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Chemical composition and sensory diversity of colourless cachaças from Paraíba: influence of geographic origin and production practices

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Abstract

Why was the work done: This study considers how geography, soil and climate (edaphoclimatic) conditions, field practices, and industrial processes, influence the chemical composition and aroma of colourless cachaça from the state of Paraíba in Brazil. Despite technological developments, the effect of regional factors on the compliance of cachaça with legal standards and sensory diversity remains underexplored.
How was the work done: 26 samples of crystal cachaça from the Mata, Agreste, and Sertão mesoregions (geographic subdivisions) of Paraíba were analysed. Physicochemical parameters (alcohol and volatile acidity) were quantified, while copper was determined using flame atomic absorption spectroscopy. Volatile compounds - including esters, alcohols, aldehydes, and ethyl carbamate - were quantified using gas chromatography with flame ionisation detection and gas chromatography-mass spectrometry.
What are the main findings: Five producers of cachaça failed to meet the legal limits for the content of copper, presumably due to inadequate cleaning of copper stills and poor distillation control. In all 85 volatile compounds were identified, revealing regional differences in aroma profiles.
Why is the work important: The findings demonstrate that the sensory and chemical diversity of cachaça is driven by complex interactions between edaphoclimatic conditions, sugarcane management, and processing methods. These factors contribute to the distinctiveness of regional cachaças, providing opportunities for market differentiation.

Keywords

cachaça, diversity, geographic origin, Industrial practice, legal parameters, aroma volatiles

Introduction

Sugarcane is one of the most widely used crops in the world, with well recognised agricultural and industrial potential. In Brazil, products include fuel ethanol, sugar, and cachaça an alcoholic beverage, (Rosa et al. 2009; Solomon 2011). Cachaça is a Brazilian spirit, legally required to contain 38–48% alcohol by volume (ABV) (Da-Silva et al. 2023). It is produced from the fermentation of fresh sugarcane juice - either spontaneous from indigenous microflora or by using pure yeast cultures - followed by distillation in stainless steel columns or copper pot stills (Borges et al. 2014; Bortoletto 2023). Cachaça is produced in all twenty-seven Brazilian states, although the largest are in São Paulo, Pernambuco, Ceará, Minas Gerais and Paraíba (Santiago et al. 2015). Distillation using copper pot stills is greatest in Paraíba, with more than 40 producers. Cachaça from this state is highly regarded for quality, reflecting a balance between industrial scale and product distinctiveness. This is closely linked to regional characteristics - including climate, soil, adaptation of sugarcane cultivars and the diversity of wild yeasts.

Paraíba is divided into four mesoregions: Sertão Paraibano (with two producers of cachaça), Agreste Paraibano (20 producers), Mata Paraibana (four producers) and Borborema (without any producers). The Sertão Paraibano is characterised by high temperature and irregular, low rainfall (Medeiros-Silva et al. 2019). The Mata Paraibana has a hot, humid tropical climate (Medeiros-Silva et al. 2019; Vilela et al. 2021), whereas the Agreste Paraibano exhibits milder temperatures with irregular rainfall and accounts for most of the cachaça production in the state (Medeiros-Silva et al. 2019). These mesoregions differ markedly in landscape, agricultural practices, and production scale, leading to terroir effects on cachaça. These shape edaphoclimatic conditions (soil, climate, and topography), field practices, industrial processes (Medeiros-Silva et al. 2019; Vilela et al. 2021; Capitello et al. 2021) and, consequently, the quality of cachaça.

There are a number of classifications of cachaça including crystal (colourless), short aged, aged, and reflecting the storage conditions in stainless steel or wooden barrels. Stainless steel containers do not promote maturation, but there has been growing interest in using wooden barrels made from tropical species such as feijó and jequitibá. These woods can enhance the chemical complexity of the spirit without significantly altering its colour (Alcarde et al. 2014; Bortoletto 2023). This approach allows producers to improve the flavour of crystal cachaça an approach which is increasingly used. Although production and quality standards are well regulated, the aroma profile - defined as the combination and intensity of volatile compounds - remains central to the sensory identity and quality of the beverage.

Cachaça production has been widely studied, generating insights that have driven technological advances in the cultivation of sugarcane, and the processes of fermentation, and distillation. Nevertheless, there remain challenges, particularly how geographic origin affects compliance with legal standards and contributes to the flavour profile of the spirit. While some studies have addressed aspects of regulation and aroma, there is limited understanding of how geographic origin - through edaphoclimatic variation - and production practices shape chemical composition and sensory properties. These features are influenced not only by soil type, climate, and cultivation methods but also by fermentation, distillation, and maturation practices. Accordingly, this study considers the volatile profile of colourless cachaças from the Mata, Agreste, and Sertão mesoregions of Paraíba and their compliance with Brazilian legal standards. Further, it seeks to clarify the contribution of geographic origin, edaphoclimatic conditions, and production practices to the chemical and sensory diversity of these spirits.

Materials and methods

Cachaça samples

Twenty-six colourless cachaça samples were collected in triplicate from twenty-six producers, located in three Paraiba mesoregions - Sertão Paraibano (two samples), Mata Paraibana (four) and Agreste Paraibano (20) (Figure 1).

All samples were produced by fermentation of fresh sugarcane juice, distilled in copper stills and stored in stainless steel tanks or freijó wood barrels for a maximum of six months before bottling. All samples were kept at 20ºC and protected from light.

Alcohol by volume

The % ABV (v/v) of cachaça was determined using alcoholmeter (Gay Lussac Alcoholometer). Results were accurate at 20°C using a correction table (AOAC 2000).

Total acidity

This method is based on titration and neutralisation of acid (AOAC 2000). Sample (50 mL) with drops of 1% phenolphthalein was titrated with 0.1 M sodium hydroxide. Results were calculated using the equation:

$$TA = \frac{n\,x\,M\,x\,f\,x\,MM}{10\,x\,V}$$

Where, n = volume (mL) sodium hydroxide, M = molarity of sodium hydroxide solution, f = correction actor for sodium hydroxide, MM = Molar Mass of acetic acid (60 g /mol), V = sample volume (mL).

Dry acidity

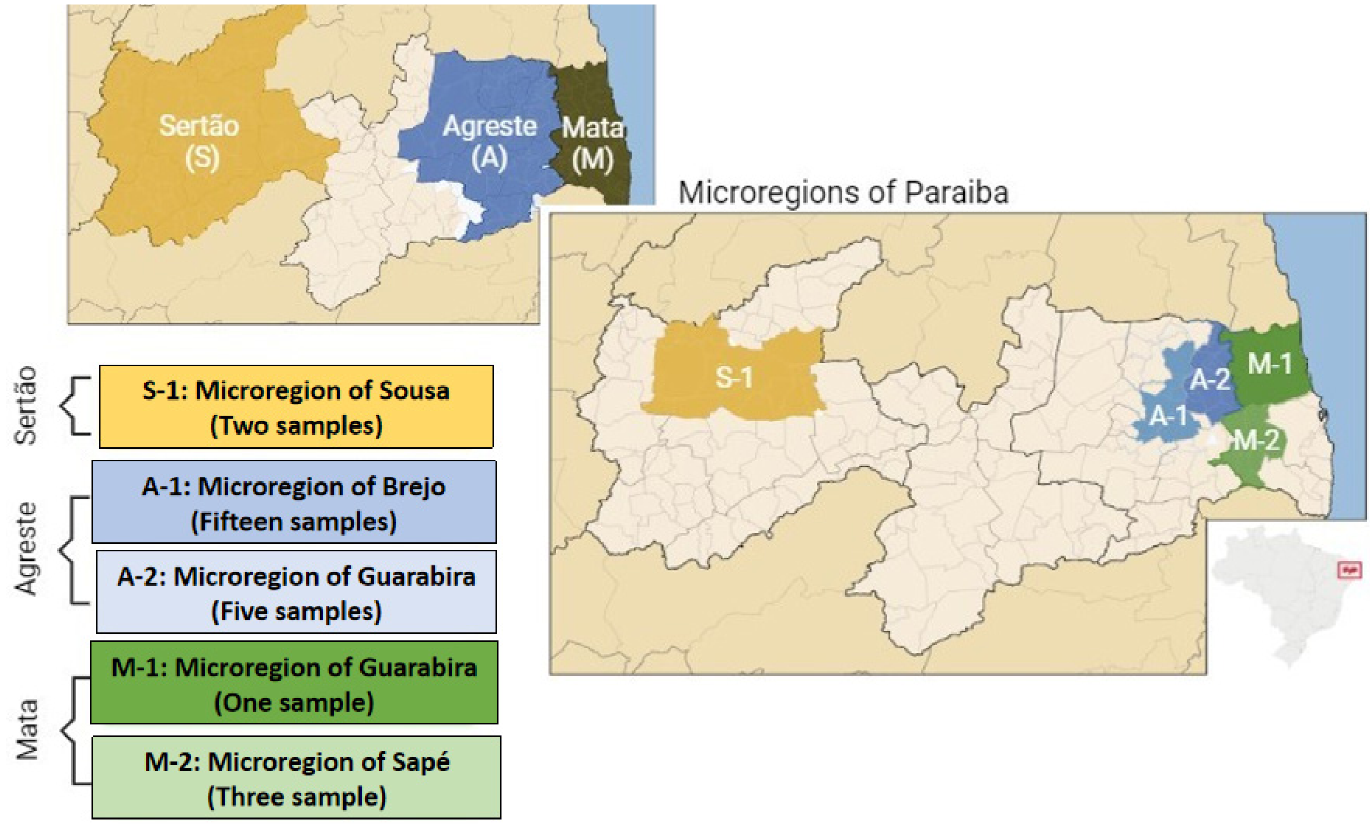
Dry acidity (DA) was determined by evaporating the sample and titrating with alkali (AOAC 2000). The sample (50 mL) was evaporated in a boiling water bath. The residue was dissolved in water (100 mL), with two drops of 1% phenolphthalein added and titrated with 0.1 M sodium hydroxide solution (AOAC 2000). Results were calculated as below.

$$DA = \frac{n\,x\,M\,x\,f\,x\,MM}{10\,x\,V}$$

Where, n = volume (mL) of sodium hydroxide, M = molarity of the sodium hydroxide solution, f = correction factor of the sodium hydroxide, MM = molar mass of acetic acid (60 g/mol), V (mL) of sample.

Figure 1.

Mesoregions and microregions in the state of Paraiba where cachaça is produced.



Volatile acidity

Volatile acidity (VA) was derived from the difference between the total acidity (TA) and dry acidity (DA) (AOAC 2000). Results are expressed in mg of acetic acid per 100 mL.

Higher alcohols and aldehydes

Determination of isobutyl alcohol, 1-propanol, isoamyl alcohol, methanol, 1-butanol, 2-butanol, ethyl acetate, acetaldehyde, acrolein and the sum of furfural and hydroxymethylfurfural was using gas chromatography (Agilent HP 6890) with a flame ionisation detector (FID) and capillary column (Varian CP-Wax 52 CB, 60m x 0.25mm x 0.25µm). Using the conditions of Bortoletto et al (2016) the temperature programme for the oven was: 40°C for 4 min, an increase to 120°C at 20°C/min, an isothermal period of 1 min, an increase to 180°C at 30°C/min and a maintenance period of 4 min. The injector and detector (FID) temperatures were respectively 245 and 250°C. The analyses were carried out with a 1:25 split ratio, using helium as the carrier gas (flow rate 1.5 mL/min). Analytical standards for the calibration curves were prepared with 40% (v/v) ethanol. Analyses were performed by injecting samples (1 µL) with 3-pentanol (internal standard).

Ethyl carbamate

Ethyl carbamate (EC) was determined using a gas chromatograph Agilent Technologies 7890B with a mass-selective detector (Agilent Technologies 5977B), with a capillary column (Agilent VF-WAXms 60m x 0.25mm x 0.25µm), coupled to a Mass Spectrometer. Operating conditions (Nóbrega et al. 2009), were an oven temperature at 90°C (2 min); 100°C/min to 150°C (0 min); and 40°C/min to 230°C (10 min). The injector temperature was 250°C, and the GC/MS interface maintained at 230°C. The MS was operated in the electron impact mode with an ionisation energy (70 eV) and helium (carrier gas) at 1.5 ml/min. The mass spectrometer detector operated in the SIM mode (62 m/z). Preparation of calibration curves and analysis were based on Serafim et al (2016). Solutions of ethyl carbamate and butyl carbamate were prepared with ethanol 40% (v/v), with butyl carbamate (150 µg/L) as internal standard. Sample (1µL) was injected in the split less mode. The limits of detection and quantitation were 10 and 40 µg/L of EC.

Copper

The method used was that of Miranda et al (2010). Deionised water (18 MΩ cm resistivity) was used for all preparations. All glassware and polypropylene flasks were cleaned with detergent, soaked in 10% (v/v) nitric acid for 24 h, rinsed with deionised water, and air dried. Reference solutions were prepared daily by diluting 1000 mg/L stock solutions of Ag, Bi, Co, Cu, and Ni (Tec-Lab, Hexis, São Paulo, Brazil).

Samples were digested using a multiwave microwave system (Anton-Paar, Graz, Austria) with perfluoroalkoxy (PFA) vessels and a temperature sensor. Cachaça (1 mL) was digested with 1 mL of 14 M nitric acid and 6 mL of deionised water in a closed vessel. The digestion process involved two heating steps; 2 mins at 300 W and 5 min at 600 W. Digested samples were suspended in deionised water (10 mL) and processed in triplicate. The copper concentration was determined using inductively coupled plasma optical emission spectrometry (ICP-OES, Vista AX, Varian, Mulgrave, Australia).

For direct analysis of copper, cachaça (5 mL) was mixed with 400 µL of a standard solution containing Ag, Bi, Co (50 mg/L), and Ni (250 mg/L) and the volume adjusted to 10 mL with 1 M HNO_3. After dilution, the concentration of internal standards was 10 mg/L Bi and 2 mg/L Ag, Co, and Ni. Calibration was performed using reference solutions with the Cu concentration ranging from 0.1 to 6 mg/L, with internal standards added to all blanks, reference solutions, and samples. Copper was quantified at 324.8 nm using Flame atomic absorption spectrometry (FS-FAAS) using a Varian AA240FS spectrometer (Mulgrave, Australia) with a deuterium lamp for background correction.

Hollow cathode lamps were used for silver (Ag), bismuth (Bi), cobalt (Co), copper (Cu), and nickel (Ni) as primary radiation sources with respective electric currents of 4, 10, 7, 4, and 4 mA. Analysis were conducted using an oxidising air (13.5 L/min)/ acetylene flame (2 L/min), with Cu measured at 324.8 nm using a spectral bandwidth of 0.5 nm.

Volatiles

Higher alcohols, aldehydes, ketones, terpenes and esters were determined using a gas chromatograph (Agilent Technologies 7890B) attached to a mass-selective detector (Agilent Technologies 5977B) with a capillary column (Agilent HP-5MS UI (30m x 0.25 mm x 0.25 µm), coupled to a Mass Spectrometer. The methodology of Zacaroni et al (2017) was used with a oven temperature of 35 to 240ºC and a heating rate of 40ºC/min. The injector temperature was 270ºC, with high purity helium 5.0 as carrier gas (flow rate of 1.78 mL/min) in 1:4 split mode injection. The temperature of the detector interface and the ion source was 240 and 200ºC. The mass spectrometer was operated in electronic impact mode (70 eV) and the mass scan range was from 50 to 400 mz^{-1} at 4.44 scan.s^{-1}.

Volatiles were recovered using headspace solid-phase microextraction (HS-SPME) with SPME device (Supelco, Bellefonte, USA). The sample was diluted to 10% ABV using ultra-pure water and 4 mL with (internal standard) 3-pentanol, transferred to a 20 mL glass vial and closed with a Teflon coated septum cap. The volatiles were extracted at 450ºC with no equilibrium, using the divinylbenzene/carboxene/polydimethylsiloxane (DVB/CAR/PDMS) 50/30 µm fibre exposed to the headspace for 50 min. Desorption of the fibre for 5 min for in the gas chromatograph with conditioning at 270ºC for 60 min before extraction. Compounds were identified using the NIST library database (2014) combined with a mass spectrum and linear retention index. The linear retention index (LRI) of each compound was calculated using the retention times of a homologous series of C6–C20 n-alkanes. Results were expressed as peak area.

Statistical analysis

All analyses were performed in triplicate with the results presented as the mean ± standard deviation. The data were submitted to Analysis of Variance (ANOVA) and Tukey's test to compare the results in relation to the parameters required by the legislation, with means with $p<0.05$ considered statistically different. Principal Component Analysis and Heat Mapping were performed for the volatile compounds. The data was analysed using XLSTAT software (version 2014.5.03, Addinsoft, USA).

Results and discussion

Twenty-six cachaça samples from Paraíba, Brazil, were analysed for alcohols, esters, aldehydes, and copper. The cachaça samples from different regions, were produced via sugarcane fermentation, distilled in copper stills, and stored before bottling.

Compliance with legal parameters

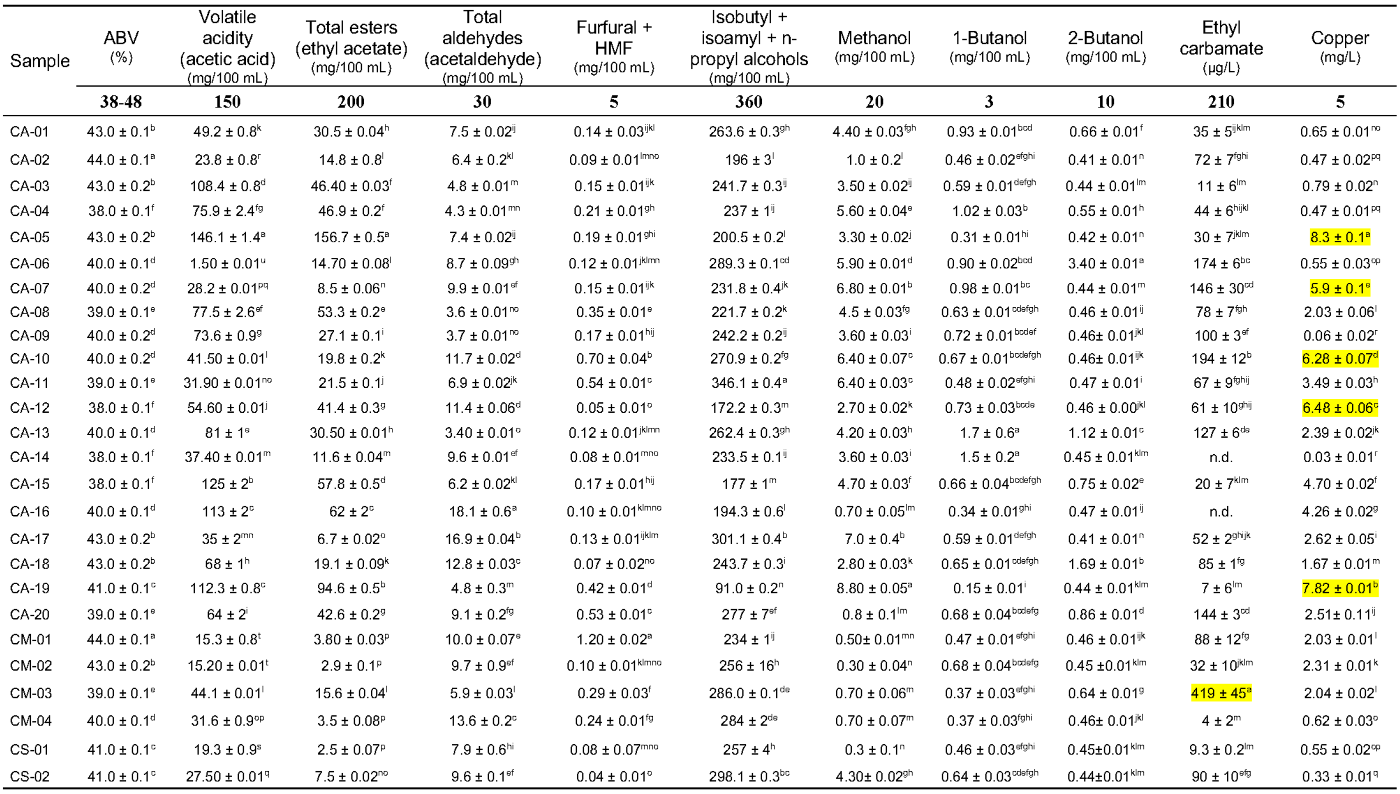
Cachaça legislation involves a group of analysis including ABV, volatile acidity, total esters, total aldehydes, sum of furfural and HMF, sum of isobutyl, isoamyl and n-propyl alcohols, methanol, 1-butanol, 2-butanol, ethyl carbamate, and copper. Each analysis is defined by a range of acceptable limit (in bold, Table 1). Most cachaça samples were within the limits required by legislation, with the exception of CA-05, CA-07, CA-10, CA-12, CA-19, and CM-03 which suggests that some producers need to improve their practices..

The alcohol content of cachaça - post fermentation and distillation - is defined by the volumetric percentage of alcohol in the spirit (Rosa et al. 2009). Table 1 shows that all samples had an appropriate ABV of 38 to 44%. Cachaça distillation can be performed using stainless steel columns or copper still pots (alembic) (Rosa et al. 2009; Bortoletto 2023). The copper still pot is the most common distillation method for the production of cachaça with good thermal conduction, resistance to corrosion and captures dimethyl sulphide during distillation which minimises sulphur off-flavours (Rosa et al. 2009).

Esters provide sweet, fruity and flowery aromas in cachaça and can increase during storage in wooden barrels (Bortoletto and Alcarde 2015; Bortoletto et al. 2018). Esters are formed by esterification of fatty acids with ethanol and higher alcohols. As the most predominant ester in cachaça, total esters are expressed as mg ethyl acetate/100 mL anhydrous alcohol (AA) (Bortoletto and Alcarde 2015; Bortoletto et al. 2016; Bortoletto et al. 2018). Sample CA-05 (156.7 mg/100 mL AA) had the highest concentration of total esters ($p<0.05$) (Table 1) with sample CS-01 (2.5 mg/100 mL AA) the lowest ($p<0.05$). Esters are primarily formed during fermentation, although distillation in copper stills can also contribute (Portugal et al. 2017).

Figure 2.

Analysis of 26 colourless cachaça samples



Sample	ABV (%)	Volatile acidity (acetic acid) (mg/100 mL)	Total esters (ethyl acetate) (mg/100 mL)	Total aldehydes (acetaldehyde) (mg/100 mL)	Furfural + HMF (mg/100 mL)	Isobutyl + isoamyl + n-propyl alcohols (mg/100 mL)	Methanol (mg/100 mL)	1-Butanol (mg/100 mL)	2-Butanol (mg/100 mL)	Ethyl carbamate (µg/L)	Copper (mg/L)
	38-48	**150**	**200**	**30**	**5**	**360**	**20**	**3**	**10**	**210**	**5**
CA-01	43.0 ± 0.1^{b}	49.2 ± 0.8^{k}	30.5 ± 0.04^{h}	7.5 ± 0.02^{ij}	0.14 ± 0.03^{ijkl}	263.6 ± 0.3^{gh}	4.40 ± 0.03^{fgh}	0.93 ± 0.01^{bcd}	0.66 ± 0.01^{f}	35 ± 5^{ijklm}	0.65 ± 0.01^{no}
CA-02	44.0 ± 0.1^{a}	23.8 ± 0.8^{r}	14.8 ± 0.8^{l}	6.4 ± 0.2^{kl}	0.09 ± 0.01^{lmno}	196 ± 3^{l}	1.0 ± 0.2^{l}	0.46 ± 0.02^{efghi}	0.41 ± 0.01^{n}	72 ± 7^{fghi}	0.47 ± 0.02^{pq}
CA-03	43.0 ± 0.2^{b}	108.4 ± 0.8^{d}	46.40 ± 0.03^{f}	4.8 ± 0.01^{m}	0.15 ± 0.01^{ijk}	241.7 ± 0.3^{ij}	3.50 ± 0.02^{ij}	0.59 ± 0.01^{defgh}	0.44 ± 0.01^{lm}	11 ± 6^{lm}	0.79 ± 0.02^{n}
CA-04	38.0 ± 0.1^{f}	75.9 ± 2.4^{fg}	46.9 ± 0.2^{f}	4.3 ± 0.01^{mn}	0.21 ± 0.01^{gh}	237 ± 1^{ij}	5.60 ± 0.04^{e}	1.02 ± 0.03^{b}	0.55 ± 0.01^{h}	44 ± 6^{hijkl}	0.47 ± 0.01^{pq}
CA-05	43.0 ± 0.2^{b}	146.1 ± 1.4^{a}	156.7 ± 0.5^{a}	7.4 ± 0.02^{ij}	0.19 ± 0.01^{ghi}	200.5 ± 0.2^{l}	3.30 ± 0.02^{j}	0.31 ± 0.01^{hi}	0.42 ± 0.01^{n}	30 ± 7^{jklm}	8.3 ± 0.1^{a}
CA-06	40.0 ± 0.1^{d}	1.50 ± 0.01^{u}	14.70 ± 0.08^{l}	8.7 ± 0.09^{gh}	0.12 ± 0.01^{jklmn}	289.3 ± 0.1^{cd}	5.90 ± 0.01^{d}	0.90 ± 0.02^{bcd}	3.40 ± 0.01^{a}	174 ± 6^{bc}	0.55 ± 0.03^{op}
CA-07	40.0 ± 0.2^{d}	28.2 ± 0.01^{pq}	8.5 ± 0.06^{n}	9.9 ± 0.01^{ef}	0.15 ± 0.01^{ijk}	231.8 ± 0.4^{jk}	6.80 ± 0.01^{b}	0.98 ± 0.01^{bc}	0.44 ± 0.01^{m}	146 ± 30^{cd}	5.9 ± 0.1^{e}
CA-08	39.0 ± 0.1^{e}	77.5 ± 2.6^{ef}	53.3 ± 0.2^{e}	3.6 ± 0.01^{no}	0.35 ± 0.01^{e}	221.7 ± 0.2^{k}	4.5 ± 0.03^{fg}	0.63 ± 0.01^{cdefgh}	0.46 ± 0.01^{ij}	78 ± 7^{fgh}	2.03 ± 0.06^{l}
CA-09	40.0 ± 0.2^{d}	73.6 ± 0.9^{g}	27.1 ± 0.1^{i}	3.7 ± 0.01^{no}	0.17 ± 0.01^{hij}	242.2 ± 0.2^{ij}	3.60 ± 0.03^{i}	0.72 ± 0.01^{bcdef}	0.46 ± 0.01^{jkl}	100 ± 3^{ef}	0.06 ± 0.02^{r}
CA-10	40.0 ± 0.2^{d}	41.50 ± 0.01^{l}	19.8 ± 0.2^{k}	11.7 ± 0.02^{d}	0.70 ± 0.04^{b}	270.9 ± 0.2^{fg}	6.40 ± 0.07^{c}	0.67 ± 0.01^{bcdefgh}	0.46 ± 0.01^{ijk}	194 ± 12^{b}	6.28 ± 0.07^{d}
CA-11	39.0 ± 0.1^{e}	31.90 ± 0.01^{no}	21.5 ± 0.1^{j}	6.9 ± 0.02^{jk}	0.54 ± 0.01^{c}	346.1 ± 0.4^{a}	6.40 ± 0.03^{c}	0.48 ± 0.02^{efghi}	0.47 ± 0.01^{i}	67 ± 9^{fghij}	3.49 ± 0.03^{h}
CA-12	38.0 ± 0.1^{f}	54.60 ± 0.01^{j}	41.4 ± 0.3^{g}	11.4 ± 0.06^{d}	0.05 ± 0.01^{o}	172.2 ± 0.3^{m}	2.70 ± 0.02^{k}	0.73 ± 0.03^{bcde}	0.46 ± 0.00^{jkl}	61 ± 10^{ghij}	6.48 ± 0.06^{c}
CA-13	40.0 ± 0.1^{d}	81 ± 1^{e}	30.50 ± 0.01^{h}	3.40 ± 0.01^{o}	0.12 ± 0.01^{jklmn}	262.4 ± 0.3^{gh}	4.20 ± 0.03^{h}	1.7 ± 0.6^{a}	1.12 ± 0.01^{c}	127 ± 6^{de}	2.39 ± 0.02^{jk}
CA-14	38.0 ± 0.1^{f}	37.40 ± 0.01^{m}	11.6 ± 0.04^{m}	9.6 ± 0.01^{ef}	0.08 ± 0.01^{mno}	233.5 ± 0.1^{ij}	3.60 ± 0.03^{i}	1.5 ± 0.2^{a}	0.45 ± 0.01^{klm}	n.d.	0.03 ± 0.01^{r}
CA-15	38.0 ± 0.1^{f}	125 ± 2^{b}	57.8 ± 0.5^{d}	6.2 ± 0.02^{kl}	0.17 ± 0.01^{hij}	177 ± 1^{m}	4.70 ± 0.03^{f}	0.66 ± 0.04^{bcdefgh}	0.75 ± 0.02^{e}	20 ± 7^{klm}	4.70 ± 0.02^{f}
CA-16	40.0 ± 0.1^{d}	113 ± 2^{c}	62 ± 2^{c}	18.1 ± 0.6^{a}	0.10 ± 0.01^{klmno}	194.3 ± 0.6^{l}	0.70 ± 0.05^{lm}	0.34 ± 0.01^{ghi}	0.47 ± 0.01^{ij}	n.d.	4.26 ± 0.02^{g}
CA-17	43.0 ± 0.2^{b}	35 ± 2^{mn}	6.7 ± 0.02^{o}	16.9 ± 0.04^{b}	0.13 ± 0.01^{ijklm}	301.1 ± 0.4^{b}	7.0 ± 0.4^{b}	0.59 ± 0.01^{defgh}	0.41 ± 0.01^{n}	52 ± 2^{ghijk}	2.62 ± 0.05^{i}
CA-18	43.0 ± 0.2^{b}	68 ± 1^{h}	19.1 ± 0.09^{k}	12.8 ± 0.03^{c}	0.07 ± 0.02^{no}	243.7 ± 0.3^{i}	2.80 ± 0.03^{k}	0.65 ± 0.01^{cdefgh}	1.69 ± 0.01^{b}	85 ± 1^{fg}	1.67 ± 0.01^{m}
CA-19	41.0 ± 0.1^{c}	112.3 ± 0.8^{c}	94.6 ± 0.5^{b}	4.8 ± 0.3^{m}	0.42 ± 0.01^{d}	91.0 ± 0.2^{n}	8.80 ± 0.05^{a}	0.15 ± 0.01^{i}	0.44 ± 0.01^{klm}	7 ± 6^{lm}	7.82 ± 0.01^{b}
CA-20	39.0 ± 0.1^{e}	64 ± 2^{i}	42.6 ± 0.2^{g}	9.1 ± 0.2^{fg}	0.53 ± 0.01^{c}	277 ± 7^{ef}	0.8 ± 0.1^{lm}	0.68 ± 0.04^{bcdefg}	0.86 ± 0.01^{d}	144 ± 3^{cd}	2.51 ± 0.11^{ij}
CM-01	44.0 ± 0.1^{a}	15.3 ± 0.8^{t}	3.80 ± 0.03^{p}	10.0 ± 0.07^{e}	1.20 ± 0.02^{a}	234 ± 1^{ij}	0.50 ± 0.01^{mn}	0.47 ± 0.01^{efghi}	0.46 ± 0.01^{ijk}	88 ± 12^{fg}	2.03 ± 0.01^{l}
CM-02	43.0 ± 0.2^{b}	15.20 ± 0.01^{t}	2.9 ± 0.1^{p}	9.7 ± 0.9^{ef}	0.10 ± 0.01^{klmno}	256 ± 16^{h}	0.30 ± 0.04^{n}	0.68 ± 0.04^{bcdefg}	0.45 ± 0.01^{klm}	32 ± 10^{jklm}	2.31 ± 0.01^{k}
CM-03	39.0 ± 0.1^{e}	44.1 ± 0.01^{l}	15.6 ± 0.04^{l}	5.9 ± 0.03^{l}	0.29 ± 0.03^{f}	286.0 ± 0.1^{de}	0.70 ± 0.06^{m}	0.37 ± 0.03^{efghi}	0.64 ± 0.01^{g}	419 ± 45^{a}	2.04 ± 0.02^{l}
CM-04	40.0 ± 0.1^{d}	31.6 ± 0.9^{op}	3.5 ± 0.08^{p}	13.6 ± 0.2^{c}	0.24 ± 0.01^{fg}	284 ± 2^{de}	0.70 ± 0.07^{m}	0.37 ± 0.03^{fghi}	0.46 ± 0.01^{jkl}	4 ± 2^{m}	0.62 ± 0.03^{o}
CS-01	41.0 ± 0.1^{c}	19.3 ± 0.9^{s}	2.5 ± 0.07^{p}	7.9 ± 0.6^{hi}	0.08 ± 0.07^{mno}	257 ± 4^{h}	0.3 ± 0.1^{n}	0.46 ± 0.03^{efghi}	0.45 ± 0.01^{klm}	9.3 ± 0.2^{lm}	0.55 ± 0.02^{op}
CS-02	41.0 ± 0.1^{c}	27.50 ± 0.01^{q}	7.5 ± 0.02^{no}	9.6 ± 0.1^{ef}	0.04 ± 0.01^{o}	298.1 ± 0.3^{bc}	4.30 ± 0.02^{gh}	0.64 ± 0.03^{cdefgh}	0.44 ± 0.01^{klm}	90 ± 10^{efg}	0.33 ± 0.01^{q}

Figures in bold are the legal limits for each parameter in cachaça. Result that is higher than the legal maximum. Results reported as 'mg/100 ml' are 'mg/100 ml anhydrous alcohol' (AA)

CA - Cachaças Agreste; CM - Cachaças Mata; CS - Cachaças Sertão. Acrolein was not detected. Different upper letters in the same column differ by Tukey test (0.05).

All the cachaças in this work were distilled using copper still pots which can result in cachaças from Paraíba having higher copper levels thanthe legal limit (> 5 mg/L) (Serafim et al. 2016). Of the 26 crystal cachaça samples (Table 1) 21 had copper levels < 5 mg/L, but with CA-05, CA-07, CA-10, CA-12 and CA-19, containing > 5 mg/L. Athough the presence of copper in cachaça reflects the use of copper stills, the level is managed through hygienic practices. Copper salts are generated through the oxidation of the internal walls and are dissolved in cachaça (Alcarde et al. 2014; Böck et al. 2022). To reduce this, the walls of the stills must be cleaned before distillation (Oliveira et al. 2020; Böck et al. 2022). Management of copper levels is important as during distillation, copper acts as a catalyst generating acetate esters from alcohols and acetic acid, and fatty acid ethyl esters from acetic acid and short and medium chain fatty acids.

Volatile acidity (VA) is reported as mg acetic acid/100 mL and is the main volatile acid in cachaça (Da-Silva et al. 2023). Results ranged from 146.1 mg/100 mL (CA-05) down to 1.5 mg/100 mL (CA-06). Acetic acid is generated during fermentation due to an accumulation of acetaldehyde (Takahashi et al. 2006), with acetate a precursor of cytosolic acetyl-CoA which is metabolically important in yeasts and in the generation of secondary compounds (including esters) (Chen et al. 2013; Galdieri et al. 2014; Pietrocola et al. 2015). Acetic acid is a volatile acid that is concentrated during the distillation of cachaça. During distillation, acetic acid is present in all three fractions ('heads', 'heart' and 'tail') with the heads containing the lowest level. The precision of the separation of the heart and tail fractions influences the final concentration of acetic acid in cachaça (which at high levels results in an unpleasant vinegar flavour).

Aldehydes are formed from oxidative reactions with alcohols, amino acids or fatty acids. Acetaldehyde contributes positively to the aroma of cachaça (Bortoletto and Alcarde 2015). Sample CA-16 (18.1 mg/100 mL AA) contained a higher concentration of acetaldehyde ($p<0.05$) (Table 1), with the least in sample CA-13 (3.4 mg/100 mL AA) ($p<0.05$). Acetaldehyde, when present in low concentrations, leads to sweet, fruity aromas, but in high concentrations it leads to a pungent odour. Appropriate cuts of the distillate fractions reduce the level of acetaldehyde in cachaça.

Furfural and hydroxymethylfurfural are produced by thermal degradation of sugars, with the dehydration pentoses and hexoses (Bortoletto and Alcarde 2015). Sample CM-01 (1.2 mg/100 mL AA) contained the highest concentration ($p<0.05$) (Table 1), with the least in sample CS-02 (0.04 mg/100 mL AA) ($p<0.05$). The concentration of these compounds may be related to the burning of sugarcane. Although prohibited, the burning of straw during manual harvesting can still occur in some regions. These compounds also originate from caramelisation and Maillard reactions during the toasting of wooden barrels (Bortoletto et al. 2016).

Higher alcohols are formed by yeast using the Ehrlich pathway, with the deamination of amino acids (Hazelwood et al. 2008). For cachaça, the legislative limits for higher alcohols are based on the sum of isobutyl (2-methyl-1-propanol,) isoamyl (2- and 3-methyl-1-butanol) and n-propyl (1-propanol) alcohols (Da-Silva et al. 2023). Sample CA-11 (346.7 mg/100 mL AA) contained the highest concentration of higher alcohols ($p<0.05$) (Table 1) with the least in sample CA-19 (91.0 mg/100 mL AA) ($p<0.05$). The higher alcohols are generated during fermentation and arev either concentrated or separated during distillation. During fermentation, yeasts consume amino acids as a nitrogen source, generating higher alcohols which are esterified with acetyl-CoA to form esters (Hazelwood et al. 2008; Vidal et al. 2014). The fermented sugarcane is an azeotropic mixture of ethanol and water (as the primary compounds), which impacts the volatility of compounds like higher alcohols.

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Higher alcohols such as propanol, isobutanol and amyl alcohols are miscible with water and highly soluble in ethanol, and they remain in the ethanol rich phase which affects their volatility during distillation. Distillation is separated into three fractions with the 'heads' fraction containing more volatile compounds, including aldehydes (acetaldehyde) and some higher alcohols (1-propanol and 2-methyl-1-propanol). 'Hearts' are the desired fraction of the distillate containing most of the flavour compounds, contributing to the flavour of the spirit (Bortoletto and Alcarde 2015). These include the higher alcohols (2-methylbutanol, 3-methylbutanol, and 2-phenylethanol), which generate fruity, malty, and floral notes (Bortoletto and Alcarde 2015; Bortoletto et al. 2016; Portugal et al. 2016). Although fermentation is the core of spirit production, distillers ensure that the hearts fraction contains the desired higher alcohols.

Contaminants present in cachaça include methanol, 1- and 2-butanol are which are formed during fermentation and distillation (Bortoletto et al. 2016). During fermentation, the pectin content in the must is metabolised by yeast, forming galacturonic acid and generating methanol (Bortoletto and Alcarde 2015). Sample CA-19 (8.8 mg/100 mL AA) contained the highest concentration of methanol ($p<0.05$) (Table 1), with sample CM-02 (0.26 mg/100 mL AA) containing the least ($p<0.05$). The presence of methanol in the heart fraction of commercial cachaça suggests that the sugarcane contained pectin which on extraction into the must resulted in the formation of methanol.

The ‘resting’ period between fermentation and distillation results in yeast separation and product stabilisation. This results in the generation of desirable flavour compounds, reduction of harsh notes, increasing complexity, and improved consistency. In long resting or aging, n-butyl alcohols (1-butanol) and sec-butyl alcohols (2-butanol) are formed by bacterial action (Bortoletto et al. 2018). Sample CA-13 (1.7 mg/100 mL AA) contains a higher concentration of 1-butanol ($p<0.05$) (Table 1), with a tenfold lower level in CA-19 (0.15 mg/100 mL AA) ($p<0.05$). This suggests that some producers will need to evaluate their practices during resting period to minimise the formation of 1- and 2-butanol which remain post distillation in the hearts fraction.

The carcinogen acrolein (2-propenal) is a mutagen of humans and animals (Zhang and Schwab 2022). It is produced during fermentation by bacterial contamination, or during distillation by dehydration of glycerol in the presence of acids on hot metal surfaces. Acrolein also contributes undesirable off-flavours together with an unpleasant peppery and horseradish-like aroma (Rosa et al. 2009; Masson et al. 2012). Acrolein is more volatile than ethanol and is removed in the heads fraction during distillation (Masson et al. 2012; Alvarenga et al. 2023). All samples of cachaça in this work were free from acrolein, suggesting they were produced using good fermentation and distillation practices.

Ethyl carbamate is also carcinogenic and is formed during fermentation, distillation and aging of cachaça (Nóbrega et al. 2009; Alcarde et al. 2012; Machado et al. 2013; Bortoletto and Alcarde 2015, Mendonça et al. 2016; Santiago et al. 2017). With the exception of CM-03 (419.4 µg/L, $p<0.05$), the other crystal cachaças (Table 1), contained levels of ethyl carbamate below the legal limit of 210 µg/L (Brazil 2022) with it undetectable in CA-14 and CA-16. Ethyl carbamate is formed by the enzymatic degradation of cyanogenic glycosides in sugar cane, involving the cyanide ion, which is oxidised to cyanate, which reacts with ethanol in the presence of copper (Lachenmeier et al. 2010; Bortoletto and Alcarde 2015). Effective separation of the heads, hearts and tails fractions reduces the levels of ethyl carbamate, as it is found primarily in the head fraction. Further, double distillation it effective in reducing the level of ethyl carbamate in cachaça (Nova et al. 2009; Alcarde et al. 2012; Rota et al. 2013; Bortoletto et al. 2016; Santiago et al. 2017).

Aroma profile by compound groups

The aroma of cachaça is important in its appeal, branding and marketing. This work identified 85 volatile compounds (31 terpenes, 21 esters, 15 alcohols, 11 aldehydes and seven ketones) (Figure 2). Cachaça produced in the Mata, Agrest and Sertão mesoregions differed reflecting the different edaphoclimatic conditions (soil and climate), field and industrial practices. Cachaça CA-02 contained the highest concentration of terpenes, alcohols and esters with CA-13, CA-20 and CM-01 containing high levels of ketones, esters, alcohols and aldehydes. Geographic origin results in variations that drive different flavour profiles and contribute to the complexity of Cachaça, which in turn is influenced by field and industrial variables.

The aroma profile of cachaça (terpenes, alcohols, esters, ketones, and aldehydes) changed when produced in a different mesoregion (Figure 2). The main compounds which changed when produced within different mesoregion were alcohols, esters, ketones, and aldehydes reflecting edaphoclimatic factors (including adaptation of sugarcane genotypes, and open fermentation vessels) and industrial practice (Figure 2). In contrast, when produced within same mesoregion, the aroma profile of cachaça was similar.

Terpenes originate from raw materials influenced by sugarcane genotype and edaphoclimatic conditions. However, terpenes are significantly influenced by the storage conditions prior to bottling such short ageing with inert stainless steel tanks or wooden barrels (freijó or jequitibá) (Alcarde et al. 2014; Bortoletto 2023). With wooden barrels, levels of acetic acid, glycerol, esters, higher alcohols, ketones, aldehydes, and terpenes change, improving the sensory character of the spirit without impacting on colour.

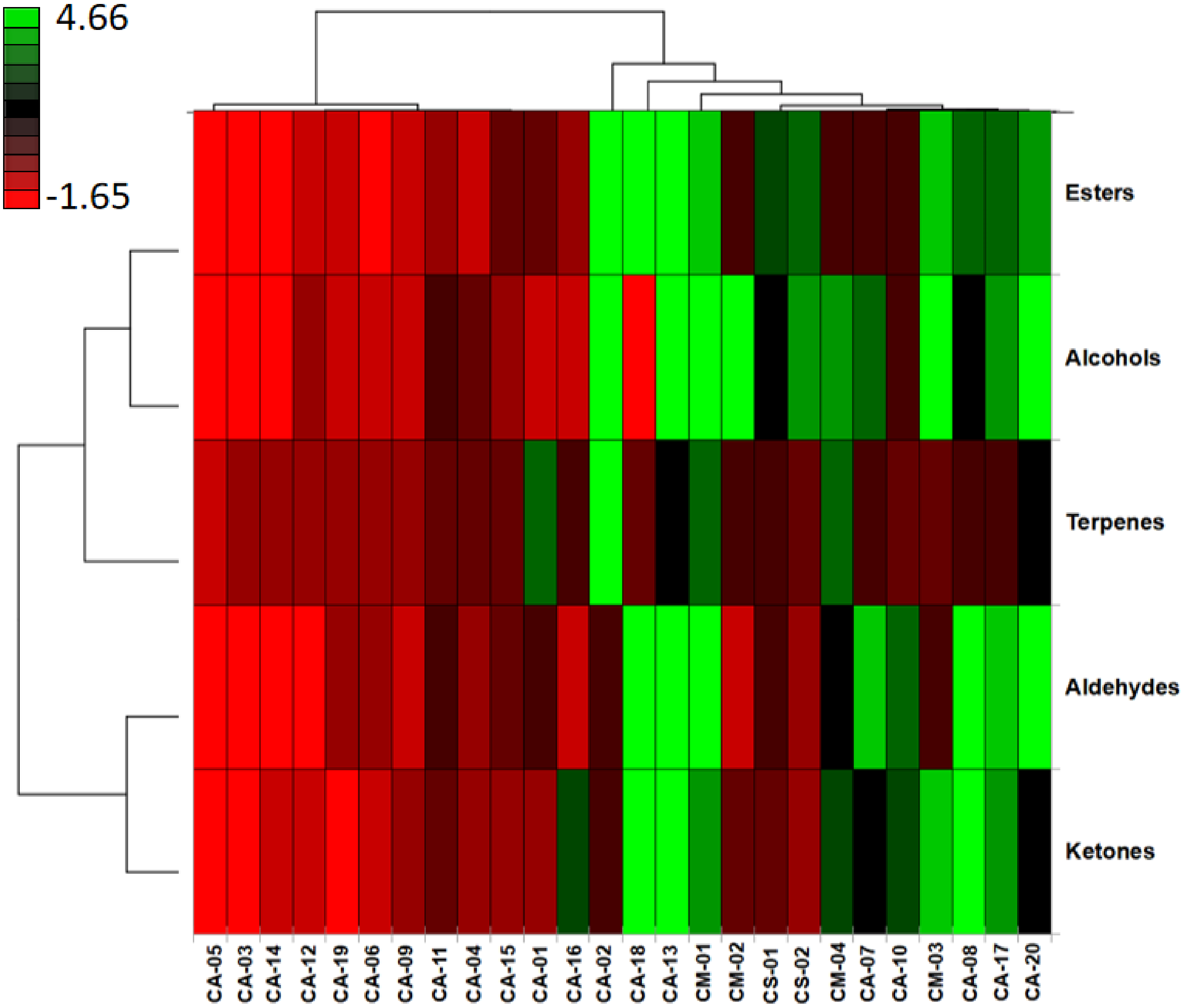
Summary of all cachaça samples

Higher alcohols

Principal component analysis (PCA) of the alcohol profile of the cachaça samples explained 65% of the data variance, with axes PC1 (38.5%) and PC2 (26.5%) accounting for the explained variance (Figure 3A). With PC1 the alcohol profile of cachaça from Sertão mesoregion (CS-01 and CS-02) differed from the Mata mesoregion (CM-01 and CM-03). However, CS-01 and CS-02 showed similarities with CM-02 and CM-04 from the Mata mesoregion. PC2 revealed that some of cachaça samples from Mata and Sertão mesoregions differed from that in Agreste mesoregion, but was not the case with CA-14, CA-19, CA-17, CA-16, CA-02, CA-20 and CA-13 (Figure 3A). Of the alcohols with important sensory characteristics, phenethyl alcohol contributes alcoholic, flowery, honey-like, rose and sweet aromas whilst isoamyl alcohol - precursor to isoamyl

Figure 2.

Heat map of volatile compounds (ketones, esters, alcohols, aldehydes and terpenes) in 26 samples of crystal cachaça produced in three mesoregions in Paraíba. CA – Cachaças do Agreste, CM – Cachaças da Mata; CS – Cachaças do Sertão.



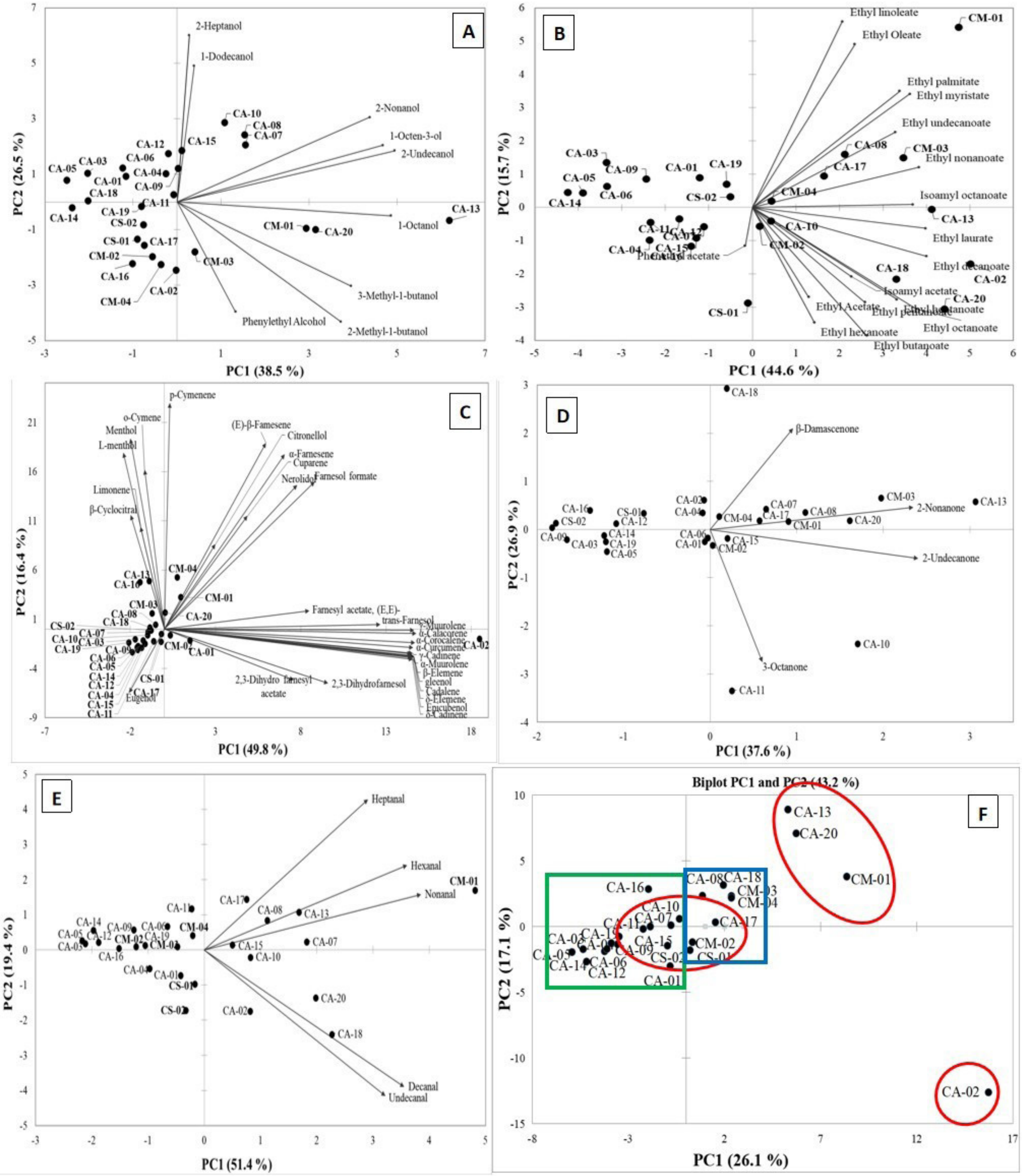
acetate - gives fruity (banana), sweet, alcoholic, winey aromas (Portugal et al. 2016). Cachaças produced in the agreste mesoregion contain low concentrations of isobutyl alcohol. Other higher alcohols such as n-propanol were not identified in cachaças from Paraíba due to removal in the head fraction.

Esters

PCA of the main components of the ester profile of cachaça (Figure 3B) explained 60.2% of the data variance with PC1 representing 44.6% and PC2 15.7%. PC1 revealed that the ester profile of twelve cachaças from the Agreste mesoregion and two from the Sertão mesoregion differed from the cachaças from the Agreste mesoregion and eight from Mata mesoregion. PC2 revealed similarities between cachaça from Mata mesoregions and the Agreste mesoregion, with others showing greater expression of phenethyl acetate. This compound contributes fruity, floral, honey and sweet aromas (Figure 3B). Cachaças from the Mata mesoregion and some from the Agreste mesoregions, contain fatty acid esters, which contribute to the aroma, flavour and viscosity of the drinks. Some are derived from fermentation, but most relate to distillation

Figure 3.

Principal component analysis (biplot) of volatile compounds in cachaça including (A) alcohols, (B) esters, (C) terpenes, (D) ketones and (E) aldehydes. PCA score plot (F) shows variations in the overall aroma profile of cachaças. 26 crystal cachaças produced in three different geographic regions were evaluated. CA – Cachaças do Agreste, CM – Cachaças da Mata; CS – Cachaças do Sertão. The compounds are represented by vectors and the cachaça samples are represented in black dots.



and aging (Bortoletto et al. 2018). However, as most of the cachaça samples were aged/rested in stainless steel tanks, most of these compounds were formed during distillation. In contrast, some producers rest crystal cachaça in wooden barrels for short periods of time which can influence the formation of these aromatic compounds (Bortoletto and Alcarde 2015).

The main components for the terpene profile of the cachaça samples explained 66.2% of the data variance, with PC1 presenting 49.8% and PC2 16.4% of the explained variance (Figure 3C). PC1 revealed that difference among the terpene profile of cachaças from the Sertão and Mata mesoregions. A lower concentration of terpenes was found in cachaça from the Sertão and Agreste mesoregions, with the exception of CA-02 (Brejo microregion), which contained high concentrations of terpenes leading to woody and herbal aromas. PC2 revealed differences among the terpene profile of cachaça produced in the Sertão and Mata mesoregions. The terpene profile of sample CA-02 differs from all other samples with the highest concentration of terpenes - muurolene, epicubenol, and cadalene and gleenol - which present floral, citrus fruity, sweet and herbal aromas.

Terpenes

Before bottling, short storage in freijó (*Cordia goeldiana*) or jequitibá wooden barrels improves the spirit without adding colour. The storage time and size of the barrels influences the compounds released into the spirit. Terpenes such as α-muurolene and δ-elemene are associated with aging in wooden barrels made from *Amburana cearenses* and *Cedrella fissilis* (Guedes et al. 2022). The terpene nerolidol is found during resting or aging in chestnut (*Bertholletia excelsa*) and cabreúva (*Mycrocarpus frondosus*) barrels. Cachaça can contain terpenes such as menthol, nerolidol, farmesol, 2,3 dihydrofarnesol, limonene, (E)-β-Famesene and eugenol, which contribute floral, citrus fruity and spicy aromas (Santiago et al 2016; Oliveira et al. 2020). Therefore, the terpene profile of colourless cachaças is impacted by geographic origin (soil and climate), field practice (sugarcane genotypes and adaptation) and industrial practice (maturation in wooden barrels).

Ketones

The main components of the ketone profile (Figure 3D) explained 64.5% of the data variance, the PC1 accounting for 37.6% and PC2 for 26.9% of the explained variance. PC1 showed a lower level of ketones in cachaça produced in the Sertão mesoregion than in the Mata mesoregion (Figure 3D). PC2 revealed differences between cachaça from the Sertão and Mata mesoregions. Ketones such as 2-heptone, 2-nonanone, and 2-undecanone were found in all samples. These compounds contribute to aroma including grass, fruity, and floral (Zhang et al. 2020). Ketones are formed by degradation of amino acids through microbial transamination (Ehrlich pathway) (Zhang et al. 2023). Amino acids - isoleucine, leucine, and valine - undergo catabolism with amino transferases, produce α-ketoic acids, which are converted into ketones (Zhang et al. 2020; 2023).

Aldehydes

The main components for the aldehyde profile of the cachaças (Figure 3E) explained 70.8% of the data variance, with PC1 accounting for 51.4% and PC2 for 19.4%. Sample CM-01 from the Mata mesoregion, the highest concentration of aldehydes than those from Agreste and Sertão.

PC2 revealed differences among cachaças from Sertão mesoregion and some from Mata and Agreste. Aldehydes are formed through oxidation of alcohols, Strecker oxidative degradation of amino acids and autoxidation of unsaturated fatty acids during fermentation (Escudero et al. 2025; Bueno-Aventin et al. 2021). Aldehydes with up to eight carbon atoms have an unpleasant aroma with those with more than ten carbon atoms contributing an unpleasant taste and aroma to beverages (Escudero et al. 2025). Good manufacturing practice, fermentation control and adequate separation of the head fraction are necessary to manage the aldehyde content. Acetaldehyde is the main aldehyde present in cachaça, which generates a fruity and an herbaceous aroma; however, high levels produce a pungent and irritating aroma (Alcarde et al. 2014; Portugal et al. 2017; Bortoletto et al. 2018).

Overall

The PCA score plot illustrates variations in the overall aroma profile of cachaças, highlighting key compounds as higher alcohols, esters, ketones, aldehydes, and terpenes (Figure 3F). The plot distinguishes four main groups based on similarities: Group 1 consisting of CA-02, Group 2 containing three samples (CA-13, CA-20, and CM-01), seven in Group 3 (CA-18, CA-08, CM-03, CM-04, CA-17, CM-02, and CS-01), and the largest Group 4 with 15 samples (CA-16, CA-10, CA-11, CA-19, CA-15, CA-07, CA-03, CA-12, CA-05, CA-06, CA-04, CS-02, CA-09, CA-14, and CA-01) (Figure 3F). This suggests that while some samples share compositional characteristics, differences exist among cachaças from the same mesoregion, reinforcing the cachaça terroir.

Variations are also seen within a single mesoregion due to microregional edaphoclimatic conditions and local industrial practices. The Agreste mesoregion consists of nine microregions, with the Brejo Paraibano being the biggest producer of cachaça in Paraíba. It is important to note that in Brejo Paraibano, Areia (a municipality) is the 'Capital Paraibana da cachaça' (CPC), reflecting the volume and quality of cachaça produced. Notably, all samples from the CPC were similar, except for CA-13 (Figure 3F). Therefore, cachaças produced in Areia differ from most of cachaças from Agreste (same mesoregion) and Mata and Sertão.

Despite belonging to the same mesoregion, cachaças from different microregions display unique characteristics, suggesting the influence of geographic origin and industrial practice. The PCA plot indicates that samples from the Agreste, Mata, and Sertão mesoregions do not form separate clusters, suggesting there are overlapping compositional traits. This may result from shared agricultural practices, similar industrial processes, or that sugarcane is obtained from other mesoregions, or that adaptations in sugarcane genotype are comparable in response to edaphoclimatic conditions. However, differences in soil composition, rainfall, and temperature across these mesoregions contribute to distinct sugarcane must fermentations, leading to variations in chemical composition of cachaça.

Edaphoclimatic factors, including soil composition, nutrient availability, and climate (temperature and rainfall), affect selection of sugarcane genotype, field management strategies, and industrial processing techniques (Carvalho and Furtado 2018; Medeiros-Silva et al. 2019). Essential nutrients in the soil determine fertilisation requirements, while insufficient rainfall requires irrigation, influencing sugarcane growth and chemical composition. These environmental conditions shape not only the raw material but also yeast metabolism during fermentation. The amino acid profile of sugarcane, determined by soil and climate conditions, influence the type and concentration of aroma compounds produced by yeast during fermentation (Parish 1965; Hazelwood et al. 2008). Field practices, shaped by environmental constraints, guide industrial decisions. In the Brejo Paraibano microregion, producers traditionally employ spontaneous fermentation in open vessels, fostering diverse microbial communities that contribute to complex flavour profiles. In contrast, producers in the Mata and Sertão mesoregions store colourless cachaça in neutral wooden barrels (jequitibá or freijó) for up to a year. Such maturation periods allow the extraction of ketones, aldehydes, higher alcohols, terpenes, and esters, enhancing aromatic complexity.

Accordingly, variations in chemical composition and aroma profile are the result of the dynamic interplay between edaphoclimatic factors, field and industrial practices (Capitello et al. 2021). This study contributes to a greater understanding of how these elements - including environmental conditions, sugarcane genotype adaptation, fermentation processes, and ageing techniques - shape the sensory and compositional attributes of cachaça. The similarities and differences across mesoregions, microregions, and even within the same microregion highlight the complex interactions between natural and human influences. This research reinforces the view that the terroir of cachaça is a multifactorial construct, shaped by the synergy between edaphoclimatic variability, agricultural decision making, and industrial technique. These factors exert an influence on the chemical composition and sensory identity of the spirit.

From an industrial standpoint, the regulatory framework governing cachaça production in Brazil is essential for maintaining product quality, safety, and market credibility. Adhering to these rigorous standards demonstrates dedication to genuine, high quality cachaça. Compliance with regulations minimises inconsistencies in quality, enhances consumer trust, and helps preserve the reputation of the spirit nationally and internationally. Cachaça's aroma profile, which consists of 85 volatile compounds - including alcohols, esters, terpenes, ketones, and aldehydes - is influenced by complex interactions. Differences in soil composition, temperature, and precipitation across the Mata, Agreste, and Sertão mesoregions impact sugarcane genotype adaptation and cultivation techniques. These environmental factors, in conjunction with field practices and industrial processing – including fermentation control, distillation management, and storage strategies - play a key role in determining the chemical composition which shapes the aroma and quality of cachaça.

Production practices contribute to the differentiation of cachaças through maturation techniques such as resting in stainless steel tanks or ageing in wooden barrels to enhance flavour complexity and aroma development while maintaining its clear appearance (Alcarde et al. 2014; Santiago et al. 2017). These storage strategies reflect how edaphoclimatic conditions, in tandem with agricultural and industrial practices, influence the final product. Consequently, cachaças from different Paraíba mesoregions with different production practices result in distinct sensory attributes and associated market appeal.

Our findings contribute to a more comprehensive understanding of the characteristics and flavour profile of cachaça, offering potential insights to consumer preference. This study underscores the importance of maintaining and improving standards of product quality while demonstrating that geographic origin, together with cultivation and production strategies, influences quality.

Furthermore, this work provides deeper insights into the geographic origin of cachaça, which encompasses the interplay of environmental factors, soil composition, sugarcane genotype adaptation, fermentation, distillation, maturation, aging, and local traditions (Da-Silva et al. 2023). These elements, collectively influenced by the edaphoclimatic context and human intervention through the production chain, define the characteristics of cachaça and contribute to its geographical indication. Given its complexity, future studies on cachaça production require a multidisciplinary approach. Research should focus on: (1) developing aging protocols for different types of wood barrels and chips, (2) the selection of yeasts from different geographic origins, (3) the differentiation of cachaça from similar geographic regions, (4) evaluating the contribution of regionally selected yeast strains to aroma and flavour, (5) applying mid-infrared (MIR) and near-infrared (NIR) spectroscopy to characterise distillation and aging, and (6) correlating MIR and NIR data with sensory analysis. Together, these studies will provide a better understanding of cachaça terroir. This will aid consumers and producers in recognising the diversity and complexity of this iconic Brazilian spirit. Such factors advocate for the unique sensory and quality attributes of cachaça, reinforcing the argument that cachaça possess a distinct terroir. This concept is important in distinguishing regional specialities and promoting the cultural and economic significance on a broader scale.

Conclusions

The compliance with legal standards for cachaças produced in the state of Paraíba was evaluated. Five producers would be advised to improve their industrial practices to ensure better control of copper levels. Specifically, producer CM-03 should optimise the separation of the head fraction during distillation, while the producers of CA-05, CA-07, CA-10, CA-12, and CA-19 need to enhance the cleaning protocols of copper stills. Variation in aroma profile is influenced by geographic origin but also by edaphoclimatic conditions, field practices (sugarcane management), and decisions during fermentation, distillation, and storage. Together, the origin and production knowledge shape the sensory appeal and market differentiation of cachaça. In this study, 85 volatile compounds were identified in colourless cachaças from different mesoregions of Paraíba, revealing regional differences. Most cachaças from the Agreste mesoregion exhibit distinct aroma profiles compared to those from the Mata region. Whereas, cachaças from the Sertão region share more similarities with those from Agreste, reflecting their similar industrial practices. Such compositional differences are a result of the interplay between soil type, climate, adaptation of sugarcane genotype, field management, and industrial techniques. Collectively, they contribute to the complexity and distinctive flavour profiles that characterise regional cachaças and influence consumer preference.

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Author contributions

Vanessa Da-Silva: conceptualisation, data curation, formal analysis, investigation, methodology, software, validation, visualisation, writing (original draft).
Eike Torres: formal analysis, methodology.
Leila Carvalho: formal analysis, methodology.
Mércia Galvão: formal analysis, methodology.
Marta Madruga: formal analysis.
Normando Ribeiro-Filho: conceptualisation, data curation, formal analysis, supervision, investigation, methodology, software, validation, visualisation, writing (original draft, review and editing).
Taliana Bezerra: conceptualisation, supervision, funding acquisition, project administration, writing (review and editing).

Conflict of interest

The authors declare there are no conflicts of interest.

References

Alcarde AR, Souza LM, Bortoletto AM. 2014. Formation of volatile and maturation related congeners during the aging of sugarcane spirit in oak barrels. *J Inst Brew* 120:529-536. https://doi.org/10.1002/jib.165

Alcarde AR, Souza LM, Bortoletto AM. 2012. Ethyl carbamate kinetics in double distillation of sugarcane spirit: Influence of type of pot still. *J Inst Brew* 118:352-355. https://doi.org/10.1002/jib.48

Alvarenga GF, Machado AMR, Barbosa RB, Ferreira VRF, Santiago WD, Teixeira ML, Nelson DL, Cardoso MG. 2023. Correlation of the presence of acrolein with higher alcohols, glycerol, and acidity in cachaças. *J Food Sci* 88:1753–1768. https://doi.org/10.1111/1750-3841.16523

AOAC (2000). Official Methods of Analysis. Gaithersburg, Maryland, USA: Association 536 of Official Analytical Chemists. *Methods* 942.06, 945.08.

Böck C F, Helfer GA, Costa AB, Dessuy MB, Ferrão MF. 2022. Low-cost method for copper determination in sugarcane spirits using Photometrix UVC® embedded in smartphone. *Food Chem* 367:130669. https://doi.org/10.1016/j.foodchem.2021.130669.

Borges GBB, Gomes FCO, Badotti F, Silva ALD, Machado AMR. 2014. Selected *Saccharomyces cerevisiae* yeast strains and accurate separation of distillate fractions reduce the ethyl carbamate levels in alembic cachaças. *Food Control* 37:380-384. https://doi.org/10.1016/j.foodcont.2013.09.013

Bortoletto AM, Alcarde AR. 2016. Assessment of ethyl carbamate contamination in sugarcane spirit (Brazilian sugarcane spirit). *Beverages* 2:28. https://doi.org/10.3390/beverages2040028

Bortoletto AM, Correa AC, Alcarde AR. 2016. Aging practices influence chemical and sensory quality of sugarcane spirit. *Food Res Int* 86:46–53. https://doi.org/10.1016/j.foodres.2016.05.003

Bortoletto AM, Silvello GC, Alcarde AR. 2018. Good manufacturing practices, hazard analysis and critical control point plan proposal for distilleries of cachaça. *Sci Agric* 75 (5). https://doi.org/10.1590/1678-992X-2017-0040

Bortoletto AM, Silvello GC, Alcarde AR. 2021. Aromatic profiling of flavor active compounds in sugarcane spirits aged in tropical wooden barrels. *Braz J Food Technol* 24, e2019071. https://doi.org/10.1590/1981-6723.07119

Bortoletto AM. 2023. Chapter 3 - Rum and cachaça, p 61-74. *In* Hill A, Jack F (eds). *Distilled Spirits,* Academic Press. https://doi.org/10.1016/B978-0-12-822443-4.00013-X

Bueno-Aventin E, Escudero A, Fernandez-Zurbano P, Ferreira V. 2021. Role of grape-extractable polyphenols in the generation of Strecker aldehydes and in the instability of polyfunctional mercaptans during model wine oxidation. *J Agric Food Chem* 69:15290-15300. https://doi.org/10.1021/acs.jafc.1c05880

Capitello R, Agnoli L, Charters S, Begalli D. 2021. Labelling environmental and terroir attributes: Young Italian consumers' wine preferences. *J Cleaner Prod* 304: 126991. https://doi.org/10.1016/j.jclepro.2021.126991

Carvalho SAD, Furtado AT. 2018. Production, technology and adaptation to climate changes: The challenges to the sugarcane sector in Brazil. *Energ Agric* 33:358-66. https://doi.org/10.17224/EnergAgric.2018v33n4p358-366

Chen Y, Daviet L, Schalk M, Siewers V, Nielsen J. 2013. Establishing a platform cell factory through engineering of yeast acetyl-CoA metabolism. *Metab Eng* 15:48-54. https://doi.org/10.1016/j.ymben.2012.11.002

Da-Silva VP, De Souza JB, De Queiroz AL, Ribeiro-Filho N, Bezerra, TK. 2023. Cachaça production: from sugar cane to spirit. *J Inst Brew* 129:259-275. https://doi.org/10.58430/jib.v129i4.40

Escudero A, Bueno-Aventín E, Ontañón I, Fernádez-Zurbano P, Ferreira V. 2025. The role of polyphenols in oxygen consumption and in the accumulation of acetaldehyde and Strecker aldehydes during wine oxidation. *Food Chem* 466:142242. https://doi.org/10.1016/j.foodchem.2024.142242

Galdieri L, Zhang T, Rogerson D, Lleshi R, Vancura A. 2014. Protein acetylation and acetyl coenzyme A metabolism in budding yeast. *Eukaryot Cell* 13:1472-83. https://doi.org/10.1128/EC.00189-14

Guedes UH, Nascimento MF, Silva DAL, Christoforo AL, Lahr FAR, Panzera TH, Aquino VBM, Saraiva RLP. 2022. Physico-chemical characterization of tropical wood species for use and production of grilling planks. *Mat Res* 25. https://doi.org/10.1590/1980-5373-MR-2021-0206

Hazelwood L, Daran J, van Maris A, Pronk J, Dickinson J. 2008. The Ehrlich pathway for fusel alcohol production: A century of research on *Saccharomyces cerevisiae* metabolism. *Appl Environ Microbiol* 74:3920-3920. https://doi.org/10.1128/AEM.02625-07

Lachenmeier DW, Lima MC, Nóbrega, IC, Pereira JA, Kerr-Corrêa F, Kanteres F, Rehm J. 2010. Cancer risk assessment of ethyl carbamate in alcoholic beverages from Brazil with special consideration to the spirits cachaça and tiquira. *BMC Cancer* 10:1–15. https://doi.org/10.1186/1471-2407-10-266

Machado AMR, Cardoso MG, Sacz, AA, Anjos JP, Zacaroni LM, Dórea HS, Nelson DL. 2013. Determination of ethyl carbamate in cachaça produced from copper stills by HPLC. *Food Chem* 138:1233-1238. https://doi.org/10.1016/j.foodchem.2012.11.048

Masson J, Cardoso Mg, Zacaroni Lm, Anjos Jp, Sackz Aa, Machado Amr, Nelson DL. 2012. Determination of acrolein, ethanol, volatile acidity, and copper in different samples of sugarcane spirits. *Food Sci Technol* 32 (3). https://doi.org/10.1590/S0101-20612012005000075

Medeiros-Silva WK, de Freitas GP, Coelho Junior LM, Pinto PALA, Abrahão R. 2019. Effects of climate change on sugarcane production in the state of Paraíba (Brazil): a panel data approach (1990–2015). *Clim Change* 154:195–209. https://doi.org/10.1007/s10584-019-02424-7

Mendonça JGP, Cardoso MG, Santiago WD, Rodrigues LMA, Nelson DL, Brandão RM, Silva BL. 2016. Determination of ethyl carbamate in cachaças produced by selected yeast and spontaneous fermentation. *J Inst Brew* 122:63-68. https://doi.org/10.1002/jib.308

Miranda K, Dionísio AGG, Pereira-Filho ER 2010. Copper determination in sugar cane spirits by fast sequential flame atomic absorption spectrometry using internal standardization. *Microchem J* 96:99-101. https://doi.org/10.1016/j.microc.2010.02.011

Nóbrega ICC, Pereira JAP, Paiva JE, Lachenmeier DW. 2009. Ethyl carbamate in pot still cachaças (Brazilian sugarcane spirits): Influence of distillation and storage conditions. *Food Chem* 117:693-697. https://doi.org/10.1016/j.foodchem.2009.04.067

Nova MXV, Schuler ARP, Brasileiro BTRV, Morais-Jr MA. 2009. Yeast species involved in artisanal cachaça fermentation in three stills with different technological levels in Pernambuco, Brazil. *Food Microbiol* 26:460–466. https://doi.org/10.1016/j.fm.2009.02.005

Oliveira RES, Cardoso MG, Santiago WD, Barbosa RB, Alvarenga GF, Nelson DL. 2020. Physicochemical parameters and volatile composition of cachaça produced in the state of Paraíba, Brasil. *Res Soc Dev* 9:e504974409. https://doi.org/10.33448/rsd-v9i7.4409

Parish DH. 1965. The amino-acids of sugar cane. I.—The amino-acids of cane-juice and the effect of nitrogenous fertilisation on the levels of these substances. *J Sci Food Agric* 16:240–242. https://doi.org/10.1002/jsfa.2740160502

Pietrocola F, Galluzzi L, Bravo-San Pedro JM, Madeo F, Kroemer G. 2015. Acetyl coenzyme A: a central metabolite and second messenger. *Cell Metab* 2:p805-21. https://doi.org/10.1016/j.cmet.2015.05.014

Portugal CB, Silva AP, Bortoletto AM, Alcarde AR. 2017. How native yeasts may influence the chemical profile of the Brazilian spirit, cachaça? *Food Res Int* 91:18-25. https://doi.org/10.1016/j.foodres.2016.11.022

Ribeiro-Filho N, Linforth R, Powell CD, Fisk ID. 2021. Influence of essential inorganic elements on flavour formation during yeast fermentation. *Food Chem* 361:130025. https://doi.org/10.1016/j.foodchem.2021.130025

Rosa CA, Soares AM, Faria JB. 2009. Chapter 34: Cachaça production, p 481-490, *In* Ingledew WM, Kelsall DR, Austin GD, Kluhspies C (eds), *The Alcohol Textbook*. 5th edition. Nottingham University Press.

Rota MB, Piggott JR, Faria JB. 2013. Sensory profile and acceptability of traditional and double-distilled cachaça aged in oak casks. *J Inst Brew* 119:251-257. https://doi.org/10.1002/jib.88

Santiago DW, Cardoso MG, Nelson DL. 2017. Cachaça stored in casks newly constructed of oak (*Quercus sp.*), amburana (*Amburana cearensis*), jatoba (*Hymenaeae carbouril*), balsam (*Myroxylon peruiferum*) and peroba (*Paratecoma peroba*): alcohol content, phenol composition, colour intensity and dry extract. *J Inst Brew* 123:232-241. https://doi.org/10.1002/jib.414

Santiago WD, Cardoso MG, Santiago JA, Teixeira ML, Barbosa RB, Zacaroni LM, Sales PF, Nelson DL 2016. Physicochemical profile and determination of volatile compounds in cachaça stored in new oak (*Quercus sp.*), amburana (*Amburana cearensis*), jatoba (*Hymenaeae carbouril*), balsam (*Myroxylon peruiferum*) and peroba (*Paratecoma peroba*) casks by SPME-GC–MS. *J Inst Brew* 122:624-634. https://doi.org/10.1002/jib.372

Serafim FAT, Pereira-Filho ER, Franco DW. 2016. Chemical data as markers of the geographical origins of sugarcane spirits. *Food Chem* 196:196-203. https://doi.org/10.1016/j.foodchem.2015.09.040

Solomon S. 2011. Sugarcane by-products based industries in India. *Sugar Tech* 13:408–416. https://doi.org/10.1007/s12355-011-0114-0

Takahashi H, Mccaffery JM, Irizarry RA, Boeke JD. 2006. Nucleocytosolic acetyl-coenzyme A synthetase is required for histone acetylation and global transcription. *Mol Cell* 23:p207-17. https://doi.org/10.1016/j.molcel.2006.05.040

Vidal EE, Morais Jr MA, François JM, Billerbeck GM. 2014. Biosynthesis of higher alcohol flavour compounds by the yeast *Saccharomyces cerevisiae*: impact of oxygen availability and responses to glucose pulse in minimal growth medium with leucine as sole nitrogen source. *Yeast* 32:47-56. https://doi.org/10.1002/yea.3045

Vilela AF, Oliveira LSC, Muniz MB, Melo BCA, Figueiredo MJ, Vieira Neto JM. 2021. Assessment of sensory and physical-chemical quality, and potential for certification of cachaças from the state of Paraíba, Brazil. *Food Sci Tech* 41:661-668. https://doi.org/10.1590/fst.13520

Zacaroni LM, Sales PF, Cardoso MG, Santiago WD, Nelson DL. 2017. Response surface optimization of SPME extraction conditions for the analysis of volatile compounds in Brazilian sugar cane spirits by HS-SPME-CG-MS. *J Inst Brew* 123: 226-231. https://doi.org/10.1002/jib.410

Zhang J, Schwab C. 2022. Is acrolein a reuterin-borne chemical hazard in biopreserved foods? *Food Chem Adv* 1:100044, https://doi.org/10.1016/j.focha.2022.100044

Zhang L, Mi S, Liu RB, Sang YX, Wang XH. 2020. Evaluation of volatile compounds during the fermentation process of yogurts by *Streptococcus thermophilus* based on odor activity value and heat map analysis. *Int J Anal Chem* 13:2020:3242854. https://doi.org/10.1155/2020/3242854

Zhang K, Zhang T, Guo R, Ye Q, Zhao H, Huang X. 2023. The regulation of key flavor of traditional fermented food by microbial metabolism: A review. *Food Chem*: X 19:100871. https://doi.org/10.1016/j.fochx.2023.100871