Chemical composition and antioxidant activity of the silverskin of three varieties of *Coffea arabica* L.

Composición química y actividad antioxidante de la película plateada de tres variedades de *Coffea arabica* L.

Composição química e atividade antioxidante da pele prateada de três variedades de *Coffea arabica* L.

Ingrid Márquez Hernández
Mercedes Campo Fernández*
Arantxa Ainoa Bustamante Quinde
Ronald Steeven Echeverría Loayza
Osmany Cuesta Rubio
Nubia Lisbeth Matute Castro

Universidad Técnica de Machala (UTMACH). Ecuador.

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Abstract

The silverskin (SS) of *Coffea arabica* L., a byproduct of coffee processing, represents a potential source of bioactive compounds with nutraceutical properties. The chemical composition (residual moisture, ash, fats, proteins, and minerals) and antioxidant capacity of the SS from three varieties of *C. arabica* (Acauã [AW], Sarchimor Rojo [CR], and Catucaí Amarillo [CA]) from the province of El Oro, Ecuador, were evaluated. The extraction of secondary metabolites (total phenols and caffeine) was performed for 60 min using ultrasound (US: 30 °C, 40 Hz) and dynamic digestion (D: 60 °C, 60 rpm), employing an ethanol:water mixture of (70:30 % v/v) and a plant material:solvent ratio of 20:80 % w/v. Total phenols were quantified using the Folin-Ciocalteu method, and caffeine analysis was performed through high-performance liquid chromatography (HPLC) with DAD detection. The evaluated samples met the residual moisture (RM) and total ash content requirements according to the NTE INEN standards, also exhibiting low percentages of fat and protein. The CR variety stood out with 44.8 $mg.g^{-1}$ of K and 24.9 $mg.g^{-1}$ of N. Method D extracted the highest amount of phenolic compounds, with CR recording the highest content at 85.0 mg $GAE.g^{-1}$ of dry extract (DE), which positively correlated with a higher Trolox equivalent antioxidant capacity (DPPH: 108.61 mg $TEAC.g^{-1}$ DE; FRAP: 122.96 mg $TEAC.g^{-1}$ DE). In contrast, caffeine levels were higher for the AW variety extracted by US (128.44 $mg.g^{-1}$ DE), being statistically different from the rest. The three varieties meet regulatory standards and demonstrate that SS is a raw material of great interest to the food and pharmaceutical industries.

*Corresponding author: mcampo@utmachala.edu.ec

Resumen

La película plateada (PP) de *Coffea arabica* L., subproducto del procesamiento del café, representa una fuente potencial de compuestos bioactivos con propiedades nutracéuticas. Se evaluó la composición química (humedad relativa, cenizas, grasas, proteínas y minerales) y la capacidad antioxidante de la PP de tres variedades de *C. arabica* (Acauã (AW), Sarchimor rojo (CR) y Catucaí amarillo (CA)), de la provincia de El Oro, Ecuador. La extracción de los metabolitos secundarios (fenoles totales y cafeína) se realizó durante 60 min mediante ultrasonido (US: 30 °C, 40 Hz) y digestión dinámica (D: 60 °C, 60 rpm), usando etanol:agua (70:30 % v/v) y una relación materia vegetal:solvente de 20:80 % m/v. La cuantificación de fenoles totales se realizó empleando el método de Folin-Ciocalteu y el análisis de cafeína mediante cromatografía líquida de alta eficiencia (CLAE) con detección DAD. Las muestras evaluadas cumplieron con el contenido de humedad residual (Hr) y cenizas totales según las normas NTE INEN, presentando, además, bajos porcentajes de grasa y proteínas. La variedad CR destacó con 44,8 mg.g^{-1} de K y 24,9 mg.g^{-1} de N. El método D extrajo la mayor cantidad de compuestos fenólicos, siendo CR la que registró el mayor contenido con 85,0 mg EAG.g^{-1} de extracto seco (ES), lo que correlacionó positivamente con una mayor capacidad antioxidante equivalente a trolox (DPPH: 108,61 mg TEAC.g^{-1} ES; FRAP: 122,96 mg TEAC.g^{-1} ES). En contraste, los niveles de cafeína, fueron superiores para la variedad AW extraída por US (128,44 mg.g^{-1} ES), siendo estadísticamente diferentes al resto. Las tres variedades cumplen los parámetros normativos y demuestran que la PP es una materia prima de gran interés para las industrias alimentaria y farmacéutica.

Palabras clave: análisis fitoquímico, café, métodos de extracción, potencial nutracéutico, subproducto agroindustrial.

Resumo

A película prateada (PP) de *Coffea arabica* L., um subproduto do processamento do café, representa uma fonte potencial de compostos bioativos com propriedades nutracêuticas. Avaliou-se a composição química (umidade residual, cinzas, gorduras, proteínas e minerais) e a capacidade antioxidante da PP de três variedades de *C. arabica* (Acauã [AW], Sarchimor Rojo [CR] e Catucaí Amarillo [CA]), da província de El Oro, Equador. A extração dos metabólitos secundários (fenóis totais e cafeína) foi realizada durante 60 min mediante ultrassom (US: 30 °C, 40 Hz) e digestão dinâmica (D: 60 °C, 60 rpm), utilizando etanol:água (70:30 % v/v) e uma proporção matéria vegetal:solvente de 20:80 % m/v. A quantificação de fenóis totais foi realizada empregando o método de Folin-Ciocalteu e a análise de cafeína por cromatografia líquida de alta eficiência (CLAE) com detecção DAD. As amostras avaliadas cumpriram com o teor de umidade residual (Ur) e cinzas totais segundo as normas NTE INEN pertinentes, apresentando, além disso, baixos percentuais de gordura e proteína. A variedade CR destacou-se com 44,8 mg.g^{-1} de K e 24,9 mg.g^{-1} de N. O método D extraiu a maior quantidade de compostos fenólicos, sendo a CR a que registrou o maior teor com 85,0 mg EAG.g^{-1} de extrato seco (ES), o que correlacionou-se positivamente com uma maior capacidade antioxidante equivalente a trolox (DPPH: 108,61 mg TEAC.g^{-1} ES; FRAP: 122,96 mg TEAC.g^{-1} ES). Em contrapartida, os níveis de cafeína foram superiores para a variedade AW extraída por US (128,44 mg.g^{-1} ES), sendo estatisticamente diferentes das demais. As três variedades cumprem os parâmetros normativos e demonstram que a PP é uma matéria-prima de grande interesse para as indústrias alimentícia e farmacêutica.

Palavras-chave: análise fitoquímica, café, métodos de extração, potencial nutracêutico, subproduto agroindustrial.

Introduction

Coffee is one of the most globally consumed beverages, with Ecuador being the fourth regional exporter of *Coffea arabica* L. (Ministry of Agriculture and Livestock [MAG], 2021). Large volumes of by-products are generated during its processing, constituting nearly 90 % of the fruit, with silverskin (SS) standing out due to its inadequate management and possible environmental impact (Hayes *et al*., 2023; Santanatoglia *et al*., 2024). The SS contains more than 40 bioactive metabolites, including phenolic compounds and alkaloids such as caffeine, which makes it particularly interesting for its antioxidant potential with possible use in nutritional or pharmaceutical therapies (Hayes *et al*., 2023; Nolasco *et al*., 2022; Barreto *et al*., 2022; Prakash and Doan, 2022; Santanatoglia *et al*., 2024). Since phytochemical research on landraces is limited, this research aims to analyze the chemical composition (residual moisture, ash, fats, proteins, and minerals) and antioxidant activity in terms of total phenols and caffeine of extracts obtained from the SS of *C. arabica* L. var. CR, CA, and AW, using chromatographic and spectrophotometric techniques, which scientifically validate their possible use in health.

Materials and methods

Study area

The SS of the three varieties of *C. arabica* (AW, CR, CA) was obtained in April 2024 from the "Don Salvador Café" coffee plantation, located in Las Lajas, El Oro, Ecuador (coordinates 03°47' S, 80°04' W; approximate altitude of 600 m.a.s.l.). The horticultural management of the plantation consisted of rainfed irrigation, soil fertilization, maintenance pruning, and integrated pest and disease control.

Sample preparation

The samples were processed in the Phytochemistry laboratory of the Technical University of Machala, Ecuador, in 2025. From 15 kg of ripe fruits processed by the wet method, the SS sample of the three varieties (AW, CR, CA) was obtained. Drying was carried out at 45 °C in an oven (MEMMERT UF 55, Germany) with 100% forced-air circulation for approximately 24 h. It was then ground in a mill (BIOBASE Disintegrator HSD-400, 25,000 rpm, China) and passed through an 850 µm mesh sieve (HUMBOLDT). All samples were packed in airtight plastic bags at room temperature (25 °C) and stored in a desiccator until the respective analyses were carried out (for approximately two months).

Proximate analysis

The proximate composition included the determination of residual moisture (RM), fats, proteins, ash, and minerals. The RM was determined using a thermobalance with a halogen heating source (OHAUS, MB90, United States), set to a temperature of 105 °C. The determination of total ash was performed according to the method established by the Association of Official Analytical Chemists (AOAC 942.05, 1990). The percentage of total fats was determined according to the methodology described by Pillco *et al*. (2021), with

some modifications described by Campo Fernández *et al.* (2024). Gravimetric determinations were performed in triplicate.

The analytical determination of proteins and minerals was carried out at the facilities of the NEMALAB S.A. laboratory. Protein content was quantified using the micro-Kjeldahl method, applying the conversion factor of 6.25 for total nitrogen. On the other hand, the quantification of minerals (expressed in $mg.g^{-1}$ of dry plant material) was performed following a wet digestion process, using a mixture of nitric acid and perchloric acid in a 2:1 ratio.

Preparation of extracts

The extracts were prepared using a hydroalcoholic mixture of ethanol:water (70:30 % v/v), employing a ratio of plant material:solvent (20:80 % m/v), using ultrasound (US) and dynamic digestion (D) methods. Ultrasound-assisted solvent extraction was performed in an ultrasound bath (ULTRASONIC BATH 5.7 L, Ficher Scientific, United States) at 30 °C, 40 Hz for 1 h; while extraction by digestion was performed in a thermostatic bath (BIOBASE, China) with constant agitation (60 rpm) and 60 °C for the same time. Once the extraction was complete, the extract was filtered with filter paper (FILTRAK) and evaporated to dryness (DE) using a rotary evaporator (HEIDOLPH LABOROTA 4001, efficient, Germany) coupled to a cryostat (LAUDA/ALPHA RA-8) and a vacuum pump (VACUUBRAND PC 600, Germany).

Quantification of total phenols using the Folin-Ciocalteu method

The quantification of total phenols was performed according to the methodology described by Campo-Fernández *et al.* (2021). Absorbance was determined using a spectrophotometer (UV-Visible SPECTROPHOTOMETER Evolution 201 Thermo Scientific, United States) at 765 nm, employing plastic microcells (BRAND GMBH, Germany). A calibration curve was performed with gallic acid 10 $mg.mL^{-1}$ (Sigma Aldrich) at concentrations between 0.1 and 0.9 $mg.mL^{-1}$ ($y= 0.9457X + 0.0029$), $R^2= 0.9916$. Results were expressed as mg of gallic acid equivalents per gram of DE ($GAE.g^{-1}$ DE).

Determination of caffeine by high-performance liquid chromatography (HPLC)

The caffeine analysis was performed following the protocol of Eticha and Bedassa (2020) with adaptations. Ten milligrams of DE were dissolved in a hydroalcoholic mixture of HPLC-grade methanol and ultrapure water (70:30 % v/v), and the solution was filtered through a 0.2 µm membrane. For the analysis, a Thermo Scientific Ultimate 3000 system, equipped with a quaternary pump, an autosampler, and a diode array detector (DAD) (DIONEX Ultimate 3000 RS, United States) managed by Thermo Xcalibur software, was employed. Chromatographic conditions included: a Hypersil GOLD C18 column (150 mm × 4.6 mm x 5 µm). An isocratic elution was performed using water (A) and methanol (B) at a ratio of 75:25 % v/v; flow rate of 1 $mL.min^{-1}$, 5 µL injection volume, and column temperature controlled at 35 °C. The detection was made by UV-Vis spectroscopy at 272 nm. A column cleaning stage was included after each run. For caffeine quantification, a calibration curve was prepared with caffeine (Supelco) within a range between 0.2 and 3.2 $mg.mL^{-1}$ ($y= 6x10^6X + 809901$), $R^2= 0.9966$. Results were expressed as mg of caffeine per gram of DE ($mg.g^{-1}$ DE)

Quantification of antioxidant capacity

Ferric ion reducing antioxidant power (FRAP)

It was carried out using the method of Benzie and Strain (1996), applying the modifications proposed by Campo-Fernández *et al.* (2021). The calibration curve was elaborated with methanolic solutions (SIGMA-ALDRICH absolute methanol for analysis) of 6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid (Trolox), at concentrations of 0.027-0.227 $mg.mL^{-1}$ ($y= 14.7533X + 0.0439$), $R^2= 0.9962$. The spectrophotometric reading was performed at 593 nm in plastic microcells. The values obtained were expressed as Trolox equivalent antioxidant capacity (TEAC) per gram of DE ($TEAC.g^{-1}$).

2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging capacity

The Brand-Williams method *et al*. (1995) was used with some modifications described by Campo-Fernández *et al.* (2021). The calibration curve was elaborated with methanolic solutions (SIGMA-ALDRICH absolute methanol for analysis) of Trolox, at concentrations of 0.027-0.227 $mg.mL^{-1}$ (% Inh= 377.62X – 1.1825), $R^2= 0.9941$. The results obtained were expressed as Trolox equivalent antioxidant capacity (TEAC) per gram of DE ($TEAC.g^{-1}$).

Statistical analysis

A multifactorial analysis of variance (ANOVA) was performed using the JAMOVI statistical software package, version 2.3.2, considering the extraction method and the *C. arabica* variety as study factors.

Results and discussion

Proximate analysis

Table 1 shows the proximate composition of SS, assays that help determine the nutritional value, shelf life, and quality of the raw material for its use in different industries (Ullah *et al*., 2023).

Table 1. Proximate chemical composition of samples from the silverskin of *C. arabica* L. var. Acauã (AW), Sarchimor Rojo (CR), Catucaí Amarillo (CA).

Parameters (%)	AW Mean ± S	CR Mean ± S	CA Mean ± S
Residual moisture	8.55 ± 0.29[a]	7.72 ± 0.14[b]	8.61 ± 0.30[a]
Total ash	0.99 ± 0.09[a]	0.65 ± 0.08[b]	0.96 ± 0.05[a]
Total fats	0.01 ± 0.00[a]	0.06 ± 0.01[b]	0.01 ± 0.01[a]
Proteins	2.38 ± 0.03[a]	2.49 ± 0.04[a]	2.44 ± 0.02[a]
Minerals ($mg.g^{-1}$)	**AW**	**CR**	**CA**
Nitrogen (N)	23.80	24.90	24.40
Phosphorus (P)	1.10	1.70	1.80
Potassium (K)	32.10	44.80	34.10
Calcium (Ca)	6.40	16.30	20.40
Magnesium (Mg)	1.60	3.20	2.30
Zinc (Zn)	0.03	0.03	0.02
Copper (Cu)	0.01	0.02	0.01
Iron (Fe)	0.23	0.22	0.17
Manganese (Mn)	0.08	0.09	0.09
Sodium (Na)	0.08	0.09	0.08

S = Standard deviation. Different letters within the same row indicate that there are statistically significant differences (α=0.05).

As can be seen, while the RM of CR differs statistically ($p<0.05$) from that obtained for AW and CA, they all comply with the established standards (NTE INEN 2392, 2017). Although other authors show values that differ from those obtained (Gottstein *et al*., 2021; Martuscelli *et al.*, 2021), all results guarantee the conservation of dry plant material during storage (RM<12 %), preventing the deterioration and proliferation of microorganisms.

In relation to the percentage of fat, low levels are present in the three varieties, being even lower than what was reported by Bobková *et al*. (2022) and Gottstein *et al*. (2021), which suggests that this residue is not a relevant caloric source, since, in general, the value of these nutrients is not usually high.

The determination of the protein percentage in the three varieties evaluated showed similar results to each other, although with values below the range of 16.3 % to 18.6 %, previously reported for cocoa husks (Gottstein *et al*., 2021; Prandi *et al*., 2021). This discrepancy could be attributed to extrinsic factors, such as sample storage time, as well as to the thermal degradation of amino acids induced by the Maillard reaction during the roasting process. However, the protein levels detected support the use of this by-product in the formulation of fortified foods or supplements, coinciding with the applications suggested by Biondić Fučkar *et al*. (2023) and Hayes (2020).

The determination of total ash showed similar contents in the AW and CA varieties, which were higher than the levels detected in CR. The values obtained were within the acceptance range, as they did not exceed the maximum limit of 5.0 % stipulated by the NTE INEN 1123 standard (2016), and were relatively similar to the value reported by Kristanto and Wijaya (2018), 1.3 %. However, it is worth noting previous findings with significantly higher percentages (6.79 % and 8.15 %), which exceed current quality standards (Gottstein *et al.,* 2021; Martuscelli *et al.,* 2021). Such discrepancies in the inorganic residue obtained from the samples can be attributed to the influence of geographical origin, soil conditions of the crop, and genotypic variations among the varieties analyzed. In addition, the three varieties presented a mineral composition dominated by potassium, nitrogen, calcium, and magnesium, with copper being identified as the element with the lowest concentration. Regarding the mineral profile shown in Table 1, it should be noted that the analysis was proposed as an exploratory screening of the samples under study; therefore, the data are presented descriptively. The reliability of these data is based on the fact that the most relevant results were consistent with previous studies (Gottstein *et al*., 2021; Martuscelli *et al*., 2021; Bojórquez-Quintal *et al*., 2024), where the prevalence of potassium in all the samples analyzed is confirmed.

Quantification of secondary metabolites and antioxidant capacity

The quantification of secondary metabolites (total phenols and caffeine) and antioxidant capacity was determined by calibration curves.

The results obtained for the quantification of secondary metabolites are presented in Table 2.

Statistical analysis revealed that both the coffee variety and the extraction technique play a decisive role in the phytochemical profile of SS. The analysis of variance (ANOVA) confirmed a highly significant interaction ($p < 0.001$) between the method and the variety for total phenols and caffeine. D significantly guaranteed the extraction of total phenols in all samples because the synergism between agitation and temperature favored solubility and mass transfer from the plant matrix (Martins de Sá *et al*., 2024). The CR variety stood out with the highest concentration (85.00 mg GAE.g^{-1} DE). It is relevant to note that the values obtained for CR (85 mg GAE.g^{-1} DE) are similar to those reported by Franca *et al*. (2024) (78.3 mg GAE.g^{-1}). It should be noted that quantification based on the DE, rather than the crude liquid extract, allowed for the concentration of the secondary metabolites and eliminated the solvent dilution effect. On the other hand, the extraction by US of the CR variety statistically equals the yield of the AW variety treated with digestion.

Table 2. Quantification of secondary metabolites in the silverskin of *C. arabica* var. Acauã (AW), Sarchimor Rojo (CR) and Catucaí Amarillo (CA).

Sample	Total phenols (mg GAE.g^{-1}DE) (Mean ± S)		Caffeine (mg.g^{-1}DE) (Mean ± S)	
	US	D	US	D
AW	58.88 ± 1.31^{*c}	73.70 ± 1.20^{*b}	128.44 ± 1.41^{*a}	111.10 ± 0.23^{*b}
CR	74.98 ± 2.12^{*b}	85.00 ± 2.04^{*a}	93.68 ± 0.20^{*c}	84.27 ± 0.31^{*d}
CA	34.31 ± 0.90^{*e}	38.82 ± 0.86^{*d}	74.13 ± 1.06^{*e}	65.07 ± 0.36^{*f}

US: Ultrasound extraction, D: Extraction by dynamic digestion. S: standard deviation. GAE: Gallic acid equivalent. Different letters in the same variable (considering rows and columns) indicate statistically significant differences according to Tukey's test ($p < 0.05$), *: There is interaction between the sample variables and the extraction method.

On the contrary, ultrasound proved to be a superior method to extract caffeine, making the AW variety reach the highest value of the study (128.44 mg.g^{-1} DE). This difference compared to dynamic digestion is not attributed to a possible thermal degradation of the alkaloid at 60 °C, since caffeine is a highly thermostable compound capable of maintaining its structure even under the severe temperatures of the roasting process (Jung *et al.,* 2021). The superiority of this method is due to the high efficiency of ultrasonic cavitation; the micro-implosions generated caused a mechanical disruption in the dense cellular matrix of SS, which facilitated a greater release of the alkaloids into the solvent, compared to the mass transfer achieved by the moderate agitation of dynamic digestion (Taweekayujan *et al.,* 2023)

The variations observed between varieties from the same geographical area suggest that the biosynthesis of these compounds is strongly regulated by specific genotypic and microenvironmental factors (Bojórquez-Quintal *et al.,* 2024).

Regarding antioxidant capacity, Table 3 shows the results obtained using two different methods: DPPH and FRAP.

The biochemical trend coincided with the quantification of phenolic compounds. In the DPPH assay, although the method-variety interaction was not globally statistically significant ($p = 0.234$), the post hoc analysis confirmed that the CR variety was the best as a hydrogen donor, without the extraction method (US vs D) generating a significant difference for it. The FRAP assay showed that the CR variety treated with dynamic digestion also registered the highest reducing power (122.96 mg.g^{-1} DE), statistically differentiating itself from the rest of the treatments.

In general, the evaluation of antioxidant capacity revealed a marked superiority of the results obtained compared to previous reports based on crude drug (Machado *et al*., 2023), which could be attributed in the first instance to the concentration of analytes in the dry extract (DE) used in this research. The discrepancies with

Table 3. Antioxidant capacity in the silverskin of *C. arabica* L. var. Acauã (AW), Sarchimor Rojo (CR) and Catucaí Amarillo (CA).

Sample	TEAC-DPPH (mg.g^{-1} DE) (Mean ± S)		TEAC-FRAP (mg.g^{-1} DE) (Mean ± S)	
	US	D	US	D
AW	81.25 ± 2.15^{c}	91.79 ± 0.87^{b}	58.34 ± 0.68^{*d}	89.61 ± 2.76^{*c}
CR	103.02 ± 5.16^{a}	108.61 ± 2.62^{a}	104.23 ± 0.09^{*b}	122.96 ± 1.39^{*a}
CA	27.33 ± 0.22^{d}	33.58 ± 0.68^{d}	35.72 ± 0.65^{*f}	39.79 ± 1.05^{*e}

US: Ultrasound extraction, D: Extraction by dynamic digestion. S: standard deviation. TEAC-DPPH: Trolox equivalent antioxidant capacity, using the DPPH free radical. TEAC-FRAP: Trolox equivalent antioxidant capacity, determined by ferric ion reducing antioxidant power. *: There is interaction between the sample variables and the extraction method. Different letters in the same variable (considering rows and columns) indicate statistically significant differences according to Tukey's test ($p < 0.05$).

the literature respond not only to the physical state of the sample (DE vs. crude drug) but also to the selectivity of the solvents and the thermodynamic conditions of the process (Franca *et al*., 2024; Taweekayujan *et al*., 2023; Vargas-Sánchez *et al.*, 2023).

In addition, Pearson correlation coefficient analysis confirmed that antioxidant capacity is intrinsically linked to the polyphenolic content of the samples evaluated (Kiss *et al.,* 2025). A strong positive correlation was identified between total phenols and the DPPH assays (R=0.977) and FRAP (R=0.971), results that confirm these metabolites as the main determinants of redox potential and radical uptake, in correspondence with what was reported by Fonseca-García *et al.* (2014) and Zengin *et al*. (2020). Likewise, the close relationship between both quantification methods (R=0.931) validates their joint use to accurately characterize these agro-industrial by-products. On the contrary, the quantification of caffeine showed a weak correlation with the DPPH (R=0.552) and FRAP (R=0.236) indices, differing from the behavior observed in the phenol analysis. This trend confirms that caffeine does not act as a reducing or radical scavenging agent under the experimental conditions of these assays. These findings are consistent with what was reported by Jung *et al.* (2021), who documented low and even negative correlations between caffeine and total polyphenols, as well as between this alkaloid and antioxidant capacity by similar methods (DPPH and FRAP), corroborating that the biological activity evaluated depends primarily on the polyphenolic composition. The weak correlation observed did not indicate an absence of antioxidant potential in caffeine, but rather a methodological limitation of the DPPH and FRAP assays. Lacking phenolic hydroxyl groups, caffeine did not participate efficiently in the electron or hydrogen atom transfer mechanisms that underpin these techniques.

Conclusions

The analysis of the SS of the AW, CR, and CA varieties revealed a valuable chemical and antioxidant profile that validates its nutraceutical use. Initially, its proximate composition demonstrated ideal characteristics for safe preservation and an outstanding mineral contribution in potassium and nitrogen. When evaluating the extraction methods, it was found that D extraction favored the obtaining of phenolic compounds, while US maximized caffeine recovery. Specifically, the CR variety stood out as the most promising option due to its concentration of polyphenols, which justified its superiority in relation to antioxidant capacity, leaving caffeine without an active role in this redox mechanism; however, if the extraction of this alkaloid is prioritized, the AW variety was positioned as the best source.

These findings confirmed that this coffee by-product transcends its status as waste, representing a sustainable and valuable raw material for the development of new functional foods and therapies aimed at human health.

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