drying reduced antioxidant activity, as well as phenolic and methylxanthine contents. Among all the techniques, traditional drying was the most effective in maintaining antioxidant capacity and the concentration of beneficial compounds (Deus *et al*., 2018) [12]. Cocoa beans are naturally rich in flavonoids, catechins, and polyphenols, which contribute to their strong antioxidant properties. However, these compounds are highly unstable during post-harvest drying, leading to a significant decline in overall antioxidant potential. Although sun drying is a commonly used and cost-effective method, it often causes substantial antioxidant losses due to prolonged exposure to sunlight and oxygen, which promotes oxidative degradation. Oven drying allows better temperature regulation, but excessive heat can still destroy heat-sensitive compounds, reducing antioxidant levels. In contrast, freeze-dried cocoa beans demonstrated greater DPPH radical scavenging activity compared to those dried by conventional methods, confirming that antioxidant activity was highest in freeze drying, followed by sun drying and then oven drying (Sulaiman *et al*., 2014) [22].

During the drying process, particularly at elevated temperatures, fat degradation can occur as a result of oxidation and enzymatic activity, leading to a decline in fat quality. Nonetheless, the overall fat content of cocoa beans generally remains fairly consistent across different drying techniques, with changes primarily affecting the composition rather than the quantity of fat. Research indicates that sun drying and other low-temperature methods are more effective at maintaining fat integrity, whereas high-temperature drying, such as oven drying, can cause partial melting or structural alterations in cocoa butter (Alean *et al.*, 2016) [16].

Cocoa bean fat, predominantly present as cocoa butter, is generally more stable than phenolic compounds; however, the method and conditions of drying can still impact its quality and quantity. Excessive drying temperatures may lead to lipid degradation or the formation of free fatty acids (FFA) through enzymatic activity. Sun drying, due to its slower rate and exposure to ambient moisture, often results in higher FFA levels, indicating partial fat breakdown. In contrast, oven drying performed at controlled, moderate temperatures tends to better preserve the structural and chemical stability of cocoa butter (Afoakwa *et al.*, 2014) [3].

Conclusion

The present study clearly demonstrates that the drying method plays a crucial role in determining the physicochemical properties of fermented cocoa beans. Among the techniques evaluated, solar drying proved to be the most effective in preserving pH, flavonoid content, and antioxidant activity, owing to its gentle and gradual drying process. The higher crude protein and phenolic content recorded in oven-dried samples may be due to the efficient inactivation of enzymes during the process. Meanwhile, the artificial dryer method retained the highest fat content, likely because the faster drying rate minimized oxidation. Overall, these findings highlight the importance of selecting appropriate drying methods based on the desired quality attributes of cocoa beans. Solar drying appears to be the most beneficial for maintaining nutritional and functional properties, particularly for conserving flavonoids and antioxidants. For cocoa processors and producers aiming to enhance bean quality through optimized post-harvest drying practices, this research provides valuable guidance and practical insights.

Table 1: The comparative results of the chemical composition and antioxidant properties of cocoa beans subjected to different drying methods are presented.

Parameter	pH	Titratable acidity (meq/100g)	Crude Protein (%)	Fat (%)	Phenol (mg/g)	Flavonoid (mg/g)	Antioxidant (mg/g)
Solar Drying (SD)	6.45	0.12	13.67	37.43	0.47	132.30	25.91
Oven Drying (OD)	6.032	0.20	13.15	30.53	0.49	130.50	24.15
Artificial Drying (AD)	6.029	0.24	14.03	39.08	0.53	128.35	24.89
SEm±	0.04	0.006	0.132	0.34	NS	2.37	0.39
CD@ 5%	0.11	0.018	0.467	1.014	NS	0.24	0.110

Fig 1: Cocoa Treatment

Fig 2: Solar tunnel dryer

Fig 3: Heat pump dryer

Fig 4: Hot air oven

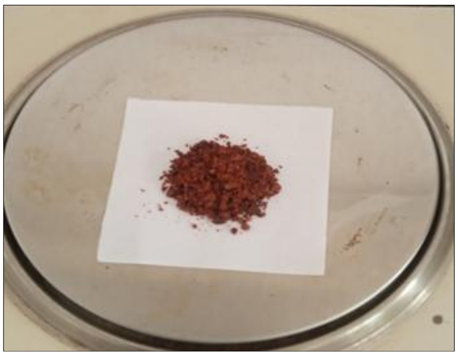

Fig 5: Cocoa bean powder

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