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ENRIQUECIMENTO FENÓLICO DE CERVEJA ARTESANAL AMERICAN PALE ALE COM EXTRATO DE CASCA DE *COFFEA ARABICA* POR INFUSÃO A FRIO

PHENOLIC ENRICHMENT OF AMERICAN PALE ALE CRAFT BEER WITH *COFFEA ARABICA* HUSK EXTRACT VIA COLD INFUSION

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RESUMO

O presente estudo teve como objetivo desenvolver uma cerveja artesanal no estilo *American Pale Ale* (APA) utilizando cascas de café arábica (*Coffea arabica* L. var. *typica*) como fonte de compostos fenólicos por meio da técnica de infusão a frio. A proposta visa promover a sustentabilidade e a inovação no setor de bebidas, aproveitando subprodutos agroindustriais do café como fonte de compostos bioativos. Foram preparadas três formulações: uma amostra controle (C_T), sem adição de extrato, e duas amostras experimentais (C_1 e C_2), suplementadas com 10 mL e 20 mL de extrato de casca de café por garrafa de 600 mL (aproximadamente 1,7% e 3,3% v/v, respectivamente). O extrato foi obtido por infusão de 450 g de cascas em 1000 mL de água mineral sob agitação a 200 rpm por 24 horas, seguida de filtração e uma etapa de tratamento com luz UV por 10 minutos, e foi adicionado no envase, após a fermentação e a maturação. As análises físico-químicas incluíram pH, acidez titulável (%), sólidos solúveis (°Brix), compostos fenólicos totais (método de Folin–Ciocalteu, mg EAG/L) e extrato real (% m/m), todas realizadas em triplicata. Os resultados não mostraram diferenças significativas no pH (4,34 a 4,37), na acidez (0,30–0,32%) e nos sólidos solúveis (4,34–4,40 °Brix). O teor de compostos fenólicos totais foi superior nas amostras com extrato (C_1: 20,11 mg EAG/L; C_2: 18,16 mg EAG/L; sem diferença significativa entre si) em comparação à amostra controle (10,70 mg EAG/L), o que corresponde a aumentos de aproximadamente 88% e 70%. Conclui-se que o extrato de casca de café é um ingrediente promissor para aumentar o teor de compostos fenólicos totais de cervejas artesanais sem alterar os parâmetros físico-químicos avaliados; a atividade antioxidante, a aceitação sensorial, a segurança microbiológica e a estabilidade ainda precisam ser avaliadas.

Palavras-chave: Cerveja artesanal. Compostos fenólicos. Infusão a frio. Resíduos agroindustriais. Sustentabilidade.

ABSTRACT

The present study aimed to develop a craft beer in the *American Pale Ale* (APA) style using Arabica coffee husks (*Coffea arabica* L. var. *typica*) as a source of phenolic compounds through the cold infusion technique. This approach aims to promote sustainability and innovation in the beverage sector by valorizing coffee agro-industrial by-products as sources of bioactive compounds. Three formulations were prepared: a control sample (C_T), with no extract addition, and two experimental samples (C_1 and C_2), supplemented with 10 mL and 20 mL of coffee husk extract per 600 mL bottle (approximately 1.7% and 3.3% v/v, respectively). The extract was obtained by infusing 450 g of peels in 1000 mL of mineral water under agitation at 200 rpm for 24 hours, followed by filtration and a UV treatment step for 10 minutes, and was added at bottling, after fermentation and maturation. Physicochemical analyses included pH, titratable acidity (%), soluble solids (°Brix), total phenolic compounds (Folin–Ciocalteu method, mg GAE/L), and real extract (% w/w), all performed in triplicate. The results showed no significant differences in pH (4.34 to 4.37), acidity (0.30–0.32%), and soluble solids (4.34–4.40 °Brix). The concentration of total phenolic compounds was higher in the samples containing extract (C_1: 20.11 mg GAE/L; C_2: 18.16 mg GAE/L; not significantly different from each other) compared with the control sample (10.70 mg GAE/L), corresponding to increases of approximately 88% and 70%. These findings indicate that coffee husk extract is a promising ingredient for increasing the total phenolic content of craft beers without altering the evaluated physicochemical parameters; antioxidant activity, sensory acceptance, microbiological safety and stability still need to be evaluated.

Keywords: Agro-industrial residues. Cold infusion. Craft beer. Phenolic compounds. Sustainability.

INTRODUCTION

Brazil is one of the world's largest coffee producers, particularly with respect to the cultivation of Arabica varieties. Alongside this substantial production, large volumes of agro-industrial residues are generated, especially coffee husks, which are generally discarded without economic or functional utilization. However, recent studies have shown that this material has a composition rich in bioactive compounds, such as polyphenols, caffeine, chlorogenic acids, and fermentable sugars (Esquivel; Jiménez, 2012; Cangussu *et al*., 2021), making it promising for application in various sectors of the food and beverage industry. In this context, strategies combining technological innovation and sustainability, while making use of resources available within the production chain, are increasingly needed. The production of fermented beverages with the addition of natural extracts or unconventional ingredients is one of the most viable alternatives in this context. In particular, craft beer has emerged as a promising matrix for the incorporation of new formulation proposals, both because of its commercial appeal and because of the versatility of its styles and production methods.

Coffee processing can be carried out by two distinct methods: dry processing and wet processing. In the dry method, the main by-product generated is the husk, which comprises the dried pulp and the parchment, including both the husk itself and the mucilage. In wet processing, by-products are obtained in separate stages: initially, wet pulp is produced, which includes the husk, and subsequently dry parchment, still containing mucilage (Esquivel; Jiménez, 2012; Klingel *et al*., 2020).

Coffee husk is considered the main by-product of dry processing and may represent up to twice the mass of the processed bean. Its use is still limited, being commonly applied as organic fertilizer, substrate for seedlings, raw material for biogas production or in fermentative processes (Freitas, 2016; Silva *et al*., 2020; Skumar; Ts; Abdulhameed, 2018). Its use in animal feed may be restricted by the presence of caffeine, tannins and polyphenols, which at high concentrations exert antinutritional effects (Faustino *et al*., 2020).

The composition of coffee husk is similar to that of the bean itself, containing various organic and inorganic materials as well as important bioactive compounds, such as chlorogenic acid. Its chemical composition includes 8–11% proteins, 0.5–3% lipids, 3–7% ash, 1–5% caffeine and tannins, and a high concentration of carbohydrates (58–85%), already considering

the fiber content (Esquivel; Jiménez, 2012; Cangussu *et al*., 2021). These wide ranges reflect the variability of the raw material, whose composition depends on species and cultivar, fruit maturity, type of processing (dry, semi-dry or wet), drying and storage conditions, and on treatments such as fermentation, which can alter the phenolic content of the husk (Palomino García; Del Bianchi, 2015b; Cangussu *et al*., 2021). Consequently, extracts obtained from different batches of husk may differ considerably in phenolic content, which makes it necessary to describe the origin and pre-treatment of the material in detail.

From a food safety perspective, the use of coffee husk in products for human consumption requires attention to its caffeine content and to possible contamination by filamentous fungi and mycotoxins, especially ochratoxin A, which may occur during drying and storage, as well as to pesticide residues (Klingel *et al*., 2020). In the European Union, coffee cherry husk and pulp have been evaluated within the novel food framework, which shows that their use in foods depends on compliance with specific safety criteria (Klingel *et al*., 2020). In Brazil, the use of coffee by-products, such as husks and pulp, in food and beverages is regulated by the Ministry of Agriculture and Livestock (MAPA) and the National Health Surveillance Agency (ANVISA). MAPA Normative Instruction No. 65/2019 allows the incorporation of optional ingredients of plant origin in beer formulations (Brasil, 2019). Regarding the food safety of novel ingredients, ANVISA establishes criteria for the safety assessment and authorization of novel foods and ingredients (Anvisa, 1999, 2023), as well as maximum tolerated limits for contaminants such as ochratoxin A (Anvisa, 2022), requiring attention from the productive sector regarding caffeine levels and toxicological safety.

The use of plant residues as ingredients in food and beverage formulations has been widely discussed in the literature as a strategy for sustainability and innovation. Arabica coffee husk is a by-product rich in phenolic compounds, antioxidants, and sugars, and has been studied as a promising source of natural ingredients (Amaral, 2021; De França Andrade *et al*., 2023). The most established application is cascara, an infusion of the dried coffee cherry husk and pulp that contains caffeine, chlorogenic acids and other phenolic compounds (Heeger *et al*., 2017). In fermented beverages, applications are more recent: Chacón-Figueroa *et al.* (2022) optimized the addition of coffee bagasse extracts to craft beers and reported higher antioxidant capacity, whereas De Francesco *et al.* (2020) showed that phenolic-rich extracts added to beer can influence its flavour stability, with effects that depend on the type and dose of extract. Freitas (2016) also demonstrated the potential of coffee husk as a substrate in fermentative processes. However, these studies used different raw materials, extraction methods and beverage matrices,

so their results cannot be directly extrapolated to coffee husk extracts obtained by cold infusion and added to finished beer.

The cold infusion technique allows the extraction of water-soluble compounds, such as polyphenols, caffeine, and aromatic compounds, without the application of heat. It is a solid–liquid extraction in which the transfer of solutes depends mainly on the diffusion of water into the plant matrix and of the solubilized compounds into the liquid. As in cold brew coffee, the extraction yield is governed by contact time, temperature, particle size, solid-to-liquid ratio, agitation and water composition (Silva; Veríssimo; Arruda, 2021). The low temperature reduces the extraction rate, which is compensated by longer contact times, but avoids the thermal degradation of heat-sensitive compounds (Sá *et al*., 2024). Other techniques, such as ultrasound-assisted extraction, increase the recovery of bioactive compounds from Arabica coffee husk (De França Andrade *et al*., 2023), showing that the extraction method determines the composition of the extract. In addition, as cold infusion does not include a thermal step, the microbiological quality of the extract must be considered when it is added to a finished product.

According to Brazilian legislation, beer is defined as an alcoholic beverage obtained through the fermentation by brewer's yeast of wort derived from malted barley or malt extract in potable water. Its composition may also include other malted or unmalted cereals, with the addition of hops or hop extract (Brasil, 2019).

Brazilian legislation allows the partial replacement of malt by other ingredients of plant origin in beer (Brasil, 2019), and craft breweries have explored fruits, spices, herbs and other unconventional ingredients to create differentiated products (Santos *et al*., 2021; Pina; Cruz; Martelli, 2022). Coffee, mainly the roasted bean, has been used in beer as an aromatic ingredient, and its by-products have recently begun to be evaluated as sources of phenolic compounds in brewing (Chacón-Figueroa *et al*., 2022). *American Pale Ale* (APA), a style originating in the United States and characterized by the balance between malt and hops, with citrus and floral notes, is frequently used in experimental studies because of its versatile base (Costantin, 2022).

Beer contains phenolic compounds derived mainly from malt and hops, which contribute to its colour, astringency, colloidal stability and flavour stability (De Francesco *et al*., 2020). The addition of extracts rich in phenolic compounds therefore alters a matrix that already contains these compounds and in which they can interact with proteins and polysaccharides. Costantin (2022) reported positive results with the addition of botanical ingredients to APA formulations. APA, in turn, is a style widely used in experimental studies due to its balanced profile and compositional versatility. Therefore, the theoretical basis of this

study is supported by the potential of coffee husk as a source of phenolic compounds, the characteristics of cold infusion as a simple and heat-free extraction technique, and the adaptability of APA as a craft beverage base for experimentation with unconventional ingredients.

Although coffee husk has been characterized as a source of phenolic compounds, caffeine and chlorogenic acids (Palomino García; Del Bianchi, 2015a; Cangussu *et al*., 2021; De França Andrade *et al*., 2023), studies on its application in beer are still scarce and have focused on other coffee by-products or on other extraction conditions (Chacón-Figueroa *et al*., 2022). To the authors' knowledge, no study has evaluated the incorporation of *Coffea arabica* husk extract obtained by cold infusion into APA-style beer, nor its effects on the physicochemical characteristics and total phenolic content of the beverage. Cold infusion is of particular interest for this application because it avoids heating, does not require organic solvents and can be easily reproduced in craft breweries.

Thus, this study aimed to develop an APA-style beer added with *Coffea arabica* husk extract obtained by cold infusion and incorporated after fermentation, and to evaluate the effect of two extract concentrations on pH, titratable acidity, total soluble solids, real extract and total phenolic content of the beverage, as well as on the estimated bitterness index (IBU). This approach may contribute to the diversification of craft beers and to the valorization of agro-industrial residues.

METHODOLOGY

The experimental design was developed in the laboratories of the Federal University of Agreste of Pernambuco (UFAPE). The activities were conducted in the Food Analysis Laboratory (LAAL) and the Transport Phenomena and Unit Operations Laboratory, both located in the Food Science and Technology Laboratories building (LACTAL) and linked to the Food Engineering program.

Initially, the inputs required for beer production were obtained, including Pilsen malt, *Munich Light* malt, *Columbus* hops, *ale*-type yeast Safale US-05, mineral water, and Arabica coffee husks of the *typica* type. Brewing inputs were purchased from specialized stores located in Recife, Pernambuco.

The coffee husks (*Coffea arabica* L. var. Typica) were donated by Café Miracica, located in the rural area of the Miracica district, Garanhuns - PE, from the 2023 harvest. They were obtained by dry processing via the natural method and dried on raised beds for

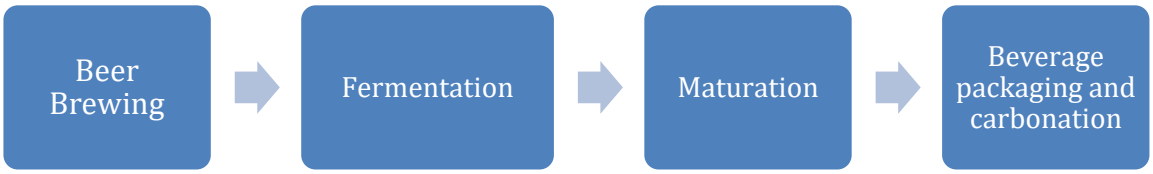
approximately 12 days until reaching a final moisture content of 11% on a wet basis. Prior to extraction, the husks were stored in sealed plastic bags at room temperature for about 30 days and were subsequently ground into a fine powder and standardized by sifting through a fine mesh sieve.

For beer production, a single 30 L batch of APA base beer was produced and divided into three equal parts (approximately 10 L each) after the wort cooling stage. This division allowed the creation of three distinct formulations: a control sample (C_T), without extract addition; sample C_1, containing 10 mL of extract per 600 mL bottle (≈ 1.7% v/v; 16.7 mL of extract per liter of beverage); and sample C_2, containing 20 mL of extract per 600 mL bottle (≈ 3.3% v/v; 33.3 mL of extract per liter of beverage). Standardization of the initial batch ensured uniformity in both the process and the sample base.

The extract was obtained based on the methodology of Sá *et al.* (2024) through a cold infusion process: 450 g of the dried husks were added to 1000 mL of mineral water (solid-to-liquid ratio of 1:2.2 (w/v) and kept under continuous agitation at 200 rpm for 24 hours at 25 °C in an orbital shaker incubator (model SL-222, Solab). After this period, the extract was filtered through coffee paper filters and subjected to a UV treatment step for 10 minutes using a germicidal UV-C lamp $\lambda = 254\,nm$, 15 W, at a distance of 4 cm, with 50 mL of extract in a 250 mL beaker, forming a liquid layer of approximately 14 mm. This step was applied as a precautionary measure; its microbiological efficacy was not evaluated in the present study. The extract was kept at 5 °C and used within 24 h.

The beer production stage followed the principles of *American Pale Ale* brewing, according to Palmer (2021). A simplified flowchart used in beer production is presented in Figure 1. The mashing stage includes malt milling, heating the milled malt in water to break down the starch and obtain the wort, boiling, and finally cooling the wort, which will be fermented in the next stage.

Figure 1 - Flowchart of craft beer preparation.

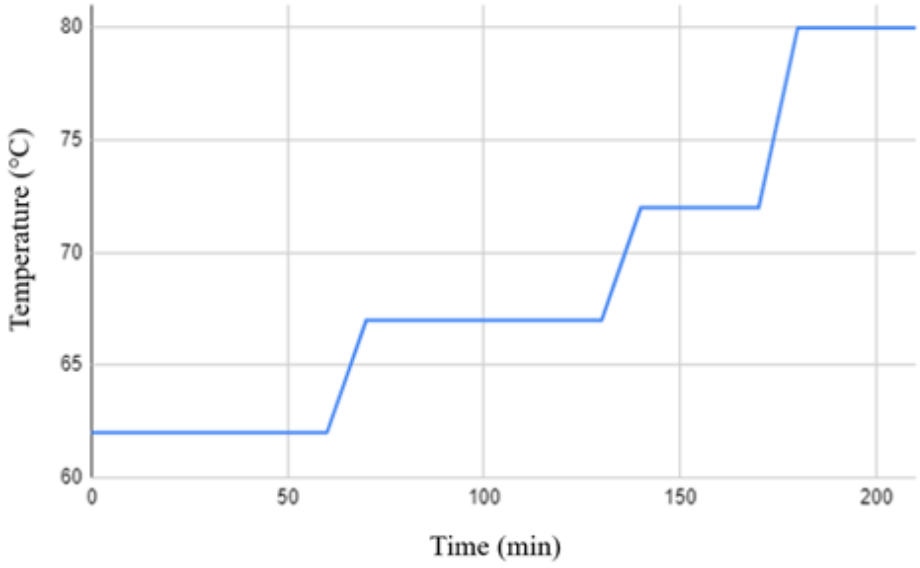


Source: Authors (2025).

Malt milling was carried out using a specialized roller mill composed of a hopper and two rollers. Mashing was carried out in an automated brewing kettle with specific temperature rests. The automated brewing kettle is equipment designed to facilitate and standardize the craft beer production process by integrating, in a single system, the mashing, clarification, boiling, and wort cooling stages. The system is electronically controlled, allowing monitoring and adjustment of variables such as temperature, time, and agitation, which are essential to ensure production repeatability.

Figure 2 shows the temperature profile used for mashing. The mash schedule followed this sequence: 62 °C for 60 minutes, 67 °C for an additional 60 minutes, 72 °C for 20 minutes, and 80 °C for 30 minutes. Mash temperature is a crucial factor in the conversion of starch into fermentable sugars during beer production. Palmer (2021) highlights that different enzymes act within specific temperature ranges, influencing the sugar profile of the wort and, consequently, the characteristics of the final beer. After mashing, the wort was filtered and sent to the boiling stage for 1 hour, with the addition of 64 g of *Columbus* hops (16 % de alfa-ácidos) during the final 10 minutes.

Figure 2: Time and temperature profile of the mash schedule.



Source: Authors (2024).

Subsequently, the wort was cooled in a plate heat exchanger, using water as the coolant. This type of exchanger uses thin metal plates arranged in parallel, through which two fluids flow in opposite directions, typically hot wort and cold water. This arrangement provides a large heat-exchange area in a compact space, resulting in rapid and efficient cooling.

The cooled wort was inoculated with yeast at a rate of 23 g of yeast per 30 L of wort, and fermentation was conducted at 19 °C for seven days. After this period, the samples underwent maturation at 4 °C for seven days.

Bottling was carried out in 600 mL bottles with the addition of 6 mL of sugar solution formulated to yield 6 g/L of sucrose, promoting natural carbonation through bottle conditioning (re-fermentation), as described by Teleginski *et al.* (2016). The coffee husk extract was added at bottling following maturation. Specifically, 10 mL of extract for formulation C_1 and 20 mL for formulation C_2 were placed in each bottle along with the priming solution, after which the bottles were filled with beer to a final volume of 600 mL, effectively replacing an equivalent volume of beer with the extract. The control group (C_T) consisted solely of pure beer with the priming solution and received no extract addition. The refermentation period lasted 15 days at a room temperature of 26 ± 1 °C.

Physicochemical analyses were performed on decarbonated samples, in triplicate, using the methods described by the Instituto Adolfo Lutz (2008). The evaluated parameters were pH (potentiometry, digital pH meter, model mPA-210, Tecnopon), titratable acidity (titration with 0.1 M NaOH solution to an endpoint at pH 8.2 using phenolphthalein indicator, expressed as % of lactic acid), total soluble solids (refractometry, °Brix), and real extract (determined by pycnometry, expressed as % w/w). Total phenolic compounds were determined by the Folin–Ciocalteu method (Singleton; Rossi, 1965), with modifications: an aliquot of 0.5 mL of undiluted decarbonated beer was mixed with 2.5 mL of Folin–Ciocalteu reagent (diluted in distilled water at 10% v/v) and, after 3 minutes, 2.0 mL of a 7.5% (w/v) sodium carbonate solution was added; the mixture was kept in the dark for 30 minutes at room temperature, and absorbance was read at 760 nm in a UV–Vis spectrophotometer (model Femto 700S, Femto). Quantification was performed using a gallic acid calibration curve from 5 to 50 mg/L; $y = 0.1021x + 0.0473$; $R^2 = 0.9947$, and the results were expressed as milligrams of gallic acid equivalents per liter (mg GAE/L).

The bitterness index (IBU) was estimated, not measured analytically, using *BrewFather*® software, version 2.11.6, based on the amount of hops, alpha-acid content and boiling time; therefore, IBU was not subjected to statistical analysis. For statistical analysis, the data were subjected to analysis of variance (ANOVA) and means were compared by the Scott-Knott test at the 5% probability level using *Sisvar*® software, version 6.7.

RESULTS AND DISCUSSION

Table 1 presents the physicochemical parameters of the three beer formulations, allowing evaluation of the impact of coffee husk extract addition on the properties of the beverage.

The pH did not differ significantly among the samples: C_T (4.36), C_1 (4.34), and C_2 (4.37), indicating that the extract did not interfere with the acid–base balance of the beverage at the concentrations used. These results corroborate the findings of De França Andrade *et al.* (2023), who reported that phenolic extracts from coffee husk exert little impact on the pH of food matrices. Regarding the bitterness index (IBU), all formulations exhibited the same estimated value of 29. This result was expected, because the calculation considers only the hop additions during boiling, and the bitter compounds in beer are derived primarily from hop iso-α-acids (De Clippeleer; De Cooman; Aerts, 2014). Since IBU was not measured analytically and no sensory analysis was performed, it is not possible to conclude whether the extract affected the perceived bitterness or astringency of the beer.

Table 1: Physicochemical parameters of the APA beers with and without coffee husk extract

Parameter (unit)	C_T (0% v/v)	C_1 (1.7% v/v)	C_2 (3.3% v/v)
pH	4.36 ± 0.01 [a]	4.34 ± 0.02 [a]	4.37 ± 0.04 [a]
IBU[†]	29 ± 0.00 [a]	29 ± 0.00 [a]	29 ± 0.00 [a]
TSS (°Brix)	4.40 ± 0.10 [a]	4.34 ± 0.06 [a]	4.37 ± 0.12 [a]
Titratable acidity (% lactic acid)	0.32 ± 0.02 [a]	0.30 ± 0.02 [a]	0.30 ± 0.02 [a]
Total phenolic compounds (mg GAE/L)	10.70 ± 0.84 [b]	20.11 ± 2.45 [a]	18.16 ± 0.57 [a]
Real extract (% w/w)	0.36 ± 0.01 [b]	0.45 ± 0.01 [a]	0.35 ± 0.00 [c]

Notes: C_T – Control (no extract); C_1 – Beer with 10 mL of extract per 600 mL bottle; C_2 – Beer with 20 mL of extract per 600 mL bottle. Values are mean ± standard deviation (n = 3). Means followed by the same lowercase letter within a row do not differ from each other according to the Scott-Knott test at the 5% probability level. TSS – total soluble solids; GAE – gallic acid equivalents. [†]IBU estimated with BrewFather® software; not subjected to statistical analysis.

Source: Authors (2025).

As for total soluble solids (TSS), the values remained close and did not differ significantly: C_T (4.40 °Brix), C_1 (4.34 °Brix), and C_2 (4.37 °Brix). This may be explained by the small volume of extract added (≤ 3.3% v/v) and by the low soluble solids content of the extract itself (4.2 °Brix), a characteristic of aqueous coffee husk extracts (Baqueta *et al.*, 2017).

Titratable acidity also did not differ significantly among the samples: C_T (0.32%), C_1 (0.30%), and C_2 (0.30%). The slightly lower numerical values in C_1 and C_2 may be related to

the composition of the extract or to its interaction with the beverage matrix; however, this difference was not statistically significant, and no mechanism was investigated experimentally in this study.

The total phenolic compound content was the parameter most affected by the addition of the extract. The control sample presented 10.70 mg GAE/L, whereas C_1 and C_2 showed 20.11 mg GAE/L and 18.16 mg GAE/L, respectively, corresponding to increases of approximately 88% and 70% in relation to the control. C_1 and C_2 did not differ significantly from each other (Table 1). According to Zhao et al. (2010), lager beers brewed exclusively from malt and hops contained total phenolic compounds ranging from 3.59 to 6.11 mg GAE/L. In this context, the higher concentration observed in the control beer may be associated with the intrinsic characteristics of the beer style evaluated in the present study. Moreover, despite the addition of a greater volume of extract, no statistically significant differences were observed among the treatments. This result may be attributed to the interaction of phenolic compounds with proteins and polysaccharides present in the beer matrix, leading to their complexation and subsequent precipitation. Additional factors, such as oxidative losses occurring during bottle conditioning and inherent analytical variability, may also have contributed to the observed results. However, these potential mechanisms were not specifically investigated in the present study.

Silva Sales (2021) reported that the incorporation of plant-derived ingredients rich in phenolic compounds can enhance the sensory complexity of beer and improve its oxidative stability during storage. In this context, coffee husk appears to be a promising functional ingredient for beer formulations, providing natural antioxidants that may retard oxidative reactions while contributing to the beverage's aroma and flavor profile. Nevertheless, phenolic compounds are susceptible to degradation during storage through oxidation, polymerization, and other transformation reactions. Since the analyses were performed after 15 days of bottle conditioning, the values reported herein represent the phenolic content at that specific stage of maturation, and their stability throughout the product's shelf life remains to be elucidated. Furthermore, the Folin-Ciocalteu assay is not specific to phenolic compounds and may also respond to other reducing substances present in beer. Consequently, the results should be interpreted as total phenolic equivalents rather than a direct measure of individual phenolic constituents transferred from the coffee husk extract.

Palomino García; Del Bianchi (2015a) identified the presence of phenolic acids in coffee husk, such as caffeic and chlorogenic acids, which may be among the compounds transferred to the beer. However, the increase observed here refers to total phenolic content and does not necessarily imply an increase in the antioxidant activity of the beverage, which was

not determined. Finally, real extract also varied among the samples: C_T (0.36 % m/m), C_1 (0.45 % m/m), and C_2 (0.35 % m/m), with significant differences among all formulations. The highest value in C_1 and the lowest in C_2 do not follow a dose-dependent pattern, and the causes of this behavior cannot be established with the present data; interactions or precipitation of extract components with beer constituents are possible, but were not evaluated.

CONCLUSIONS

The addition of *Coffea arabica* husk extract obtained by cold infusion to an *American Pale Ale* craft beer after fermentation increased the total phenolic content of the beverage (from 10.70 to 18.16–20.11 mg GAE/L) without significantly changing pH, titratable acidity and total soluble solids. The estimated bitterness index was the same for all formulations.

The two extract concentrations (approximately 1.7% and 3.3% v/v) resulted in statistically similar phenolic contents; therefore, the lower concentration (C_1) was sufficient to obtain the observed increase and also showed the highest real extract.

This research indicates that coffee husk is a promising raw material for agro-industrial residue valorization and for the diversification of craft beers; however, its use has not yet been validated as a technology and depends on further studies.

It should be noted, however, that this study presents some limitations. No sensory evaluation was performed, which would be essential to confirm the acceptance of the beverage by consumers. The antioxidant activity and the phenolic profile of the extract and the beers were not determined. Microbiological safety of the extract and of the final product was not assessed, the efficacy of the UV treatment was not verified, the stability of the phenolic compounds during storage was not evaluated, and the bitterness index (IBU) was estimated using software rather than measured analytically. Future studies should include sensory analysis, determination of antioxidant activity and phenolic profile, microbiological characterization, shelf-life assessment, and scale-up trials to validate the industrial applicability of the proposed formulations.

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