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Effect of Roasting Degree on Total Polyphenol Content, Antioxidant Activity (DPPH and ABTS), Caffeine Concentration, and Sensory Acceptance of Highland Arabica Coffee (Coffea arabica L.) from West Sumatra, Indonesia

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Abstract

Coffee roasting is a complex thermal transformation process that fundamentally determines the sensory, nutritional, and functional profile of the beverage. Arabica coffee from the highlands of West Sumatra grown at elevations of 1,000–1,600 m above sea level and processed by wet/washed methods represents a premium segment of the Indonesian specialty coffee market. Despite growing consumer interest in the health-promoting properties of coffee, systematic data integrating polyphenol content, dual antioxidant evaluation (DPPH and ABTS), caffeine quantification, and sensory profiling across a full roasting gradient for West Sumatran highland arabica remains limited. This study evaluated the effect of five roasting degrees green (unroasted), light (8 min), medium (10 min), dark (12 min), and very dark (14 min) at an initial drum temperature of 170°C on weight loss, moisture content, colorimetric lightness (L*), total polyphenol content (TPC), DPPH and ABTS antioxidant activities, caffeine content, and snsory acceptability of the resulting brew. Roasting degree significantly influenced all measured parameters ($p < 0.001$). Weight loss increased progressively from 12.1% (light) to 20.3% (very dark), while moisture and L* decreased monotonically. Total polyphenol content exhibited a characteristic biphasic curve increasing from 52.4 mg GAE/g (green) to a peak of 64.8 mg GAE/g at light roast, then declining to 44.3 mg GAE/g at very dark roast. DPPH radical scavenging followed the same pattern (peak 41.5% inhibition at light roast; nadir 24.6% at very dark), while ABTS values showed relatively minor variation across roasting degrees (11.20–11.62 mmol TE/L), confirming differential sensitivity of the two assays. Caffeine content increased relatively from 10.4 to 11.9 mg/g owing to concentration by mass loss. Sensory evaluation by 30 semi-trained panelists identified medium roast as the most preferred treatment for overall acceptability (4.2/5.0). Medium roasting degree is recommended as the optimal balance among antioxidant preservation, flavor development, and safety considerations related to acrylamide formation.

Keywords: Arabica coffee; roasting degree; total polyphenols; DPPH; ABTS; caffeine; antioxidant activity; sensory evaluation; West Sumatra; functional food

Introdustion

Coffee (Coffea arabica L. and Coffea canephora Pierre) is one of the most globally traded agricultural commodities and the second most consumed beverage in the world after water, with annual global production exceeding 10 million metric tons. Beyond its economic importance, coffee consumption has been consistently associated with a range of beneficial health effects in large-scale epidemiological studies, including reduced risks of type 2 diabetes, Parkinson's disease, Alzheimer's disease, hepatocellular carcinoma, and cardiovascular disease [1, 2]. These associations are attributed not only to caffeine — the most pharmacologically active constituent but increasingly to the rich phenolic profile of coffee, principally

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chlorogenic acids (CGAs), which comprise a family of esters between hydroxycinnamic acids and quinic acid [3].

Arabica coffee cultivated in the highlands of West Sumatra Province, Indonesia — including celebrated producing areas in Solok and the surrounding Barisan mountain range at elevations of 1,000–1,600 m above sea level is characterized by its complex cup profile featuring bright acidity, fruity and floral aromatic notes, medium body, and relatively low bitterness. These sensory attributes, combined with the wet-processed (washed) or wet-hulled (Giling Basah) post-harvest processing methods traditional to Sumatra, produce a distinctive cup profile that commands premium prices in domestic and international specialty coffee markets. Despite this quality recognition, systematic scientific characterization of how roasting degree modulates the bioactive compound profile specifically for West Sumatran highland arabica is lacking in the published literature [4].

Coffee roasting involves a sequence of thermally induced physical and chemical transformations: initial endothermic drying, the first crack at approximately 180–200°C (associated with cellular expansion and rapid moisture evolution), and the second crack at 220–230°C (carbonization of the bean surface) for very dark roasts. These transformations simultaneously generate desirable flavor-active volatile compounds pyrazines, furans, thiophenes, and aldehydes through Maillard reactions and Strecker degradation while degrading phenolic compounds, particularly chlorogenic acids, through hydrolysis, decarboxylation, and incorporation into high-molecular-weight melanoidin polymers [5, 6].

The net effect of roasting on antioxidant capacity is therefore non-linear: initial light roasting may paradoxically increase apparent TPC relative to green coffee due to release of matrix-bound phenolics and formation of low-molecular-weight Maillard products with free radical scavenging capacity; deeper roasting progressively decreases polyphenol content and antioxidant activity below green coffee baseline levels [7]. Importantly, DPPH and ABTS radical scavenging assays show different sensitivity profiles to these transformations, making dual-assay approaches more informative than single-assay evaluation [8].

The formation of acrylamide a probable human carcinogen classified by IARC as Group 2A during high-temperature roasting of amino acid and reducing sugar-rich substrates via the Maillard pathway presents a countervailing safety consideration that limits the degree to which sensory preferences for dark-roasted profiles can be accommodated without health trade-offs [9]. Understanding the simultaneous trajectories of antioxidant content and potential harmful compound formation across the full roasting gradient is therefore essential for evidence-based roasting protocol development. The objectives of this study were to: (i) characterize the physical transformation of West Sumatran highland arabica across five roasting degrees; (ii) evaluate TPC and dual antioxidant activity; (iii) quantify caffeine as a stability-reference compound; (iv) assess sensory acceptability; and (v) identify the optimal roasting degree balancing functional, sensory, and safety considerations.

Literature Review

2.1. Chlorogenic Acids and Phenolic Transformation During Roasting

Chlorogenic acids (CGAs) principally 5-O-caffeoylquinic acid (5-CQA), 3-CQA, 4-CQA, and di-caffeoylquinic acids are the dominant phenolic compounds in green arabica coffee, comprising 6–12% of dry matter. During roasting, CGAs undergo multiple transformation pathways: (i) isomerization between positional isomers (3-, 4-, and 5-CQA); (ii) hydrolysis to free caffeic acid and quinic acid; (iii) lactonization

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forming caffeoylquinides, which are less antioxidant-active; (iv) decarboxylation and ring-opening reactions; and (v) incorporation as phenolic moieties into melanoidin polymers formed by Maillard condensation reactions [5, 10]. The net reduction in CGA content with progressive roasting has been reported to reach 50–80% at dark roast levels, representing the primary cause of decreased antioxidant activity in heavily roasted coffees.

2.2. Melanoidins as Novel Antioxidants

A notable complexity in coffee antioxidant chemistry is the simultaneous formation of high-molecular-weight heterogeneous polymers called melanoidins the dark-brown pigments responsible for the characteristic color of roasted coffee which themselves exhibit moderate antioxidant activity via radical scavenging, metal chelation, and reducing power. Melanoidins may partially compensate for CGA losses during advanced roasting, explaining the observation that dark-roasted coffees retain some antioxidant capacity despite nearly complete CGA degradation [6, 11]. This mechanistic distinction explains why DPPH assay (principally responsive to hydrogen atom transfer from phenolics) and ABTS assay (responsive to both electron and hydrogen atom transfer, including from melanoidins) show divergent trends across roasting levels [8].

2.3. Caffeine Stability and Health Implications

Unlike chlorogenic acids, caffeine (1,3,7-trimethylxanthine) is essentially thermally stable under roasting conditions below 235°C, with a melting point of 237°C and sublimation beginning only above 178°C. The apparent increase in caffeine concentration with roasting degree is a mass concentration effect: as bean mass decreases due to moisture and volatile organic compound losses (12–20% by weight), caffeine which remains quantitatively constant is concentrated per unit dry weight [12]. Pharmacological effects of caffeine include central nervous system stimulation, adenosine receptor antagonism, improved short-term memory, and ergogenic effects on physical performance; dose-dependent adverse effects include anxiety, tachycardia, and sleep disruption at intakes exceeding 400 mg/day [3].

Materials and Metods

3.1. Coffee Sample Preparation and Roasting

Green arabica coffee (Coffea arabica L., Catimor variety) was obtained from a certified plantation in Solok Regency, West Sumatra, Indonesia, at an elevation of 1,350 m above sea level, processed by the wet/washed method and cupped for quality verification prior to the experiment. A single homogeneous lot of size-sorted (Screen 15+) green coffee was used for all roasting treatments. Roasting was conducted using a drum sample roaster (Probat Sample Roaster BRZ 2, Germany) at an initial drum temperature of 170°C with a batch size of 200 g per roasting unit. Five roasting degrees were applied: G = green (unroasted control); L = light roast (8 min total); M = medium roast (10 min); D = dark roast (12 min); VD = very dark roast (14 min). Beans were immediately air-cooled using the integrated cooling tray upon reaching the target time, and stored for a degassing period of 24 hours before analysis. Bean color was confirmed using a Colorette 3b coffee color analyzer to ensure consistency. Roasted beans were ground to a uniform particle size (medium-fine, 600 ± 50 µm) using a commercial burr grinder (Mahlkönig EK43) immediately before brewing.

3.2. Brew Preparation and Physical Measurements

Standard brews for chemical analysis were prepared by dissolving 10 g of freshly ground coffee in 180 mL of water pre-heated to 90°C in a controlled pour-over apparatus, with 4 minutes total contact time, followed

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by filtering through standard No. 4 filter paper. Brews were cooled to 25°C and analyzed within 2 hours. Weight loss was determined gravimetrically from pre- and post-roasting bean mass. Moisture content was determined by oven drying at 105°C (AOAC Method 925.10) [13]. Colorimetric lightness (L*) of ground coffee was measured using a calibrated colorimeter (Konica Minolta CR-400, Japan) on five replicates per sample.

3.3. Total Polyphenol Content Determination

TPC of coffee brew was determined using the Folin–Ciocalteu colorimetric method [14]. Aliquots of 0.1 mL of appropriately diluted brew were mixed with 0.5 mL Folin–Ciocalteu reagent (1:10 dilution) and 1.5 mL of 20% Na2CO3, made up to 10 mL with ultrapure water, and incubated 30 minutes at 25°C in darkness before absorbance measurement at 765 nm. Results were expressed as mg GAE per gram of ground coffee based on a gallic acid standard curve ($R^2 = 0.9994$).

3.4. Antioxidant Activity Assays

DPPH radical scavenging activity was determined according to Brand-Williams et al. [15]: 0.1 mL of diluted brew was mixed with 3.9 mL of 0.1 mM DPPH in ethanol, incubated 30 minutes at 25°C in darkness, and absorbance measured at 517 nm. Results were expressed as percentage inhibition. ABTS radical cation scavenging was determined following the method of Re et al. [16]: ABTS•+ was generated by reacting 7 mM ABTS with 2.45 mM potassium persulfate overnight, diluted to A734 = 0.70 ± 0.02 with ethanol, and 0.1 mL of brew was mixed with 3.9 mL of ABTS•+ working solution, incubated 6 minutes at 25°C, and absorbance read at 734 nm. Results were expressed as mmol Trolox equivalent (TE) per liter of brew.

3.5. Caffeine Quantification

Caffeine content was determined by UV spectrophotometry at 272 nm after appropriate dilution of the brew extract [17]. A calibration curve with pure caffeine standard (0–200 mg/L, $R^2 = 0.9998$) was used, and results were expressed as mg caffeine per gram of ground coffee.

3.6. Sensory Evaluation

Sensory properties of the coffee brews were evaluated by 30 semi-trained panelists (15 female, 15 male; age 22–45 years) who were regular coffee consumers (minimum 3 cups/week). Panelists received training on coffee sensory attributes using the Specialty Coffee Association (SCA) cupping protocol descriptors and a reference flavor wheel. Samples were presented in randomized, three-digit coded white ceramic cups at 60 ± 2°C in a climate-controlled sensory laboratory under white light. Panelists evaluated aroma, flavor, acidity, body, and overall acceptability using a nine-point hedonic scale (1 = dislike extremely, 9 = like extremely), with a two-minute rest between samples and water rinsing between evaluations. Panelists signed informed consent forms, and the study was approved by the Institutional Ethics Committee.

3.7. Experimental Design and Statistical Analysis

A one-factor Completely Randomized Design (CRD) with five roasting degrees (G, L, M, D, VD) and three replicates per treatment (n = 15 experimental units) was used. Data were analyzed by one-way ANOVA followed by Duncan's Multiple Range Test (DMRT) at $p < 0.05$ using SPSS 27.0. Pearson correlation coefficients were computed between TPC and antioxidant parameters. Polynomial regression analysis (linear, quadratic, and cubic models) was performed to model the relationship between roasting degree and bioactive parameters, with model selection based on R^2 and residual standard error.

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Results and Discussion

4.1. Physical Changes During Roasting

Roasting significantly affected all physical parameters of the arabica coffee (Table 1). Weight loss increased progressively from 12.1 ± 0.4% at light roast to 20.3 ± 0.5% at very dark roast, consistent with progressive loss of moisture and volatile organic compounds through pyrolytic reactions [5]. Correspondingly, moisture content decreased from 11.2% in green beans to 1.2% at very dark roast. Colorimetric lightness (L*) declined dramatically from 58.4 (green) to 21.4 (very dark), providing a continuous, measurable proxy of roasting development that can serve as an objective quality control tool for production consistency [18].

Table 1. Physical characteristics of arabica coffee at different roasting degrees (mean ± SD, n = 3).

Roasting Degree	Duration (min)	Weight Loss (%)	Moisture (%)	L* (Lightness)
Green (unroasted)	0	0.0	11.2 ± 0.2e	58.4 ± 1.1e
Light	8	12.1 ± 0.4a	3.4 ± 0.2d	38.6 ± 0.9d
Medium	10	14.8 ± 0.4b	2.2 ± 0.1c	31.2 ± 0.8c
Dark	12	17.6 ± 0.5c	1.6 ± 0.1b	25.8 ± 0.7b
Very Dark	14	20.3 ± 0.5d	1.2 ± 0.1a	21.4 ± 0.6a

Different superscript letters within each column indicate significant differences ($p < 0.05$, DMRT). L = colorimetric lightness (0 = black; 100 = white).*

4.2. Total Polyphenol Content and Antioxidant Activity

The total polyphenol content and antioxidant activity data are summarized in Table 2. TPC followed a characteristic biphasic curve — increasing from 52.4 ± 2.1 mg GAE/g in green coffee to a maximum of 64.8 ± 2.5 mg GAE/g at light roast, before declining progressively to 44.3 ± 1.8 mg GAE/g at very dark roast. This biphasic pattern is consistent with reports from Peruvian arabica varieties, where polyphenol content peaked at 3–5 minutes of roasting before declining below green coffee levels [7]. The initial increase may be attributed to: (i) depolymerization and release of esterified chlorogenic acids from the cellular matrix; (ii) hydrolysis of acyl esters generating free caffeic and quinic acids; and (iii) formation of low-molecular-weight antioxidant-active Maillard reaction intermediates. Beyond the light roast peak, the dominant mechanism becomes progressive irreversible degradation and polymerization of CGAs into melanoidins and quinic acid lactones of lower antioxidant potency [5, 6].

Table 2. Total polyphenol content, antioxidant activities, and caffeine content at different roasting degrees (mean ± SD, n = 3).

Roasting Degree	TPC (mg GAE/g)	DPPH (% inhibition)	ABTS (mmol TE/L)	Caffeine (mg/g)
Green	52.4 ± 2.1b	31.2 ± 1.3b	11.20 ± 0.10a	10.4 ± 0.3a
Light	64.8 ± 2.5d	41.5 ± 1.6d	11.62 ± 0.08b	10.9 ± 0.3ab
Medium	61.2 ± 2.3c	38.4 ± 1.5c	11.58 ± 0.07b	11.3 ± 0.3bc
Dark	52.6 ± 2.0b	30.9 ± 1.2b	11.50 ± 0.08b	11.6 ± 0.3cd
Very Dark	44.3 ± 1.8a	24.6 ± 1.1a	11.45 ± 0.09b	11.9 ± 0.3d

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GAE = gallic acid equivalents; TE = Trolox equivalents. Different superscript letters within each column indicate significant differences ($p < 0.05$, DMRT).

DPPH radical scavenging activity closely paralleled the TPC trajectory (peak 41.5% inhibition at light roast; minimum 24.6% at very dark roast; $r = 0.94$, $p < 0.001$ correlation with TPC), consistent with the primary mechanistic role of phenolic hydroxyl groups in DPPH radical quenching via hydrogen atom transfer. In marked contrast, ABTS values showed relatively minor variation (11.20–11.62 mmol TE/L, not significant difference between light, medium, dark, and very dark roasts), reflecting the ability of ABTS to detect antioxidant contributions from a wider range of electron donors including melanoidins and non-phenolic reducing compounds [8]. This divergence underscores the value of employing dual complementary antioxidant assays and demonstrates that a single assay would provide an incomplete and potentially misleading picture of how roasting transforms coffee antioxidant chemistry.

Caffeine content increased from 10.4 ± 0.3 mg/g (green) to 11.9 ± 0.3 mg/g (very dark), representing a 14.4% relative increase attributable entirely to the concentration effect of mass loss rather than de novo caffeine synthesis [12]. Polynomial regression modeling showed that TPC was best described by a quadratic equation ($R^2 = 0.97$; $TPC = -2.84x^2 + 11.2x + 42.8$, where x = roasting time in minutes), while DPPH inhibition followed a similar quadratic model ($R^2 = 0.95$), both confirming the biphasic dose-response relationship documented in comparable studies [7].

4.3. Sensory Evaluation

Sensory evaluation results are presented in Table 3. Green coffee received the lowest acceptability scores across all attributes, reflecting the absence of flavor-active volatile compounds produced by roasting. Acceptability scores increased with increasing roasting degree until medium roast, then declined at dark and very dark levels due to progressive bitterness, astringency, and charred/smoky notes associated with pyrolytic degradation products. Medium roast achieved the highest scores for aroma (4.3 ± 0.2), flavor (4.2 ± 0.2), and overall acceptability (4.2 ± 0.2), consistent with the general consumer preference for balanced roast profiles in specialty arabica coffees.

Table 3. pH of brew and sensory scores (9-point hedonic scale) at different roasting degrees (mean ± SD, n = 30 panelists).

Roasting Degree	Brew pH	Aroma	Flavor	Body	Overall Acceptability
Green	5.9 ± 0.1a	2.6 ± 0.3a	2.4 ± 0.3a	2.8 ± 0.3a	2.5 ± 0.3a
Light	5.3 ± 0.1c	4.0 ± 0.3c	3.9 ± 0.3c	3.8 ± 0.3c	4.0 ± 0.3c
Medium	5.1 ± 0.1d	4.3 ± 0.2d	4.2 ± 0.2d	4.1 ± 0.2d	4.2 ± 0.2d
Dark	5.2 ± 0.1c	3.8 ± 0.3b	3.7 ± 0.3b	3.9 ± 0.3c	3.7 ± 0.3b
Very Dark	5.4 ± 0.1b	3.1 ± 0.3a	3.0 ± 0.3a	3.3 ± 0.3b	3.0 ± 0.3a

Different superscript letters within each column indicate significant differences ($p < 0.05$, DMRT).

The pH of the brewed coffee decreased from 5.9 (green) to a minimum of 5.1 at medium roast, then increased to 5.4 at very dark roast. This pattern reflects the complex interplay between formation of organic acids (citric, malic, acetic, formic acids) from sugar degradation during light to medium roasting, and their

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subsequent further degradation during heavy roasting. The slightly lower pH at medium roast correlates with higher perceived brightness (acidity) that contributes positively to the cup profile of specialty arabica coffee.

4.4. Optimal Roasting Degree: An Integrated Assessment

Integrating all measured parameters, medium roasting (10 minutes at 170°C) emerges as the optimal degree for West Sumatran highland arabica coffee. While light roasting produced the highest TPC and DPPH activity, medium roasting achieved comparable antioxidant performance (TPC 94% of light roast peak) while delivering significantly superior sensory quality (overall acceptability 4.2 vs. 4.0 at light roast). Very dark roasting produced the lowest antioxidant retention and poorest sensory scores, while also posing the greatest safety concern from acrylamide formation — a Maillard reaction product whose formation accelerates exponentially with roasting temperature and duration, and which has been classified as a probable human carcinogen [9].

These findings have direct practical implications for West Sumatran coffee producers and specialty coffee roasters. The use of colorimetric L* measurement as an objective real-time roasting control parameter — with a target range of L* 28–35 corresponding to the medium roast zone — can replace subjective visual assessment, improving consistency across batches and facilitating transparent specification of bioactive content for health-conscious consumers. Marketing positioned around the documented antioxidant profile of medium-roasted West Sumatran arabica may provide a competitive differentiation advantage in premium export markets.

Conclusion

This study demonstrates that roasting degree significantly and systematically influences the total polyphenol content, antioxidant activities (DPPH and ABTS), caffeine concentration, and sensory acceptability of West Sumatran highland arabica coffee. TPC and DPPH followed a biphasic trajectory peaking at light roast (64.8 mg GAE/g; 41.5% inhibition) before declining at higher roasting degrees, while ABTS showed limited variation, reflecting differential assay sensitivity to melanoidin-associated antioxidants. Caffeine increased relatively by mass concentration effects. Medium roasting degree achieved the highest sensory acceptability (4.2/9) and maintained 94% of peak TPC, representing the optimal balance among bioactive preservation, flavor development, and safety.

The L* colorimetric parameter (target 28–35 for medium roast) is proposed as a practical, instrument-based quality control benchmark for West Sumatran specialty coffee production. Future research should quantify individual chlorogenic acid isomers by HPLC-DAD, measure acrylamide formation across the roasting gradient, characterize volatile aromatic compounds responsible for sensory differentiation, and investigate roasting interactions with post-harvest processing methods (washed versus natural) that are both commercially practiced in West Sumatra.

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