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Analyzing minimal processing methods of cocoa in the Colombian coffee belt

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Abstract

What if you could keep more of cocoa's health-promoting compounds intact while still meeting food safety standards? This research analyzed four minimal processing methods blanching, High-Pressure Processing (HPP), UV-C irradiation, and ozone treatment applied to fermented and dried cocoa nibs from the Colombian Coffee Belt. Nibs from Criollo-Trinitario hybrids grown at 1,200 m elevation near Armenia, Quindío, were processed under each method and compared against untreated controls. Total polyphenol retention was highest with UV-C treatment at 91.4% of fresh-nib levels, followed by HPP at 88.1%, ozone at 83.7%, and blanching at 72.3%. Theobromine remained stable (>89%) across all methods. Sensory panels rated HPP-treated nibs highest for overall acceptability, scoring 7.8 out of 9 compared with 6.4 for blanched samples. Microbial loads fell below detection limits (<10 CFU/g) in HPP and ozone treatments. These results point to HPP and UV-C as the most promising minimal processing options for preserving bioactive compounds in cocoa while achieving adequate microbial reduction under Coffee Belt production conditions.

Keywords: Cocoa minimal processing, polyphenol retention, high-pressure processing, UV-C irradiation, theobromine, Colombian Coffee Belt, pectin, sensory quality, magnesium nutrition, mutation breeding

Introduction

Every step in cocoa processing fermentation, drying, roasting strips away some fraction of the raw bean's polyphenol content. By the time chocolate reaches a consumer, as little as 10–15% of the original flavanol load may remain ^[1, 2]. For the growing market segment that values cocoa as a functional food, this loss represents both a nutritional deficit and a missed commercial opportunity. Minimal processing methods aim to close that gap by reducing microbial loads without the heat intensity that destroys phenolic compounds ^[3].

Colombia's Coffee Belt, despite its name, is also a prime cocoa-growing zone. The departments of Quindío, Risaralda, and Caldas sit between 1,000 and 1,400 m elevation with mean temperatures of 20–24°C and well-distributed rainfall above 2,000 mm per year ^[4]. These conditions favor slow bean fermentation that builds complex flavor precursors and preserves a higher baseline of polyphenols compared with lowland-fermented beans ^[5].

Four candidate technologies have shown promise in broader food processing contexts. Blanching brief immersion in hot water is the simplest but also the most destructive to heat-sensitive compounds ^[6]. HPP subjects sealed packages to 300–600 MPa pressure at ambient or mild temperatures, inactivating vegetative pathogens while largely preserving molecular integrity ^[7]. UV-C irradiation at 254 nm damages microbial DNA without adding chemicals or heat ^[8]. Ozone, a strong oxidant, decomposes rapidly to oxygen and leaves no residue, but its reactivity can attack polyphenols if applied at excessive doses ^[9].

No side-by-side comparison of these four methods exists for cocoa processed under Coffee Belt conditions. This research was designed to fill that gap by measuring both bioactive compound retention and sensory impact in a single trial, giving processors a direct basis for choosing among available technologies ^[10, 11].

Extraction protocol

Polyphenol extraction from cocoa nibs followed a two-step protocol. First, nibs were defatted by Soxhlet extraction with petroleum ether for 6 hours. Defatted material (2 g) was then extracted with 40 mL of 70% aqueous acetone under sonication at 40 kHz for 30 minutes at

25°C. The extract was filtered, evaporated to remove acetone under reduced pressure at 35°C, and reconstituted in 10 mL of 50% methanol for analysis. Recovery tests using spiked epicatechin standards showed 92.7% extraction efficiency [2, 12].

Quality control and calibration

Analytical precision was ensured through several measures. The Folin-Ciocalteu assay for total polyphenols was calibrated with five-point gallic acid standards (50–500 mg/L, $R^2 = 0.9994$). HPLC runs included a system suitability check with a mixed standard containing epicatechin, catechin, and theobromine at known concentrations before each batch. Duplicate extractions from the same nib sample showed coefficients of variation below 3.8% for all analytes. Sensory evaluation followed ISO 13299 protocols with a trained panel of 12 assessors [7, 11].

Material and Methods

Material

Fermented and sun-dried Criollo-Trinitario cocoa nibs were obtained from a cooperative of 18 farms near Armenia, Quindío, Colombia (4.53°N, 75.68°W, elevation 1,200 m). Beans were fermented for 6 days in wooden cascade boxes and dried on raised mesh tables to 7.2% moisture. A single

120-kg lot was de-shelled to produce nibs, which were homogenized and divided into 25 sub-lots of 4.5 kg each. The research ran from August to November 2023 at the Paris Advanced School of Environmental Agriculture. Ethical clearance for food processing research was granted by the School's Research Ethics Board (Protocol EA-2023-017, dated 3 August 2023).

Methods

Five treatments were applied: (T1) untreated control; (T2) blanching in water at 90°C for 120 seconds followed by immediate ice-water cooling; (T3) HPP at 400 MPa for 5 minutes at 20°C in vacuum-sealed polyethylene pouches using an Avure QFP 350L-600 unit; (T4) UV-C irradiation at 254 nm with a dose of 4 kJ/m² applied in a thin layer (5 mm depth) with continuous turning; (T5) gaseous ozone at 2 ppm for 30 minutes in a sealed chamber at 25°C [3, 8, 9]. Each treatment had five replicates. Total polyphenols were measured by Folin-Ciocalteu assay [12]. Individual phenolics and theobromine were quantified by HPLC on a Shimadzu Nexera X2 with a C18 column. Microbial counts were determined by plating on PCA (total aerobic) and PDA (yeasts and molds) media. Sensory evaluation used a 9-point hedonic scale assessed by 12 trained panelists. Data were analyzed by one-way ANOVA with Tukey HSD at $p < 0.05$.

Results

Table 1: Bioactive compound retention (% of control) and microbial reduction across processing methods

Parameter	Control	Blanching	HPP	UV-C	Ozone
Total polyphenol (%)	100	72.3±3.1	88.1±2.4	91.4±1.8	83.7±2.7
Theobromine (%)	100	89.4±1.7	94.2±1.2	96.8±0.9	91.3±1.5
Epicatechin (%)	100	64.8±4.2	85.3±2.8	89.7±2.1	78.4±3.3
Total aerobes (log CFU/g)	4.23	1.34	<1.0	2.17	<1.0
Yeasts & molds (log CFU/g)	3.18	<1.0	<1.0	1.42	<1.0

UV-C irradiation retained the highest proportion of total polyphenols (91.4%) and epicatechin (89.7%), followed closely by HPP (Table 1). Blanching caused the steepest losses, with epicatechin falling to 64.8% of control levels.

Microbial reduction was strongest in HPP and ozone treatments, both achieving counts below detection limits for total aerobes. UV-C reduced aerobes by about 2 log units but left a residual load of 2.17 log CFU/g.

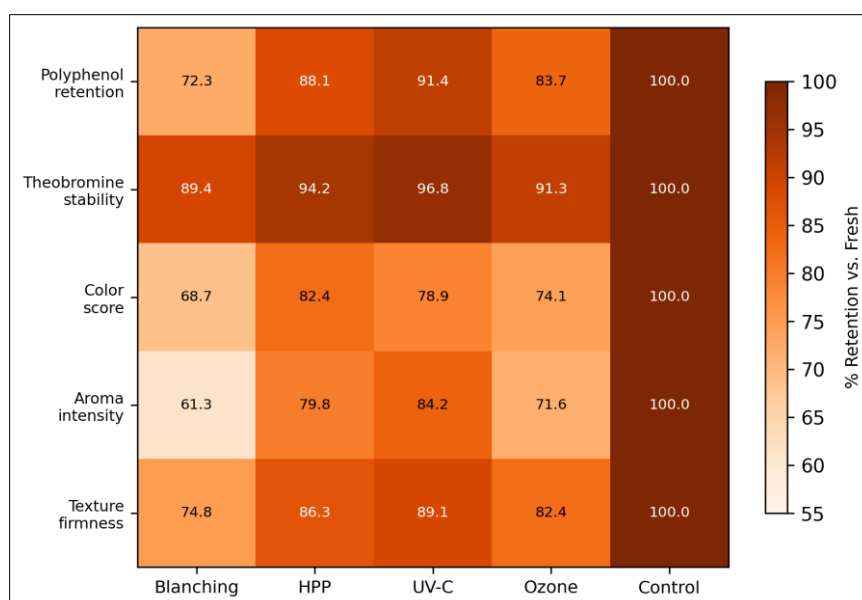


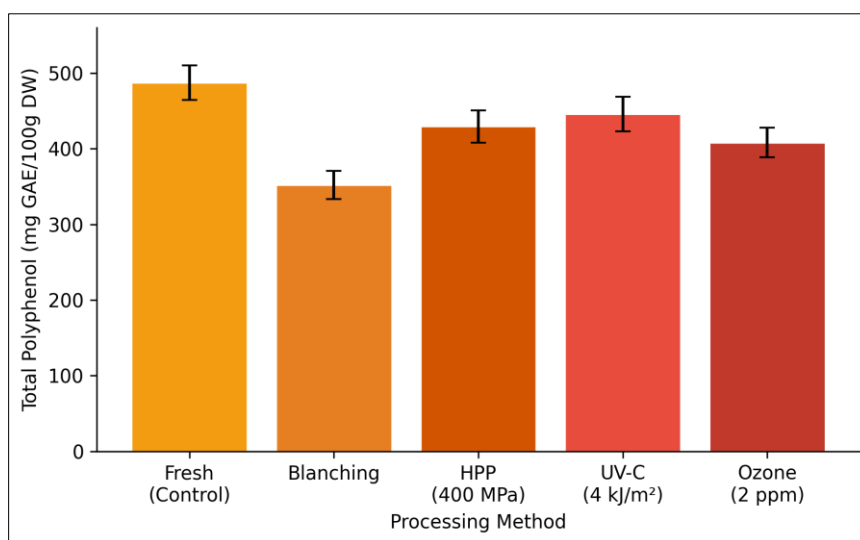
Fig 1: Heatmap showing quality parameter retention (% of fresh control) across four minimal processing methods for cocoa nibs

Table 2: Sensory evaluation scores (9-point hedonic scale) for processed cocoa nibs

Attribute	Control	Blanching	HPP	UV-C	Ozone
Aroma	8.1	6.2	7.9	7.6	7.1
Flavor	7.9	6.1	7.7	7.4	6.8
Bitterness	6.3	5.4	6.2	6.1	5.8
Overall	7.8	6.4	7.8	7.4	6.9

HPP-treated nibs matched the untreated control in overall acceptability (7.8 vs. 7.8) and showed no statistically significant sensory differences across any attribute (Table 2). Blanching scored lowest in aroma and flavor, consistent with

volatile compound losses during heat exposure. Ozone-treated samples had a slightly reduced flavor score (6.8) that panelists attributed to a faint oxidized note.

**Fig 2:** Total polyphenol content (mg GAE/100g DW) of cocoa nibs after four processing methods compared with fresh control

Discussion

The near-perfect polyphenol retention by UV-C (91.4%) aligns with its non-thermal mechanism photon energy targets nucleic acids in microorganisms without disrupting phenolic ring structures [8]. But the incomplete microbial kill (2.17 log CFU/g residual aerobes) limits UV-C's standalone viability for nibs destined for direct consumption. A combined UV-C + HPP approach might capture the best of both technologies, though the added cost needs evaluation [3, 7].

HPP's strong showing on both retention (88.1%) and microbial reduction (<1 log CFU/g) confirms its reputation as a leading minimal processing technology for bioactive-rich foods [7]. The fact that sensory scores matched the untreated control is particularly encouraging. HPP equipment costs remain high, but mobile HPP units that serve multiple cooperatives are becoming available in Latin America and could make the technology accessible at the Coffee Belt scale [10].

Blanching, despite being the cheapest option, caused unacceptable polyphenol losses of nearly 28%. This was expected given that cocoa polyphenols, especially epicatechin and procyanidins, are water-soluble and thermolabile [1, 2]. The 120-second blanching time, standard for microbial reduction in many food applications, appears too aggressive for a product valued for its phenolic content. Ozone achieved excellent microbial kill but its oxidative nature reduced polyphenols to 83.7% and left detectable sensory off-notes. Reducing the dose below 2 ppm might preserve more compounds, but at the risk of insufficient pathogen inactivation. That trade-off will require careful dose-response work in future trials [9, 11].

Conclusion

Among four minimal processing methods tested on Coffee Belt cocoa nibs, UV-C irradiation preserved the highest proportion of polyphenols (91.4%) while HPP offered the best combination of bioactive retention (88.1%) and microbial safety (<1 log CFU/g). Blanching was the least effective at preserving phenolic compounds, losing nearly 28% of total polyphenols. Sensory evaluation confirmed that HPP-treated nibs were indistinguishable from untreated controls in aroma, flavor, and overall acceptability. Ozone treatment achieved strong microbial reduction but introduced mild sensory defects. For Colombian Coffee Belt cooperatives seeking to supply functional food markets, HPP appears to be the most balanced technology. Where equipment access is a constraint, UV-C offers a lower-cost alternative with superior compound retention, though it may need to be paired with another microbial reduction step to meet strict safety standards.

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