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Elaboration of infusion from the peel of the coffee fruit

Jorge Luis Leiva-Piedra (jleiva@utp.edu.pe)
Daniela Olaya Muro-Neyra (U17103686@utp.edu.pe)
Carmen Odette Zapata-Lopez (1611980@utp.edu.pe)
Walter Manuel Hoyos-Alayo (C23712@utp.edu.pe)
Universidad Tecnológica del Perú

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Abstract: Coffee is a major global agricultural commodity with sustained market growth each year. Its processing generates large amounts of residues that usually lack proper management, which creates environmental impact. This study aimed to prepare an infusion using the peel of the coffee fruit. An infusion was prepared with 10 g of peel dried at 70 °C for 7 hours, 35 °C for 3 days, and in a solar dryer. A hedonic test was applied to all treatments. The three treatments with the highest acceptability were subjected to physicochemical and microbiological analyses. The results were examined using analysis of variance (ANOVA), Tukey tests, and linear regression between physicochemical parameters. The findings indicated that the treatment labelled Tto achieved the highest acceptability, with scores for aroma, flavour, and appearance between 4.4 and 4.3, and a light brown colour. In the physicochemical analysis, it showed the highest phenolic content at 3544 mg gallic acid equivalent (GAE) per 100 g. Antioxidant capacity and anthocyanins were higher in Tto2 by 3.36 % and 38.8 %, respectively. The colour of the infusion was closely associated with phenolic compounds (r = 0.94 L*, r = -0.74 a*, r = 0.99 b*) and anthocyanins (r = -0.92 L*, r = -0.74 a*, r = -0.99 b*). The pH and acidity were related to anthocyanins (r = -0.98 and r = -0.82) and phenolic compounds (r = 0.98 and r = 0.81). All treatments showed microbial counts below the permissible limits. The results indicate that coffee peel is a suitable raw material for infusion production.

Keywords: Anthocyanins, antioxidant activity, coffee husk, *Coffea arabica.*

Resumo: O café é uma importante commodity agrícola global, com crescimento de mercado sustentado a cada ano. O seu processamento gera grandes quantidades de resíduos, que em geral não recebem manejo adequado, o que gera impacto ambiental. Este estudo teve como objetivo preparar uma infusão utilizando a casca do fruto do café. Foi preparada uma infusão com 10 g de casca seca a 70 °C por 7 horas, a 35 °C por 3 dias e em secador solar. Aplicou-se um teste hedônico a todos os tratamentos. Os três tratamentos com maior aceitabilidade foram submetidos a análises físico-químicas e microbiológicas. Os resultados foram avaliados por análise de variância (ANOVA), testes de Tukey e regressão linear entre parâmetros físico-químicos. Os achados indicaram que o tratamento identificado como Tto apresentou a maior aceitabilidade, com notas de aroma, sabor e aparência entre 4,4 e 4,3, e coloração marrom-clara. Na análise físico-química, apresentou o maior teor de fenólicos, com 3544 mg de equivalente de ácido gálico (EAG) por 100 g. A capacidade antioxidante e as antocianinas foram maiores em Tto2 em 3,36 % e 38,8 %, respectivamente. A cor da infusão esteve fortemente associada aos compostos fenólicos (r = 0,94 L*, r = -0,74 a*, r = 0,99 b*) e às antocianinas (r = -0,92 L*, r = -0,74 a*, r = -0,99 b*). O pH e a acidez se relacionaram com as antocianinas (r = -0,98 e r = -0,82) e com os compostos fenólicos (r = 0,98 e r = 0,81). Todos os tratamentos apresentaram contagens microbianas abaixo dos limites permitidos. Os resultados indicam que a casca de café é uma matéria-prima adequada para a produção de infusões.

Keywords: Antocianinas, atividade antioxidante, casca de café, Coffea arabica.

1. INTRODUCTION

Coffee (*Coffea arabica* L., Rubiaceae) is one of the most widely traded products in Peru and is recognised for its high quality, with exports increasing by 328 % in 2022 compared with 2021, making it one of the country's main export commodities [1]. Its processing generates large amounts of residues such as husk and pulp [2]. These residues represent between 30 % and 50 % of the total weight of the coffee fruit [3]. The annual production of solid residues has been estimated at 2.5 million tonnes, and improper management of these residues generates significant environmental impact [4]. According to De la Hoz Ortega & Merlano Alarcón [5], less than 5 % of the waste generated during coffee processing is used. In Peru, it has been estimated that around two million quintals of coffee husk are produced and often disposed of in water bodies such as rivers and lakes [6].

The peel of the coffee fruit currently has no profitable use and contains caffeine, chlorogenic acid and tannins, which limit its use as animal feed or fertiliser due to their negative effects on animal health and plant growth [7]. As a result, about 50 % of this residue is dumped or burned in open fields, which generates environmental damage [8]. This situation has created the need to identify production mechanisms that improve residue management, add value and reduce environmental impacts [4]. The circular economy has become an important framework for sustainable resource management. It focuses on the reuse and valorisation of by-products to reduce environmental impact [9]. In this context, coffee peel is an underused resource with strong potential for innovation and economic value [10]. The management of this residue is a major challenge that requires feasible alternatives that promote its reuse and reduce its environmental footprint [11].

The growing coffee production in Peru and the consequent increase in residues make it necessary to identify alternatives for their utilization [12]. Several studies have shown that coffee peel has properties that allow its use in food, cosmetic and renewable energy industries [13]. Its nutritional composition, which includes energy value, proteins, carbohydrates and other elements, offers opportunities to produce value added products and reduce the environmental impact of the coffee sector [14], [15]. Coffee peel also contains antioxidants and phenolic compounds, which may contribute to human health through functional foods and

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dietary supplements and extend the shelf life of food products, with benefits for both health and the economy [10]. Coffee peel contains high levels of sugars, minerals and antioxidants that surpass those of several commonly consumed fruits [16].

In the food sector, coffee peel is gaining interest due to its content of anthocyanins, caffeine, chlorogenic acids and dietary fibre [17]. These characteristics make it a promising ingredient for safe and appealing food products [10]. It also has considerable potential as a raw material for functional beverages and fortified foods, and its use may contribute to a more sustainable value chain in the coffee industry [18], [19]. The valorisation of coffee peel is therefore an important strategy for advancing towards a more sustainable circular economy [9]. Coffee peel is a potential raw material for functional products because of its high content of dietary fibre, probiotics and antioxidants, with an approximate fibre content of 34 %, which supports the regulation of blood sugar and insulin production [20]. This study aimed to prepare an infusion using the peel of the coffee fruit.

2. Materials and methods

2.1 Location

The study was conducted in the Industrial Technology Laboratory of the Universidad Tecnológica del Perú, Chiclayo campus, located in the district and province of Chiclayo, Lambayeque region, Peru. The campus lies at approximately 6°45’49” south latitude and 79°51’47” west longitude, at an elevation of about 27 m a.s.l. Chiclayo has a warm desert climate, with a mean annual air temperature close to 21.3 °C and low annual rainfall of around 200 mm, conditions that are characteristic of the northern Peruvian coast. The experimental work was carried out between March and June 2025, during the warm dry season. During the study period, all trials were carried out in an enclosed food technology laboratory under routine cleaning and ventilation practices, so outdoor weather conditions did not interfere with the experimental procedures.

2.2 Preparation of the infusion

Peruvian commercial coffee production relies almost exclusively on *Coffea arabica* L., Rubiaceae with plantations composed predominantly of Typica and Caturra cultivars and smaller proportions of Catimor, Bourbon, Pache and related lines, which are adapted to the agroecological conditions of the Andean foothills and valued for beverage quality and yield [21]. In northern Peru, including Lambayeque, commercial lots commonly integrate Typica, Caturra and Catimor at altitudes between about 500 and 1 600 m, supplying regional roasters and export markets with washed Arabica coffee of consistent sensory profile [22].

The peel was then dried using two systems. In the first system, the material was placed in a passive solar dryer until reaching a constant mass. In the second system, drying took place in a forced air convection dehydrator at two temperature and time regimes, 35 °C for 3 days and 70 °C for 7 hours. These parameters defined the experimental treatments, together with a commercial infusion used as control, and were coded as commercial control, Tto 1 (solar dryer), Tto 2 (dehydrator at 35 °C for 3 days) and Tto 3 (dehydrator at 70 °C for 7 hours). The dried peel from each treatment was milled in a laboratory grinder until a homogeneous particle size suitable for filter infusion bags was obtained. Portions of 3 g of ground peel were weighed and packed in heat sealed filter bags. Twenty bags were prepared for each treatment and stored in airtight containers at room temperature until use.

2.3 Hedonic test

Sensory acceptability of the infusions was evaluated through a hedonic test. Thirty untrained panellists, regular consumers of herbal infusions, participated on a voluntary basis. The test was carried out in a sensory analysis room under white lighting and at ambient temperature, using individual booths to minimise communication among panellists. Each participant received a coded glass containing approximately 30 ml of infusion prepared from each treatment. Infusions were obtained by steeping one filter bag in 150 ml of potable water at 70 °C for 3 minutes and serving the beverage warm. The order of presentation of the samples followed a random balanced sequence to control order effects.

Panellists evaluated colour, aroma, flavour, aftertaste and overall acceptance using a five-point hedonic scale, where 1 indicated very unpleasant, 2 unpleasant, 3 neutral, 4 pleasant and 5 very pleasant. Water was provided for rinsing the mouth between samples. Each panelist by treatment combination was considered an experimental unit, resulting in 30 sensory observations per treatment for each attribute.

The use of a five point hedonic scale is widely accepted in consumer sensory evaluation of herbal teas and related beverages, and has been applied in studies on tisanes, herbal tea powders and functional herbal products with panels of 25 to 30 or more assessors, where scores from 1 to 5 reflect progressive levels of dislike and liking [9]. This type of structured scale is considered appropriate for screening formulations and determining consumer acceptance when the aim is to compare overall liking and specific attributes such as colour, aroma and flavour under controlled testing conditions [23].

2.4 Experimental design

The study followed a completely randomised design with four infusion treatments, corresponding to the commercial control and the three drying regimes applied to the coffee peel. For sensory analysis, the design considered one factor with four levels and 30 replications per treatment. For physicochemical and microbiological analyses, each treatment was prepared independently and all determinations were carried out in triplicate, so the unit experimental for these variables was one analytical sample of infusion or dehydrated peel.

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2.5 Physicochemical analysis

All physicochemical analyses were conducted on infusions prepared under the same conditions as for the sensory test, using additional bags from each treatment. Results are presented as mean ± standard deviation of three independent determinations.

2.6 Phenolic compounds

Total phenolic content was determined using the Folin Ciocalteu method described by Quiceno Cano et al. (2021), with minor adaptations. A volume of 100 µl of the infusion was mixed with 7 ml of distilled water and 500 µl of Folin Ciocalteu reagent. The mixture was kept in the dark at room temperature for 5 minutes. Then 1200 µl of 0.25 M NaOH were added, the solution was mixed and left to react for 2 hours at room temperature. Absorbance was measured at 765 nm in a bench top UV VIS spectrophotometer equipped with 1 cm path length quartz cuvettes. A calibration curve was constructed with gallic acid standards and results were expressed as mg gallic acid equivalents per 100 g of dried coffee peel.

2.7 Antioxidant capacity

Antioxidant capacity was determined by measuring the scavenging activity of the DPPH free radical (2,2 diphenyl 1 picrylhydrazyl), following the procedure of Franco Agurto & Suárez Quirumbay (2014) with modifications. A stock extract of coffee peel was prepared and serial dilutions were obtained to give a concentration range between 0.29 and 1.54 mg per ml. For the DPPH solution at 60 µM, a 10 mM stock solution was prepared by dissolving 0.00394 g of DPPH in methanol and adjusting the volume to 10 ml. A volume of 60 µl of the DPPH stock was then diluted with methanol to obtain the working solution.

Aliquots of the sample dilutions were mixed with the DPPH working solution and incubated in the dark for 30 minutes at room temperature. Absorbance was measured at 515 nm using the UV VIS spectrophotometer. The percentage of radical inhibition was calculated using Equation 1:

$$I\% = 100 \times \left(1 - \frac{A\ sample}{A\ control}\right) \quad (1)$$

Where I% is the inhibition percentage, A control is the absorbance of the DPPH solution without sample and A sample is the absorbance of the mixture of DPPH solution and sample at 515 nm. The concentration of each dilution was plotted against its inhibition percentage. A linear trend was fitted using the equation Y = A + BX, where Y is inhibition percentage and X is concentration. The IC50 value, defined as the concentration required to inhibit 50 % of the initial DPPH absorbance, was obtained from this relationship (Equation 2).

$$IC50 = \frac{\left(\left(\frac{\%\ inhibition}{2}\right) - intercept\right)}{slope} \quad (2)$$

2.8 Anthocyanins

Monomeric anthocyanin content was determined using the pH differential method, as described by Giusti & Wrolstad (2001) and adapted for coffee peel extracts by Ruíz Ulric (2021). Two buffer systems were prepared, one at pH 1.0 using potassium chloride and the other at pH 4.5 using sodium acetate. Appropriate volumes of infusion were diluted separately in each buffer. Absorbance was measured at 520 nm and 700 nm for both pH values. The difference in absorbance was calculated according to the pH differential method and anthocyanin content was expressed as mg cyanidin 3 glucoside equivalents per 100 g of dried peel, using the corresponding molar absorptivity and molecular weight.

2.9 pH

The pH of the infusions was determined with a bench top pH meter fitted with a glass electrode, following Cunha et al. (2016). Because of the intense colour of the samples, a dilution of 1 in 100 with distilled water was prepared prior to measurement. The electrode was calibrated with standard buffer solutions at pH 4.0 and 7.0 before each set of readings. Three measurements were performed for each treatment and the mean value was reported.

2.10 Acidity

Titratable acidity was measured to estimate the total acidity of the infusions, according to Cunha et al. (2016). An aliquot of the infusion was diluted with distilled water and titrated with 0.1 N NaOH to an endpoint of pH 8.2, monitored with the pH meter. The percentage of acidity was calculated with Equation 3.

$$\%AC = \frac{ml(NaOH)x\ N(NaOH)x\ correction\ factor\ x\ (250ml)x\ \mu e\ x\ 100\ \%}{sample\ mass\ (g)} \quad (3)$$

Where % AC is the acidity percentage, ml NaOH is the volume of sodium hydroxide used in the titration, N NaOH is the normality of the NaOH solution, the correction factor corresponds to the standardisation of the 0.1 N NaOH solution and the sample mass is the mass of infusion taken for the assay, expressed in grams. Finally, µe is equivalent to the milliequivalent of acid in the sample.

2.11 Instrumental colour

Instrumental colour was measured on infusions prepared from each treatment. The samples were poured into colourless glass cells and colour readings were taken with a tristimulus colorimeter operating in the CIE Lab* system, using D65 illumination and a 10° standard observer, following Restrepo et al. (2023). The parameters recorded were L* for lightness, a* for the red green axis and b* for the yellow blue axis, where positive a* denotes red, negative a* denotes green, positive b* denotes yellow and negative b* denotes blue. Three measurements were taken per treatment and the mean values were reported.

1.12 Microbiological analysis

Microbiological quality was assessed in line with the Peruvian Technical Standard for herbal infusions (R.S.M. N° 615

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2003 SA DM) and the procedure described by Morales & Luis (2014). To determine mould and Enterobacteriaceae counts in the dehydrated coffee peel and in the infusions, 10 g of dried peel were weighed aseptically and placed in a sterile container with 90 ml of sterile distilled water. The mixture was homogenised to obtain the initial dilution. From this suspension, a series of decimal dilutions was prepared. Appropriate dilutions were surface plated on potato dextrose agar for moulds and on selective medium for Enterobacteriaceae. Plates were incubated at 25 °C for 5 days for moulds and at 37 °C for 24 hours for Enterobacteriaceae. Colonies were counted and results were expressed as colony forming units per millilitre (CFU/ml) for the infusions or per gram of dried peel. All microbiological determinations were performed in triplicate.

2.13 Statistical analysis

All data were subjected to one way analysis of variance to evaluate the effect of treatments on sensory, physicochemical and microbiological variables. When the F test indicated significant differences, Tukey's multiple comparison test with $p < 0.05$ was applied to compare means. Simple linear regression was used to determine relationships between physicochemical parameters and between these parameters and colour coordinates. The assumptions of normality and homogeneity of variances of residuals were checked before applying the parametric tests. Statistical analyses were carried out using R software, version 4.3.2.

3. Results

3.1 Sensory analysis

Table 1 shows that Tto3 reached the highest acceptability scores for aroma and flavour, with means of 4.4 for both attributes. The control recorded 4.3 for aroma and 4.3 for flavour. Tto1 and Tto2 scored lower, with 3.9 and 4.0 respectively. The statistical analysis indicated significant differences among treatments for aroma and flavour, with $p < 0.001$. The multiple comparison letters confirm that Tto3 and the control formed the upper group, while Tto1 and Tto2 formed a group with lower preference.

For colour, Tto3 also ranked first with 4.4, followed by the control with 4.3, and Tto1 and Tto2 with 4.0. The statistical contrast was significant for colour, with $p < 0.001$. This pattern supports that drying at 70 °C for 7 hours generated a chromatic appearance that was highly valued by the panel, compared with the other dehydration regimes and the commercial product.

Overall appearance did not differ among treatments. Means ranged between 4.2 and 4.3, all sharing the same letter in the multiple comparison and without statistical significance. This suggests that, regardless of drying regime, the infusions maintained a stable and acceptable presentation for the panel. In general, scores equal to or higher than 4 indicate a positive sensory response. Tto3 consistently stood out in the attributes that showed differences, and therefore emerges as the treatment with the greatest potential for sensory acceptance within the evaluated set, as shown in Table 1.

Table 1. Statistical analysis of sensory attributes in infusions prepared from coffee fruit peel under different drying treatments.

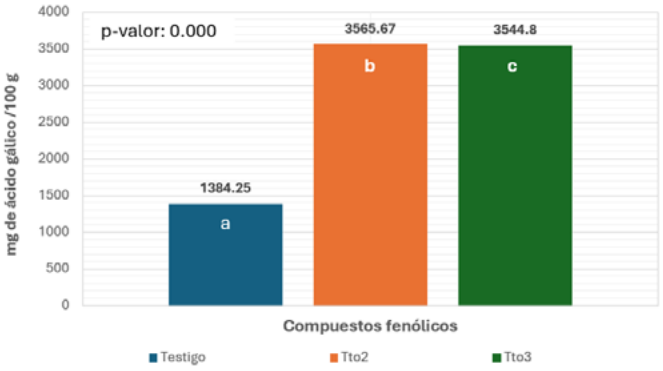
Treatment	Aroma	Flavour	Appearance	Colour
Control	4.3 ± 0.06^{a}	4.3 ± 0.08^{a}	4.3 ± 0.02^{a}	4.3 ± 0.5^{a}
Tto1	3.9 ± 0.02^{b}	3.9 ± 0.07^{b}	4.2 ± 0.01^{a}	4.0 ± 0.4^{b}
Tto2	4.0 ± 0.05^{b}	4.0 ± 0.06^{b}	4.2 ± 0.01^{a}	4.0 ± 0.6^{b}
Tto3	4.4 ± 0.02^{a}	4.4 ± 0.08^{a}	4.3 ± 0.03^{a}	4.4 ± 0.4^{a}
p value	0.000	0.000	4.84	0.000
Sig.	**	**	N.S.	**

Source: Authors.
Note: Values are expressed as mean ± standard deviation. Sig.: statistical significance; N.S.: not significant; **: significant difference at $p < 0.01$.

3.2 Phenolic compounds

Figure 1 presents the statistical analysis of phenolic compound content. The p value obtained (0.000) was lower than 0.05, which shows that the dehydration process applied in the treatments affected the phenolic content of the coffee peel. Tukey's test also showed clear significant differences among treatments. Tto2 recorded the highest value with 3565.67 mg GAE per 100 g of dry matter, while the control had the lowest value with 1384.25 mg GAE per 100 g of dry matter. This behaviour is consistent with the non controlled temperature in the solar dryer, below 30 °C, which may activate enzymes that degrade phenolic compounds. In contrast, the higher temperature applied in Tto3 may favour thermal oxidation. The stability of phenolic compounds is usually reported between 30 °C and 60 °C.

Figure 1. Statistical analysis of physicochemical properties (phenolic compounds).



Source: Authors.

The correlation between phenolic compounds and colour parameters showed strong associations. For L* there was a strong positive correlation, $r = 0.94$, $p = 0.0002$ and $R^2 = 88.35$ %. For a* the relationship was negative and of moderate magnitude, $r = -0.74$, $p = 0.024$ and $R^2 = 54.17$ %. For b* the association was almost perfectly negative, $r = -0.99$, $p < 0.001$ and $R^2 = 99.9$ %. Together, these results show that increases in phenolic content were associated with higher lightness and with decreases in a* and b* values in the infusion. This suggests that phenolic

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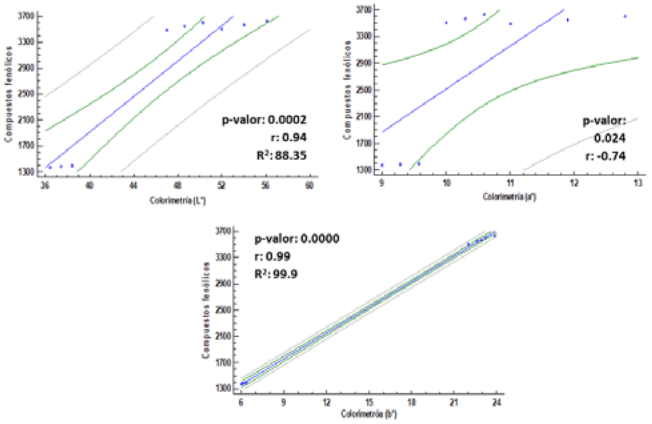
concentration is linked to a less saturated red and yellow colour profile, which is consistent with the instrumental characterisation described in the colourimetry section and with the influence of thermal treatment on infusion colour, as shown in Figure 2.

Figure 2. Correlation of physicochemical properties (phenolic compounds) with colour parameters: (a) L*, (b) a* and (c) b*.

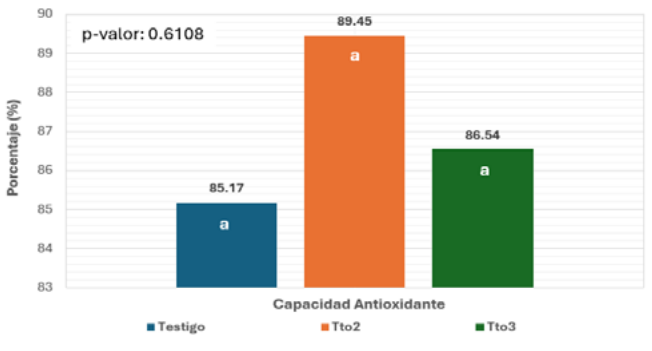


Source: Authors.

3.3 Antioxidant capacity

Figure 3 shows the statistical analysis for antioxidant capacity in the infusions by treatment. The p value obtained (0.6108) was higher than 0.05, which indicates that the dehydration process did not have a significant effect on this parameter. Tukey's test at 0.05 confirmed that there were no significant differences among treatments, indicating statistical similarity. Even so, Tto2 reached the highest value with 89.45 %, while the control showed the lowest value with 85.17 %. This suggests that the drying temperature of 35 °C in Tto2 helped to preserve antioxidant capacity and highlights the thermal sensitivity of the compounds present in coffee peel. In spite of the absence of significant differences, the results support the potential of Tto2 to provide radical scavenging activity in the infusion.

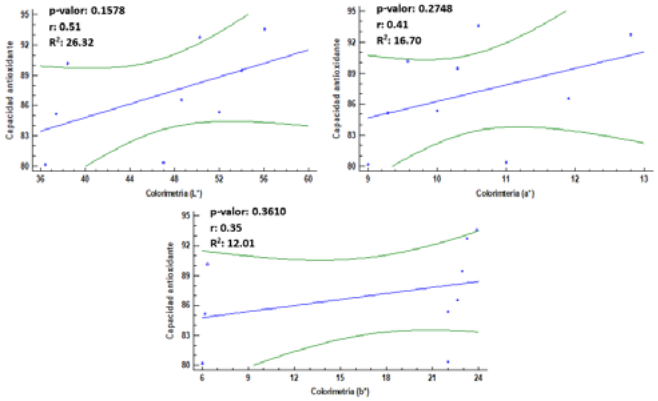
Figure 3. Statistical analysis of physicochemical properties (antioxidant capacity).



Source: Authors.

The correlation analysis in Figure 4 between antioxidant capacity and colour parameters showed no significant relationships. The p values for L*, a* and b* were 0.1578, 0.2748 and 0.3610 respectively, all higher than 0.05. The correlation coefficients were low, r = 0.51 for L*, r = 0.41 for a* and r = 0.35 for b*. These results indicate that variation in antioxidant activity did not influence lightness or a* and b* values. This reflects that, although the infusions may display high antioxidant capacity, this property would mainly protect pigments from oxidation without having a direct effect on infusion colour.

Figure 4. Correlation of physicochemical properties (antioxidant capacity) with colour parameters: (a) L*, (b) a* and (c) b*.

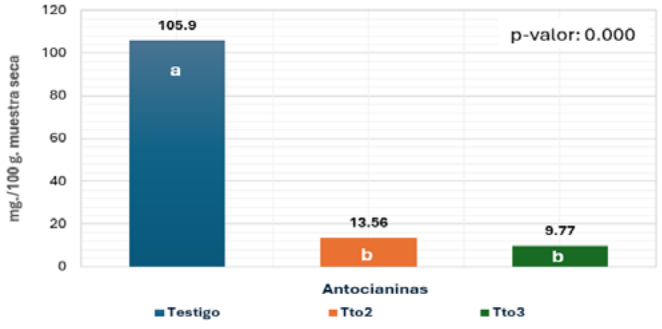


Source: Authors.

3.4 Anthocyanins

Figure 5 presents the statistical analysis of anthocyanin content. The p value obtained (0.000) was lower than 0.05, which shows that the drying temperatures and times applied in the treatments affected the anthocyanin content of the infusions. Tukey's test indicated that the control recorded the highest value, 105.9 mg / 100 g of dry sample, whereas Tto2 and Tto3 showed much lower contents, 13.56 and 9.77 mg / 100 g of dry sample respectively, and were statistically similar. These results show that the control product has a higher pigment load and that, among the experimental treatments, the dehydration parameters did not generate increases in anthocyanin content.

Figure 5. Statistical analysis of physicochemical properties (anthocyanins).



Source: Authors.

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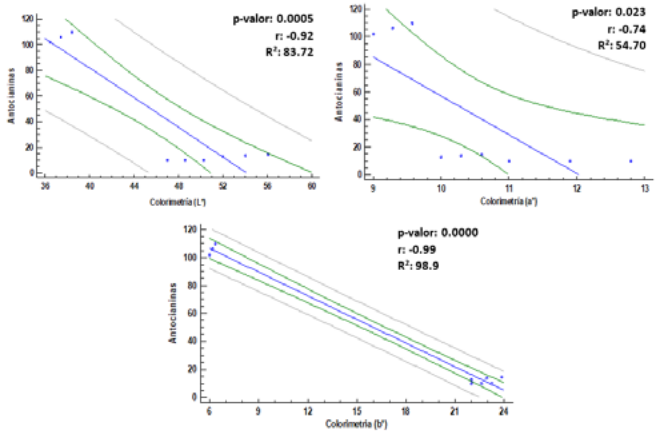
The correlations between anthocyanin content and colour parameters L*, a* and b* in the infusions by treatment showed strong relationships. The p values were 0.0005 for L*, 0.023 for a* and 0.000 for b*, all lower than 0.05. The correlation coefficients were r = −0.92 for L*, r = −0.74 for a* and r = −0.99 for b*, indicating strong negative associations. These results show that increases in anthocyanin content reduced lightness and shifted infusion colour towards greenish blue tones, which supports a darker and less saturated chromatic profile, as illustrated in Figure 6.

Figure 6. Correlation of physicochemical properties (antioxidant capacity) with colour parameters: (a) L*, (b) a* and (c) b*.



Source: Authors.

3.5 pH and acidity

pH differed among treatments. Tto3 recorded 4.80 ± 0.01 and Tto2 4.48 ± 0.01, both clearly distinct from the control with 2.99 ± 0.01. Titratable acidity showed the highest value in Tto3 with 5.66 ± 0.01, followed by Tto2 with 2.62 ± 0.01 and the control with 0.37 ± 0.01. Multiple comparisons confirmed differences for both pH and acidity, with $p < 0.001$ in both cases. The pattern indicates that the evaluated dehydration regimes markedly modified total acidity and pH of the infusion, as shown in Table 2.

Table 2. Statistical analysis of pH and acidity values.

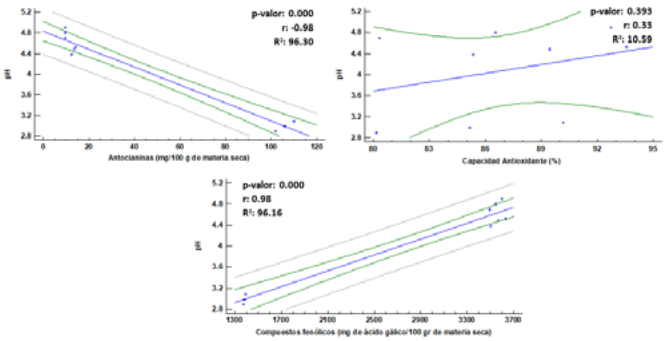
Treatment	pH	Acidity
Control	2.99 ± 0.01^a	0.37 ± 0.01^a
Tto2	4.48 ± 0.01^b	2.62 ± 0.01^b
Tto3	4.80 ± 0.01^b	5.66 ± 0.01^c
p value	0.000	0.000
Sig.	**	**

Source: Authors.
Note: Values are expressed as mean ± standard deviation. Sig.: statistical significance; **: significant difference at $p < 0.01$.

The relationships between pH and physicochemical parameters showed contrasting patterns, as presented in Figure 7. For anthocyanins there was a very high negative correlation, r = −0.98, p = 0.000 and R^2 = 96.30 %. For antioxidant capacity there was no statistical association, r = 0.33, p = 0.393 and R^2 = 10.59 %. For phenolic compounds there was a very high positive correlation, r = 0.98, p = 0.000 and R^2 = 96.16 %. Overall, higher pH values were associated with lower anthocyanin content and higher phenolic concentration, without a clear relationship with antioxidant activity.

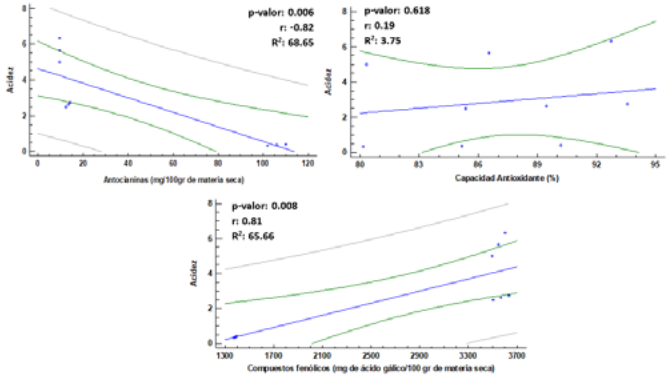
Titratable acidity showed a positive association with phenolic compounds, r = 0.81, p = 0.008 and R^2 = 65.66 %. It showed a negative association with anthocyanins, r = −0.82, p = 0.006 and R^2 = 68.65 %. No relationship was observed with antioxidant capacity, r = 0.19, p = 0.618 and R^2 = 3.75 %. In general, higher acidity levels were linked to increases in phenolic content and decreases in anthocyanin content, while antioxidant activity did not vary in line with acidity within the evaluated range, as shown in Figure 8.

Figure 7. Correlation of pH with physicochemical parameters: (a) anthocyanins (mg per 100 g dry matter), (b) antioxidant capacity (%) and (c) phenolic compounds (mg gallic acid per 100 g dry matter.



Source: Authors.

Figure 8. Correlation of acidity with physicochemical parameters: (a) anthocyanins (mg per 100 g dry matter), (b) antioxidant capacity (%) and (c) phenolic compounds (mg gallic acid per 100 g dry matter).



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3.6 Colourimetry

All three colour parameters differed among treatments. For L*, Tto2 had the highest value with 54.02 ± 0.5, followed by Tto3 with 48.63 ± 0.2 and the control with 37.45 ± 0.1. Multiple comparison letters show that the three means were different, with p = 0.000. For a*, Tto3 recorded 11.9 ± 0.06, Tto2 10.3 ± 0.04 and the control 9.29 ± 0.05, with significant differences, p = 0.001. For b*, Tto3 reached 26.62 ± 0.2, Tto2 22.93 ± 0.3 and the control 6.17 ± 0.4, with p = 0.000.

This pattern indicates that Tto2 produced the brightest infusion, while Tto3 increased saturation on the red and yellow axes. The control showed the lowest lightness and the lowest a* and b* values. These results agree with the previous correlations, in which higher phenolic contents were associated with higher L* and lower a* and b* values, as seen when comparing Tto2 and Tto3 in Table 3.

Table 3. Statistical analysis of experimental colour.

Treatment	L*	a*	b*	Representation
Control	37.45 ± 0.1^{a}	9.29 ± 0.05^{a}	6.17 ± 0.4^{a}	
Tto2	54.02 ± 0.5^{c}	10.3 ± 0.04^{b}	22.93 ± 0.3^{b}	
Tto3	48.63 ± 0.2^{b}	11.9 ± 0.06^{c}	26.62 ± 0.2^{c}	
p value	0.000	0.001	0.000	
Sig.	**	**	**	

Source: Authors.
Note: Values are expressed as mean ± standard deviation. Sig.: statistical significance; **: significant difference at p < 0.01.

3.7 Microbiological analysis

Enterobacteriaceae were not detected in any treatment, with mean counts of 0 CFU/ml in Tto1, Tto2 and Tto3. This indicates adequate hygienic control during processing and handling of the raw material and the infusion. For mould counts, mean values were 2.67 × 10^2 CFU/ml in Tto1, 4.76 × 10^2 CFU/ml in Tto2 and 1.00 × 10^2 CFU/ml in Tto3. All values were lower than the maximum limit M of the Peruvian Technical Standard NTP, set at 10^3 CFU/ml, and Tto3 matched the threshold m of 10^2 CFU/ml. Tto3 was therefore the treatment with the lowest fungal load, while Tto2 showed the highest value, although still within specification. Overall, the three treatments met the microbiological criteria required for infusions, as shown in Table 4.

Table 4. Counts of Enterobacteriaceae and moulds (CFU/ml) in the treatments under study.

Treatment	Mean CFU/ml Enterobacteriaceae	Mean CFU/ml moulds	N.T.P (R.S.M. N° 615-2003-SA/DM)	
			m	M
Tto1	0	2.67 x 10^2	10^2	10^3
Tto2	0	4.76 x 10^2		
Tto3	0	1.00 x 10^2		

Source: Authors.
Note: CFU: colony forming units; UFC: unidades formadoras de colonia; NTP: Peruvian Technical Standard; m: acceptable microbiological value; M: maximum permitted microbiological value.

4. Discussion

Sensory acceptability favoured drying at 70 °C for 7 hours, with higher scores for aroma and flavour as shown in Table 1. This behaviour indicates that the temperature increase intensified the release of pleasant volatile compounds derived from Maillard reactions and early caramelisation, such as aldehydes and furanones, also reported in infusions of Coffea arabica [31], [32]. However, the absence of differences in overall appearance suggests that the process did not alter the visual stability of the product, which is relevant for commercial presentation [2]. This finding is consistent with previous sensory evaluations of coffee and tea by-products, where olfactory and gustatory perception determines final preference more strongly than surface colour [7].

The behaviour of phenolic compounds showed an opposite trend. Drying at 35 °C for 3 days maximised total phenolic content, in line with studies reporting better preservation of thermosensitive metabolites under mild drying conditions [8], [11]. Figure 1 supports this response, and its relationship with colourimetry (Figure 2) reinforces the idea that phenolics directly influence extract clarity [33]. The decrease in a* and b* in treatments with higher phenolic load indicates lower chromatic saturation, which can be attributed to controlled oxidation of these compounds, a phenomenon described in coffee matrices rich in chlorogenic acids and flavonoids [17].

Antioxidant capacity followed the same pattern of thermal protection, with slight but meaningful differences among treatments. Drying at 35 °C for 3 days maintained higher radical scavenging activity, consistent with reports linking antioxidant stability to the preservation of phenolic acids and flavones [11]. Figure 3 confirms this ranking, and Figure 4 shows that colour parameters do not explain variation in antioxidant capacity, indicating that redox potential depends more on molecular integrity than on visual appearance [34]. This functional independence between colour and antioxidant activity adds value for the design of functional beverages [35].

Anthocyanins contributed to defining colour shades and the balance between functionality and preference [36]. The control showed the highest pigment content, reflecting the use of industrial matrices with additional copigments [37]. Among the treatments, drying at 35 °C for 3 days preserved pigments more effectively, in agreement with studies reporting losses greater than 40 percent in anthocyanins at temperatures above 60 °C [38], [39]. Figure 6 shows negative correlations between pigments and L*, a* and b*, confirming that higher anthocyanin content darkens the product and reduces saturation along the red and yellow axes [3], [40]. This visual effect may influence perceived freshness, although it favours antioxidant stability and the natural identity of the infusion [41].

pH and titratable acidity, presented in Table 2, were sensitive to thermal conditions. Higher pH was associated with lower anthocyanin concentration and higher phenolic content, while

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acidity correlated positively with phenolics and negatively with pigments [9]. This physicochemical balance, illustrated in Figures 7 and 8, determines the taste profile and colloidal stability of the product [42]. Recent studies on coffee husk and Camellia sinensis infusions indicate that maintaining pH between 4.2 and 4.6 improves sensory perception and limits non-enzymatic browning, which is consistent with the range observed in the best performing treatments [43], [44], [45].

Table 3 confirms that Tto2 showed the highest lightness (L*), while Tto3 had the greatest saturation in a* and b*, allowing colour control to be used as a lot-release tool [3], [40]. In plant-based beverages, instrumental colour is used as a predictor of stability and uniformity, so defining target bands for L*, a* and b* is a practical strategy to balance appearance and bioactive content [46], [47]. In this case, intermediate a* and b* values with moderate L* reflect a more natural and stable product, consistent with the sensory preferences observed [3], [48].

In Table 4, microbial counts show that all treatments comply with regulatory limits. Tto3 had the lowest fungal load, confirming that the applied time and temperature were sufficient to ensure safety without compromising chemical quality [49]. This agrees with reports on drying of agro-industrial residues, where temperatures above 65 °C achieve microbial reductions greater than 90 percent, consolidating their role as a critical stabilisation step [11], [49], [50].

Taken together, the findings reveal a trade-off between sensory and bioactive attributes. Tto3 provided the best acceptance and microbiological stability, whereas Tto2 optimised phenolic content, pigments and antioxidant capacity [2]. This balance supports the possibility of a stepwise drying strategy, with a primary low-temperature stage to preserve thermosensitive compounds and a short final high-temperature stage to ensure safety [32]. The evidence shown in Figures 2, 6, 7 and 8 supports this approach as a replicable technical alternative for the valorisation of coffee by-products [31].

In terms of scaling up, it is recommended to standardise peel particle size, airflow and drying time, and to implement instrumental colour monitoring as an in-line control parameter [23], [50]. In addition, consumer acceptance tests and storage stability analyses would allow the product's performance to be validated under commercial conditions [7].

At scientific level, this research provides evidence on the interaction among thermal, colourimetric and biochemical variables in plant matrices rich in polyphenols, contributing to the understanding of degradation and preservation mechanisms during processing [12]. The inverse correlation between L* and phenolic content observed here suggests a darkening pathway associated with phenol oxidation, a phenomenon that has been little described in coffee by-products [46], [47]. Recognising these relationships may inform the design of drying and formulation strategies for functional beverages with improved stability and sensory value, which will still require validation at pilot and industrial scales [51], [52].

Finally, this study has some limitations that should be considered when interpreting the results, particularly the moderate size of the sensory panel, the use of coffee peel from a single origin and the laboratory scale of the drying trials under one set of processing conditions. Future studies should increase sample size, include volatile compound profiling and assess the influence of peel varietal origin on chemical and sensory profiles [53], [54]. These lines of research will strengthen model reproducibility and consolidate the integral use of the coffee fruit as a source of healthy and sustainable products.

5. Conclusions

Coffee fruit peel proved to be a technically viable raw material for the preparation of infusions that achieve consumer acceptance comparable to that of a commercial reference, while complying with the microbiological criteria established in the Peruvian technical standard for herbal infusions. This outcome is supported by the combination of hedonic scores in the positive range of the scale and microbial counts below the regulatory limits in all evaluated treatments.

The comparison of drying regimes showed that a moderate convective temperature preserved phenolic compounds, pigments and antioxidant capacity more effectively, whereas a higher temperature regime improved sensory perception of aroma and flavour and reduced fungal load. These patterns, evidenced by the joint analysis of phenolic content, anthocyanins, radical scavenging activity, colour coordinates and microbiological indicators, clarify the functional and sensory trade off associated with the thermal processing of coffee peel.

The correlations observed between phenolic compounds, anthocyanins, pH, titratable acidity and instrumental colour indicate that coffee peel infusions constitute a model system for studying the links between composition, colour development and stability in plant based beverages. This integrative approach contributes new information on how drying conditions modulate both the visual and functional attributes of infusions obtained from coffee processing residues.

Overall, the study provides experimental support for the valorisation of coffee fruit peel as an ingredient for the formulation of sustainable infusions, using controlled drying schemes that combine sensory quality, preservation of bioactive compounds and microbiological safety as guiding criteria for process design.

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