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Comparative Phytochemical Evaluation of Indonesian Single-Origin Arabica Coffees: Caffeine, Total Phenolic Content, and DPPH Antioxidant Activity

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Abstract: Coffee (*Coffea arabica*) is a globally significant commodity, and Indonesia's diverse archipelagic geography produces beans with distinct origin-associated characteristics. Although the antioxidant properties of coffee are well-documented, the influence of specific geographical origins on its secondary metabolites is less understood. This study aims to investigate the variations in Total Phenolic Content (TPC), caffeine concentration, and antioxidant activity (IC_{50}) across eight prominent Indonesian single-origin Arabica coffees: Aceh Gayo, Ciwidey, Papua Wamena, Bali Kintamani, Kerinci, Toraja, Bajawa, and Temanggung. Utilizing standardized medium-roast samples and ethanolic extraction, the phytochemical profiles were quantified and statistically analyzed via one-way ANOVA and linear regression. The results revealed significant variations ($p < 0.001$) across all measured parameters based on geographical origin. High-altitude coffees, specifically from Ciwidey and Papua, exhibited the highest TPC (up to 42.72 mg GAE/g) and the most potent antioxidant activity (IC_{50} of 40.15 ppm and 44.90 ppm, respectively). Conversely, Temanggung coffee, cultivated at lower elevations with nutrient-rich volcanic soil, demonstrated the highest caffeine concentration (1.31%) but the lowest TPC and antioxidant capacity. A strong linear correlation ($R^2 = 0.793$) between TPC and antioxidant activity confirms that phenolic compounds are the primary drivers of radical scavenging efficacy. Ultimately, this study demonstrates that geographical origin significantly shapes the chemical profile and antioxidant capacity of Indonesian Arabica coffees, providing a practical scientific framework for origin authentication and quality evaluation.

Keywords: Indonesian *Coffea arabica*; single-origin; caffeine; antioxidant activity; polyphenols

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1. INTRODUCTION

Coffee (*Coffea sp.*) is a pivotal commodity in the global trade market and plays a strategic role in Indonesia's economy. As the world's fourth-largest coffee producer, Indonesia is endowed with a vast diversity of growing environments, yielding beans with distinct flavor profiles known as single-origin coffees (USDA Foreign Agricultural Service, 2024). Current global consumption trends have shifted significantly towards specialty coffee, where consumers demand not only superior organoleptic quality but also increasingly value the functional health benefits associated with coffee intake, particularly its antioxidant properties (Acidri *et al*., 2020; Lee, 2000).

Environmental factors, including altitude, mean temperature, precipitation, and UV radiation exposure, elicit distinct physiological responses in coffee plants (Gebrekidan *et al*., 2019; Legesse, 2019; *Worku et al*., 2018; Pereira *et al*., 2018; Scholz, Kitzberger and Prudencio, 2018). Arabica coffee cultivated at higher altitudes tends to undergo a prolonged bean maturation period due to lower temperatures. This extended duration facilitates a more optimal accumulation of secondary metabolites, such as chlorogenic acids and other phenolic compounds, compared to coffee grown at lower elevations (Worku *et al*., 2018; Scholz, Kitzberger and Prudencio, 2018). Furthermore, the Genotype X Environment

interaction serves as a primary determinant in the variation of coffee bean biochemical composition (Cheng *et al*., 2016).

From a food chemistry perspective, the primary bioactive compounds of interest in coffee are caffeine and polyphenols. Caffeine (1,3,7-trimethylxanthine), a heat-stable alkaloid, functions as a central nervous system stimulant and contributes significantly to the characteristic bitterness of the brew (Seninde and Chambers, 2020). Concurrently, polyphenols, particularly Chlorogenic Acids (CGA), are recognized for their potent antioxidant activity, capable of scavenging free radicals and mitigating oxidative stress (Liang and Kitts, 2016; Singh, Singla and Pandey, 2023). Given Indonesia's archipelagic geography, spanning from Sumatra in the west to Papua in the east, with varying volcanic soil compositions and microclimates, significant variations in the levels of these bioactive compounds among producing regions are highly anticipated.

Despite Indonesia's status as a key producer with premier Arabica centers, comprehensive scientific data comparing the phytochemical profiles of these origins within a single controlled study remains limited. Existing literature has largely concentrated on specific processing or brewing variables within isolated contexts. For instance, recent studies have focused on the physicochemical characteristics of Robusta cold brew from Temanggung based on roasting profiles (Salsabila, Asmoro and Tari, 2024) or the properties of Gayo coffee brewed by the boiling method with varying particle sizes (Yufita *et al*., 2025). Furthermore, research regarding the environmental impact on quality is often restricted to single-region case studies. Abubakar *et al*. investigated the effect of variety and farm altitude specifically in the Gayo Highland, while Latunra *et al*. examined whether altitude affects bean quality in Bantaeng Geographical Indication coffee. Although broader studies have analyzed the influence of climate and growing region on chlorogenic acids and aromatic compounds in an international context (Rusinek *et al*., 2025), a comprehensive dataset benchmarking the major Indonesian Arabica origins using a unified extraction protocol is still lacking. While these existing studies provide valuable insights into specific regions or isolated preparation methods, they introduce significant confounding variables—such as non-standardized roasting degrees, varying extraction solvents, differing brewing techniques, and non-synchronized harvest seasons. These inconsistencies make a direct, cross-regional phytochemical comparison scientifically invalid, leaving the available data highly fragmented and preventing an objective mapping of the chemical quality potential across the Indonesian archipelago.

This study directly addresses this critical gap by establishing the first strictly unified and controlled benchmarking framework for Indonesian Arabica. Unlike previous fragmented reports, this research evaluates eight prominent single-origins harvested during the identical season, processed under an identical medium-roast profile, and subjected to a uniform ethanolic extraction protocol. By eliminating methodological compounding factors, this approach allows for a precise and direct delineation of how geographical origin alone modulates caffeine, TPC Total Phenolic Content, and antioxidant activity across the major Indonesian coffee belts, providing a definitive chemical database for geographic authentication and quality evaluation.

2. MATERIAL AND METHODS

2.1 Materials and Instrumentation

The primary materials employed in this study were Arabica coffee beans (*Coffea arabica*) sourced from eight distinct Geographical Indication (GI) regions in Indonesia: Aceh (Gayo), West Java (Ciwidey), Central Java (Temanggung), Bali (Kintamani), Flores (Bajawa), Sulawesi (Toraja), Jambi (Kerinci), and Papua (Wamena). All samples were harvested during the same harvest season to minimize seasonal variability. All chemicals used were of analytical grade (p.a.), including methanol (Merck, Darmstadt, Germany), ethanol (Merck, Darmstadt, Germany), distilled water, caffeine standards (Sigma-Aldrich, St. Louis, MO, USA), gallic acid (Merck, Darmstadt, Germany), Folin-Ciocalteu reagent (Merck, Darmstadt, Germany), sodium carbonate (Na_2CO_3) (Merck, Darmstadt, Germany), 2,2-diphenyl-1-picrylhydrazyl (DPPH) (Sigma-Aldrich, St. Louis, MO, USA) and L-ascorbic acid (Sigma-Aldrich, St. Louis, MO, USA). The instrumentation employed included standard laboratory glassware, an analytical

balance (Mettler Toledo) and a UV-Vis spectrophotometer (Shimadzu UV-1800).

2.2 Sample Collection and Preparation

Eight samples of Arabica coffee green beans were obtained from distinct Indonesian geographical indications: Aceh Gayo, Ciwidey, Kerinci, Toraja, Bajawa, Papua, Bali, and Temanggung. The specific geographical attributes and altitude ranges of each origin are presented in Table 1 (DJKI, 2024). The selected beans were roasted at 200°C for 10-15 minutes to achieve a medium roast level. The roasting process was evaluated to ensure all samples achieved a uniform medium-brown color profile. This roast appearance is consistent with roasted beans remaining dry, whereas darker roasts are described as darker brown and, at sufficiently advanced roasting, can become oily (Wang and Lim, 2014). The roasted beans were allowed to cool to room temperature and subsequently ground using a commercial coffee grinder. The coffee powder was sieved through a 60-mesh sieve to ensure particle size homogeneity.

Table 1. Geographical characteristics and altitudes of the eight Indonesian Arabica coffee origins

Origin (Region)	Island	Estimated Altitudes (m asl)
Aceh Gayo	Sumatra	1,200 – 1,600
Kerinci	Sumatra	1,300 – 1,500
Ciwidey	Java	1,500 – 1,700
Temanggung	Java	1,000 – 1,300
Bali Kintamani	Bali	1,100 –1,500
Bajawa	Flores (NTT)	1,200 – 1,550
Toraja	Sulawesi	1,400 –1,700
Papua Wamena	Papua	1,600 – 2,000

2.3 Sample Extraction

Finely ground roasted Arabica beans (1.0 g) were quantitatively macerated in 50 mL of 70% ethanol at room temperature for 24 h (Rojo-Poveda *et al*., 2025; Alkaltham *et al*., 2020). The mixture was filtered using Whatman No. 1 paper, and the residue was rinsed with the solvent to ensure maximum recovery of bioactive compounds. The resulting filtrate was then aliquoted and adjusted to specific volumes (as detailed in sections 2.4 and 2.5) to serve as the standardized stock for subsequent assays.

2.4 Determination of Total Polyphenol Content (TPC)

The TPC was quantified using the Folin-Ciocalteu colorimetric method (Aryal *et al*., 2019). The initial extract was quantitatively transferred into a volumetric flask and diluted to a final volume of 100 mL (0.1 L). A further ten-fold dilution was yielding a final tested sample concentration of 1 mg/mL (roasted coffee equivalent), to maintain the absorbance within the linear calibration range of the gallic acid standard (10 – 100 µg/mL). A 0.5 mL aliquot of this solution was reacted with 2.5 mL of 10% Folin-Ciocalteu reagent for 5 minutes, followed by the addition of 2.0 mL of 7.5% Na_2CO_3. After a 60-minute incubation in a dark environment, the absorbance was measured at 765 nm using a UV-Vis spectrophotometer. The results were calibrated against a gallic acid standard curve and expressed as milligrams of gallic acid equivalent per gram of sample (mg GAE/g roasted coffee).

2.5 Determination of Caffeine Content

Caffeine levels were determined via UV spectrophotometry following the liquid-liquid extraction method (Belay *et al*., 2008) with slight modifications. The initial extract was quantitatively adjusted to a total volume of 250 mL and subjected to a ten-fold dilution. To isolate caffeine from interfering phenolic matrices, the solution was treated with Na_2CO_3 to precipitate tannins and neutralize acids, followed by extraction using chloroform as the organic solvent (Tadesse and Gunta, 2020). The chloroform layer was isolated, and its absorbance was recorded at 272 nm. The caffeine concentration was derived from a standard curve ($R^2 > 0.99$) and expressed as a weight percentage (%) relative to the initial sample mass.

2.6 Antioxidant Activity (DPPH Assay)

The antioxidant capacity was evaluated using the DPPH free radical scavenging assay (Brand-Williams, Cuvelier and Berset, 1995; Olechno *et al*., 2021). The DPPH radical stock solution (0.1 mM) was freshly prepared by dissolving DPPH powder in analytical-grade methanol and stored in an amber bottle at 4°C until use. L-ascorbic acid was utilized as the positive control standard. Serial dilutions of the extract (10, 20, 40, 60, and 80 ppm) were prepared. A 2.0 mL aliquot of each dilution was mixed with 2.0 mL of 0.1 mM DPPH solution. For the negative control (blank), 2.0 mL of methanol was mixed with 2.0 mL of the DPPH solution. Following a 30-minute incubation in the dark, the absorbance was recorded at 517 nm. The percentage of DPPH radical inhibition was calculated using the following equation:

$$\text{Inhibition}(\%) = \frac{A_{\text{control}} - A_{\text{sample}}}{A_{\text{control}}} \times 100$$

Where $A_{control}$ is the absorbance of the negative control (DPPH without extract) and A_{sample} is the absorbance of the reaction mixture containing the extract or standard. The IC_{50} value, representing the concentration required to inhibit 50% of DPPH radicals, was calculated through linear regression analysis of the inhibition percentage versus extract concentration.The experimental procedures should be described in sufficient detail to enable others to repeat the experiments

2.7 Statistical Analysis

All experimental procedures were performed in triplicate (n = 3), and the results were expressed as mean ± standard deviation. Data were analyzed using One-way Analysis of Variance (ANOVA) to determine the statistical significance of the geographical origin on the phytochemical and antioxidant profiles. Significant differences between means were further evaluated using Tukey's Honestly Significant Difference (HSD) post-hoc test, with a p-value of less than 0.05 considered statistically significant. Additionally, simple linear regression analysis was performed to evaluate the correlation between Total Phenolic Content (TPC) and antioxidant activity (IC50).

3. RESULTS AND DISCUSSION

The phytochemical profiles and antioxidant activities of Arabica coffee from eight distinct Indonesian geographical indications (GIs) were comprehensively evaluated. The characterization focused on three key parameters: caffeine content, total polyphenol content (TPC), and DPPH radical scavenging activity. To ensure the reliability of the comparative analysis, all measurements were conducted in triplicate, and the data were subjected to one-way ANOVA to determine the influence of geographical origin on the chemical constituents.

Table 2. Phytochemical Components and Antioxidant Activity of Eight Indonesian Arabica Coffee Origin

Coffee Geographical Origin	Estimated Altitudes (m asl)	Caffeine (%)	TPC (mg GAE/g)	IC_{50} (ppm)
Ciwidey	1,500 – 1,700	$1.18 \pm 0,04^{c}$	42.72 ± 1.09^{a}	40.15 ± 1.13^{f}
Kerinci	1,300 – 1,500	$1.25 \pm 0,05^{b}$	37.38 ± 1.18^{b}	52.20 ± 2.72^{b}
Toraja	1,400 –1,700	$1.22 \pm 0,05^{bc}$	39.81 ± 1.13^{ab}	41.20 ± 1.71^{f}
Aceh (Gayo)	1,200 – 1,600	$1.18 \pm 0,04^{c}$	39.09 ± 1.18^{b}	43.50 ± 2.08^{e}
Bajawa	1,200 – 1,550	$1.28 \pm 0,06^{ab}$	37.98 ± 1.34^{b}	49.30 ± 2.81^{c}
Papua	1,600 – 2,000	$1.14 \pm 0,04^{c}$	42.12 ± 1.22^{a}	44.90 ± 1.47^{de}
Bali	1,100 –1,500	$1.24 \pm 0,04^{b}$	36.05 ± 1.10^{c}	54.80 ± 2.61^{ab}
Temanggung	1,000 – 1,300	$1.31 \pm 0,04^{a}$	35.45 ± 1.15^{c}	56.50 ± 1.21^{a}

Note: Data are presented as mean ± standard deviation (n = 3). Values in the same column followed by different superscript letters indicate statistically significant differences ($p < 0.05$) according to Tukey's HSD test.

The results, encompassing Total Polyphenol Content (TPC), caffeine concentration, and antioxidant activity (IC_{50}), are summarized in Table 2. Statistical analysis using One-way ANOVA revealed significant variations ($p < 0.001$) across all measured parameters, indicating that the geographical origin and its broad regional conditions exert a profound influence on the secondary metabolite accumulation

in the coffee beans. The overall results indicated a substantial diversity in the bioactive composition of the samples, reflecting the unique environmental and terroir characteristics of the Indonesian archipelago.

3.1 Total Polyphenol Content (TPC)

Coffee is widely recognized not only as a global beverage but also as a premier source of dietary antioxidants in the modern diet (Grosso *et al*., 2017). This health-promoting property is primarily attributed to its phenolic compounds, which serve a dual purpose: acting as a natural shield for the coffee plant against environmental stress and providing functional bioactivity for human health (Liang and Kitts, 2016). Within the plant's physiology, these compounds function as secondary metabolites synthesized in response to external pressures, thus making their concentration a unique "biochemical fingerprint" of the specific geographical origin (Worku *et al*., 2018; Tolessa *et al*., 2017).

Consequently, the evaluation of Total Polyphenol Content (TPC) is fundamental in determining the phytotherapeutic potential of coffee beans, as phenolics represent the most abundant group of antioxidant metabolites in the Coffea genus. In this study, TPC analysis revealed significant variations across the eight Indonesian Arabica coffee origins. Statistical analysis via one-way ANOVA demonstrated a highly significant influence of geographical origin on phenolic accumulation ($F = 15.35$, $p < 0.001$). This pronounced variance underscores that TPC diversity is primarily driven by specific environmental factors, such as altitude and soil composition, rather than experimental variability.

Quantitative data (Table 2) showed that TPC ranged significantly from 35.45^{c} to 42.72^{a} mg GAE/g. Ciwidey recorded the highest phenolic concentration (42.72^{a} mg GAE/g), followed closely by Papua (42.12^{a} mg GAE/g), while Temanggung exhibited the lowest (35.45^{c} mg GAE/g). The superior phenolic content observed in Ciwidey and Papua (both categorized in subset 'a') is fundamentally linked to their high-altitude terroirs (>1,500 m asl). This correlation aligns with findings by Worku *et al*. who established that high-altitude environments prolong bean maturation, allowing for greater accumulation of organic acids and phenolics. At these elevations, coffee plants are exposed to critical abiotic stressors, including intensified UV radiation and lower ambient temperatures. These environmental conditions stimulate the phenylpropanoid pathway, triggering the plant to synthesize secondary metabolites as a robust protective mechanism against oxidative stress (Cheng *et al*., 2016; Somporn *et al*., 2012).

This range aligns with Vignoli *et al*. who established that high-altitude Arabica beans from diverse global regions exhibit similar phenolic density. Consequently, the slower maturation process at higher altitudes allows for a more concentrated accumulation of polyphenols, which serves as a natural 'chemical shield' for the beans, ultimately enhancing their functional value.

This physiological adaptation is further supported by Somporn *et al*. who noted that exposure to more intense solar radiation at higher elevations triggers the upregulation of phenylalanine ammonia-lyase (PAL), a key enzyme in phenolic biosynthesis. Consequently, the lower temperatures associated with higher altitudes lead to a prolonged maturation period, allowing for a more extensive accumulation of hydroxycinnamic acids, particularly chlorogenic acids, within the endosperm. In contrast, the lower TPC observed in Temanggung (35.45 mg GAE/g) coincides with its highest caffeine concentration. This inverse relationship reflects a distinct metabolic shift likely driven by its lower growing elevation. Lower altitudes are generally associated with higher environmental temperatures, which can accelerate cherry maturation. This rapid development limits the time available for the extensive synthesis of carbon-based phenolics, while potentially favoring the accumulation of nitrogen-based alkaloids such as caffeine as an environmental response.

3.2 Caffeine Content Analysis

Caffeine (1,3,7-trimethylxanthine) is the predominant purine alkaloid in coffee, serving not only as a key determinant of the beverage's characteristic bitterness and stimulating properties but also as a vital chemical defense mechanism (Seninde and Chambers, 2020). Biologically, the plant synthesizes

caffeine as a natural biopesticide to deter herbivores and mitigate environmental stressors, effectively acting as a 'chemical shield' for the developing seeds (Nathanson, 1984; Ashihara *et a*l., 2008). In this study, quantitative analysis revealed significant diversity in caffeine content across the eight origins ($F_{calc} = 7.02$, $p < 0.001$). The concentration levels followed a descending order: Temanggung > Bajawa > Kerinci > Bali > Toraja > Aceh > Papua > Ciwidey.

Notably, the accumulation trend of caffeine exhibited an inverse relationship with Total Polyphenol Content (TPC). Temanggung, which recorded the lowest TPC, possessed the highest caffeine levels (1.31^{a}%). As illustrated in Figure 1a, the regression plot highlights this metabolic trade-off, showing a clear negative slope where samples with high phenolic density consistently exhibit lower alkaloid concentrations. Rather than soil nutrient variations, this phenomenon is more likely governed by elevational differences. Lower altitudes generally experience higher environmental temperatures, a condition known to stimulate the biosynthesis of caffeine as an environmental stress response or defense mechanism. Simultaneously, these warmer temperatures accelerate cherry ripening, thereby limiting the duration available for the extensive synthesis of carbon-based phenolics.

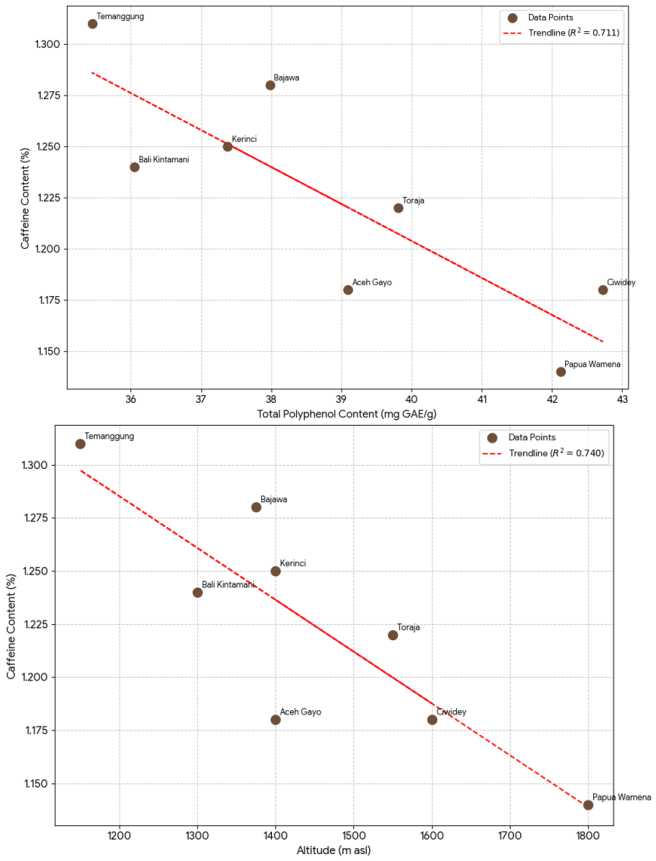

Figure 1. (a) The metabolic trade-off between Total Polyphenol Content (TPC) and Caffeine, illustrating the Carbon-Nutrient Balance (CNB) hypothesis. (b) Linear regression showing the inverse correlation between altitude (midpoint elevation) and caffeine content across eight Indonesian Arabica origins.

Furthermore, the elevated caffeine content in Temanggung can be contextualized by its specific topographical cultivation profile. While both regions produce highland coffee, they occupy different elevation ranges that influence their respective microclimates. Temanggung's coffee cultivation spans the slopes of Mount Sindoro and Sumbing, with Arabica typically grown from medium-high to high elevations ranging from 900 to >1,400 m a.s.l. (Fiqhry, 2023). In contrast, the mountainous Arabica belt of South Bandung, which includes Ciwidey, is situated at strictly higher elevations, generally exceeding 1,000 up to 1,700 m a.s.l. (Pratamaningsih, 2025; Chairani, 2017). Consequently, the cultivation of Temanggung Arabica at relatively lower elevation thresholds exposes the plants to

slightly warmer ambient temperatures compared to the cooler, more humid environment of the Ciwidey highlands. This observation aligns with Worku et al. (2018), who established that caffeine content is inversely correlated with altitude, tending to accumulate more densely in beans cultivated in warmer, lower-elevation environments. This inverse correlation is visually demonstrated in Figure 1b, where a linear regression analysis (R^2 = 0.74) confirms that caffeine levels systematically decrease as the cultivation altitude increases. From a physiological perspective, since nitrogen is a critical limiting precursor in the xanthosine pathway (Ashihara, Sano, and Crozier, 2008), the elevated synthesis of caffeine in warmer climates likely functions as a specific physiological adaptation to the environmental pressures associated with lower elevations.

3.3 Antioxidant Activity (IC_{50})

The biological value of coffee is frequently defined by its antioxidant capacity, specifically its ability to neutralize harmful free radicals that contribute to oxidative stress. Quantitative studies indicate that the antioxidant potential of coffee beans often surpasses that of other established functional beverages, such as green tea, cocoa, or red wine, primarily due to the high concentration of chlorogenic acids and the bioavailability of melanoidins formed during roasting (Yashin *et al*., 2013; Richelle *et al*., 2001). This protective effect results from a complex synergy between various secondary metabolites, where phenolic acids act as electron or hydrogen donors to stabilize reactive oxygen species (ROS) via the Hydrogen Atom Transfer (HAT) mechanism (Liang and Kitts, 2014). To quantify this potency, the IC_{50} value is employed as a standardized metric; a lower IC_{50} value is highly desirable, as it indicates greater efficiency in achieving 50% radical inhibition at lower concentrations.

Statistical evaluation via one-way ANOVA revealed that geographical origin exerts a highly significant influence on radical scavenging capacity ($F = 27.57$, $p < 0.001$). The IC_{50} values ranged from 40.15^{f} to 56.50^{a} ppm, with Ciwidey demonstrating the most potent activity (lowest value, subset ‘f’), while Temanggung exhibited the lowest (highest value, subset ‘a’). This high potency in the Ciwidey samples is mechanistically linked to their high TPC levels, confirming that hydroxyl groups in phenolics are the primary contributors to the radical-quenching ability of the extract (Liang and Kitts, 2014).

According to the classification established by Blois, the majority of the Indonesian Arabica samples—including Ciwidey, ~~Kerinci~~, Toraja, Aceh Gayo, Bajawa, and Papua—are categorized as "very strong" antioxidants ($IC_{50} < 50$ ppm). The robust activity observed in Toraja samples, for instance, aligns with recent findings by Astuti *et al*., who reported that the specific roasting profile of Toraja Arabica retains significant radical scavenging activity despite thermal degradation. Furthermore, the significantly higher IC_{50} in Temanggung coffee (56.50^{a} ppm), despite its high caffeine content, confirms that caffeine's radical-trapping efficiency is subordinate to that of the chlorogenic acids prevalent in phenolic-rich origins (Müller *et al*., 2011). This divergence highlights that the specific environmental conditions of the Indonesian highlands not only produce unique flavor profiles but also strictly dictate the therapeutic potential of the beans.

3.4 Correlation and Mechanistic Interrelationships

To evaluate the contribution of specific metabolites to antioxidant capacity, a Pearson correlation analysis was conducted. The analysis revealed a strong, statistically significant inverse linear correlation between Total Phenolic Content (TPC) and IC_{50} values, yielding a Pearson correlation coefficient (r) of -0.891 (95% confidence interval [CI]: -0.952 to -0.762; $p < 0.001$). This strong negative association is depicted in Figure 2, where the linear regression model (R^2 = 0.793) indicates that phenolic accumulation accounts for approximately 79.3 % of the variation in antioxidant capacity across the distinct origins. The negative sign of the r coefficient mathematically confirms the expected biochemical mechanism: an increase in the concentration of phenolic compounds systematically drives down the IC_{50} value. This confirms that phenolic compounds are the primary determinants of radical

scavenging activity in Indonesian Arabica, a finding consistent with the mechanistic role of hydroxyl groups in neutralizing reactive oxygen species (Liang and Kitts, 2014).

However, the deviation from a perfect linear correlation (the remaining 21 % variance) is scientifically noteworthy. For instance, Toraja exhibited a relatively high antioxidant potency (IC_{50} = 41.20 ppm) despite having a moderate TPC (39.81^{ab} mg GAE/g). This suggests that the chemical profile of the phenolics, specifically the ratio of isomers, may play a more critical role than total quantity alone. It is plausible that Toraja samples contain higher proportions of dicaffeoylquinic acids (di-CQA) compared to monocaffeoylquinic acids (CQA). As noted by Farah and Donangelo (2006), di-CQA isomers possess more hydroxyl groups available for radical neutralization, thereby exhibiting superior antioxidant efficacy per unit mass compared to standard CQA.

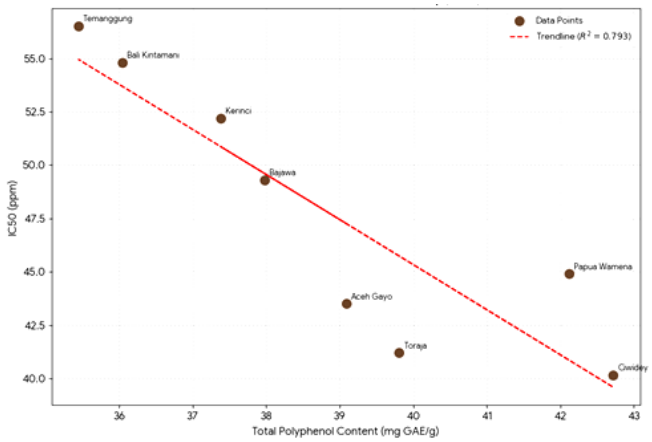

Figure 2. Linear regression analysis showing the strong negative correlation (R^2 = 0.793) between Total Polyphenol Content (TPC) and Antioxidant Activity (IC_{50}) across eight Indonesian Arabica origins.

Conversely, the correlation between caffeine and IC_{50} was positive (r = 0.747). Since a higher IC_{50} indicates weaker antioxidant activity, this result implies that coffee beans with high caffeine content (like Temanggung) tend to have lower antioxidant potential. This is likely not due to a direct inhibitory effect of caffeine, but rather stems from the metabolic trade-off described by the CNB hypothesis (Gebrekidan *et al*., 2019). When the plant allocates resources towards synthesizing nitrogen-rich alkaloids (caffeine), it inherently reduces the carbon budget available for synthesizing antioxidant-rich phenolics. This interrelationship highlights that the terroir of Indonesia does not merely affect individual chemical levels but fundamentally shifts the plant's metabolic flux, dictating the functional and therapeutic value of the resulting coffee beans (Sunarharum, Williams and Smyth, 2014).

4. CONCLUSION

This study conclusively demonstrates that the geographical origin acts as a primary determinant in modulating the bioactive profile of Indonesian Arabica coffees. The quantitative analysis revealed a significant metabolic divergence driven by environmental factors, where high-altitude regions such as Ciwidey and Papua favored the accumulation of phenolic compounds and exhibited superior antioxidant capacity (IC_{50} < 45 ppm). Conversely, the distinct edaphic conditions of Temanggung favored the synthesis of caffeine (1.31%), supporting the Carbon-Nutrient Balance (CNB) hypothesis regarding the metabolic trade-off between nitrogen-based alkaloids and carbon-based phenolics in nutrient-rich environments.

Furthermore, the robust linear correlation (R^2 = 0.793) between Total Polyphenol Content (TPC) and IC_{50} confirms that phenolic compounds are the dominant drivers of radical scavenging efficacy in Indonesian Arabica beans. However, the specific antioxidant potency observed in Toraja samples suggests that qualitative phenolic composition, specifically the ratio of chlorogenic acid isomers, may play a critical role alongside total concentration. These findings provide a scientific framework for the geographical authentication of Indonesian specialty coffees and offer strategic insights for the coffee

industry to develop functional products targeted at specific health benefits, such as high-antioxidant blends from high-altitude origins. Nevertheless, several inherent limitations of the present study must be acknowledged, as the broad origin-associated variations cannot map precise micro-environmental effects due to the lack of lot-specific soil and climatic data. Additionally, the scope of this research is constrained by a limited sample size of eight geographical indications, the reliance on a modified UV-Vis spectrophotometric method for caffeine determination rather than liquid chromatography, and the absence of individual phenolic compound profiling. Future research incorporating high-resolution chromatographic techniques and controlled multi-locational field trials is highly recommended to systematically validate these preliminary geographic chemical markers.

5. ACKNOWLEDGMENT

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