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Review Article

A state-of-the-art review of the chemical composition of sugarcane spirits and current advances in quality control

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ABSTRACT

Sugarcane spirits (*cachaça*) is one of the most traditional drinks in Brazil, being the third most consumed distilled beverage in the world. Chemically, a sugarcane spirit is considered a complex product and, among the production steps, the type of distillation directly influences the chemical composition and sensory characteristics of the product. However, some substances considered undesirable may be present in sugarcane spirits which can pose a risk to human health or decrease the sensory quality of the drink. Sugarcane spirit producers face major challenges, mainly related to the adoption of good production practices, which reflect the loss of quality and lack of standardization of the drink. The use of different instrumental analytical techniques used to identify and quantify the chemical compounds in sugarcane spirit was discussed in this study. Modern chemometric and artificial intelligence tools for data processing were reported, as well as the use of computer vision as a promising strategy in the identification of fraud, adulteration and non-compliance with legislation. Innovative methods are a trend in determining the quality of beverages, considering that most of them are characterized by being simple, fast, relatively low cost, efficient and environmentally correct.

1. Introduction

Cachaça is the typical and exclusive designation of the sugarcane spirits produced in Brazil, containing 38–48 % ethanol (v/v) at 20 °C, obtained by the single distillation of fermented sugarcane juice and can be aged or not (Bortoletto and Alcarde, 2013). *Sugarcane spirit* is the most widely consumed distilled beverage in Brazil (Cravo et al., 2019) being the third most consumed in the world (Oliveira et al., 2019) and it is important to highlight that the production is closely linked to regional heritage and geographic characteristics (Portugal et al., 2017).

Nationally, there are General Rules on Registration, Standardization, Classification and Inspection and Inspection of Production and Commerce of Beverages (Brazil. Ministério da Agricultura e do Abastecimento, 2009), following the parameters described in the ‘Normative Instruction N°. 13′ of July 29th, 2005 (Brazil. Ministério da Agricultura, Pecuária e Abastecimento, 2005) with modifications in the ‘Normative Instruction N°. 28 of August 8th, 2014 (Brazil. Ministério da Agricultura, Pecuária e Abastecimento, 2014). According to the sugarcane spirits yearbook of Brazil’s Ministry of Agriculture, Livestock and Food Supply (MAPA - Ministério da Agricultura, Pecuária e Abastecimento, 2021), in 2020, the number of Brazilian producers of sugarcane spirits was increased by 6.8 % in comparison to 2019, totalling 955 establishments with valid registration. Concerning trademark, this increase is even bigger (18.5 %), which in 2020, 4743 brands of sugarcane spirit were produced in Brazil. The state with the largest production is Minas Gerais, with Brazil’s southeast states corresponding to nearly 69

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% of the total production, showing the high economic importance of this spirits in the country (MAPA - Ministério da Agricultura, Pecuária e Abastecimento, 2021).

The production process of sugarcane spirits can be seen in Fig. 1. It is important to point out that while the aging process increases the product's overall quality and cost, it is not mandatory. Furthermore, the distillation process is one of the most important steps when it comes to ensuring product quality. This process can also be performed in two different devices: copper stills (usually used in the production of artisanal sugarcane spirits) or stainless-steel columns (favored in large scale production), as shown in Fig. 2.

According to sugarcane spirits connoisseurs, artisanal sugarcane spirits are of a higher quality than those industrially made. Artisanal sugarcane spirits produced in stills are described as having improved flavour and overall better sensory properties, furthermore, they may also be aged in wood barrels before selling, which increases their market value even further (Cardoso, 2021). During aging, many complex reactions take place, such as oxidation and esterification. These reactions reduce the concentration of important substances that improve the quality of the product from a sensory point of view (Aquino et al., 2006).

The greatest challenge that many sugarcane spirit producers face is to find new ways to increase product quality, while reducing the chances of possible contaminants (Ferreira et al., 2020), as well as joining the global market in order to increase export sales (Paiva et al., 2017). There is also the need to improve the production process as a whole, for, despite all the economic importance and tradition attributed to the production of sugarcane spirit, the production chain is not homogeneous in a technological sense. Thus, there is a need to pursue new technologies to improve and control the quality, as well as standardize the beverage (Santiago et al., 2020). Sugarcane spirit is also highly regarded for its characteristic flavour and aroma, which are formed during fermentation, distillation, and aging. The age of the spirits may be successfully determined based on the concentration of phenolic compound markers extracted from the lignin of the barrel's inner surface (Castro et al., 2020).

Due to market expansion, the average sugarcane spirits consumer becomes more and more discerning regarding the beverages' complex sensory properties. It is known that each vintage's characteristics are unique, however, chemical and sensory variations may occur even in a single harvest. The growth in production and the appreciation of sugarcane spirit in the domestic and foreign markets have directed the production of the beverage in Brazil with a focus on its quality and added value, seeking to obtain international recognition and increase exports (Caetano et al., 2021a).

A beverage's flavour and aroma tend to be the main attributes that a potential consumer considers when making their choice. In the case of alcoholic beverages, flavour and aroma are composed of many organic substances, volatile or not, formed during fermentation that remain even after the beverage undergoes the distilling process. Thus, it is possible to say that the chemical composition, flavour, and aroma of a specific alcoholic beverage are intimately linked to the manufacturing process (Silva et al., 2020a). Knowing that a beverage's sensory properties are a key consideration when attracting new customers, the proper knowledge of which components contribute to the product's sensory properties is essential for improving the quality of both artisanal and industrially made sugarcane spirits. With this in mind, this study aims to provide an overview of the chemical composition of sugarcane spirits and current advances in quality control.

2. Brazilian legislation

The distillation of sugarcane derived fermented wort results in a product that is composed of water, alcohols, aldehydes, acids, ketones and esters. The recently distilled beverage presents aggressive sensory features and a strong alcoholic flavour, aversive attributes that can be attenuated by aging. The volatile fraction of sugarcane spirits plays an important role in ensuring product quality and acceptance. Certain compounds may enhance the quality of sugarcane spirits and add aromatic notes to the bouquet of the beverage; however, above determined limits, they may lead to flaws. Volatile congeners are formed during the fermentation process and their presence in the product depends on the distillation method used (Alcarde et al., 2014).

The expansion of the sugarcane spirits consumer market encourages improvements in the production chain via the implementation of stricter controls and more detailed studies regarding the beverage's production process, as well as a focus on improving its chemical and sensory quality (Barbosa et al., 2016). A useful tool for the quality control of sugarcane spirit is the identification of its chemical compounds. Producers should control and evaluate the chemical composition of their beverages via periodic analyses, following the sampling procedures determined by Brazilian Law 8918 (Brazil. Ministério da Agricultura e do Abastecimento, 2009), so that their products remain in accordance with the minimum and maximum limits established by Brazil's Ministry of Agriculture, Livestock and Food Supply in the 'Normative Instruction N^{o}. 13′ (Brazil. Ministério da Agricultura, Pecuária e Abastecimento, 2005). This specific legislation determines the quality and identity parameters for sugarcane spirits produced in Brazil, with the parameters to be evaluated, alongside their minimum and maximum levels are described in Table 1. Besides the determination of compounds presented in Table 1, the concentration of total phenolic compounds must be verified in samples submitted to the aging process.

In order to modify the characteristics of a given product, as well as to

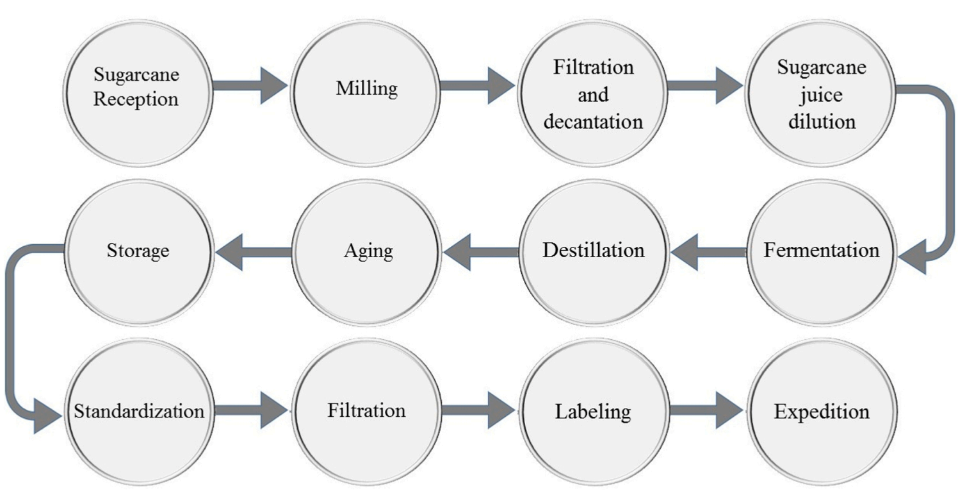

Fig. 1. Depiction of the major production stages of sugarcane spirits.

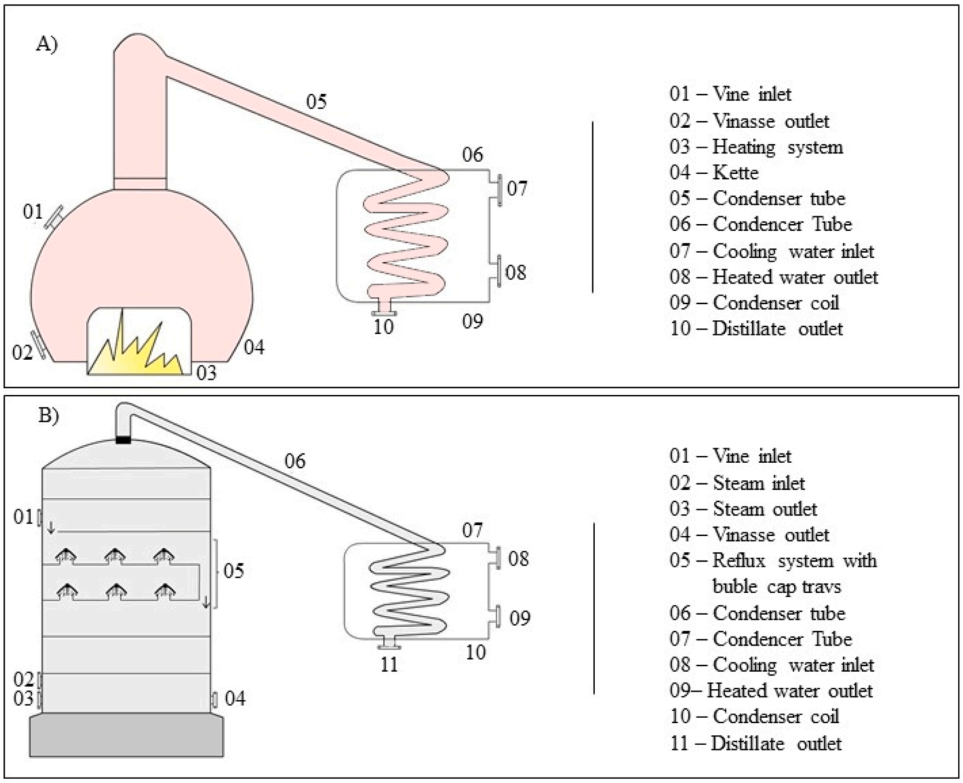

Fig. 2. Copper still (A) and continuous column distiller (B).
Source: Adapted from Riachi et al. (2014).

Table 1
Minimum and maximum tolerable limits for different components of *sugarcane spirit* according to Brazilian legislation.

	LIMITS Min. Max.	UNIT
COMPONENTS		
Alcohol content	38 48	% (v/v) of ethanol at 20 °C
Volatile acidity, as acetic acid	- 150	
Total esters, as ethyl acetate	- 200	
Total aldehydes, as acetaldehyde	- 30	
Furfural and Hydroxymethylfurfural	- 5	mg (100 mL of anhydrous alcohol)$^{-1}$
Higher alcohols *	- 360	
Congeners **	200 650	
CONTAMINANTS		
Methanol	20	
2-butanol	- 10	
1-butanol	- 3	mg (100 mL of anhydrous alcohol)$^{-1}$
Acrolein (2-propenal)	- 5	
Ethyl carbamate ***	- 210	
Lead	- 200	µg L^{-1}
Arsenic	- 100	
Copper	- 5	mg L^{-1}

Source: Brazil. Ministério da Agricultura, Pecuária e Abastecimento (2005).
Source: Brazil. Ministério da Agricultura, Pecuária e Abastecimento (2014).
* Higher alcohols: 2-metil-1-propanol, 2-metil -1−360-butanol + 3 metil-1-butanol, and 1- propanol.
** Congeners: Volatile acidity + esters + aldehydes + furfural+Hydroxymethylfurfural + higher alcohols.
*** Change made in legislation.

successfully implement quality control tools, it is crucial to know the final product's chemical composition (Bueno et al., 2020). Only through extensive quality control would it be possible to locate and treat possible contaminants that may be present in raw materials, all the way to the finished product. The presence of contaminants in distilled beverages has been the focus of many studies, mostly due to the impact they may have on the product's sensory characteristics, as well as the possibility of negatively impacting the consumer's health (Silva et al., 2022; Silva al., 2020b; Santiago et al., 2017; Duarte et al., 2017; Mendonça et al., 2016; Machado et al., 2014; Lachenmeier et al., 2010).

Table 2 shows the studies focused on the quality control of commercial products and a summary of the results is presented. According to Brazilian legislation, the concentration of ethanol in sugarcane spirit must be between 38 and 48 % ethanol at 20 °C. However, it is possible to observe that a relatively low amount of sugarcane spirit samples evaluated by Vilela et al. (2021) have ethanol contents above 48 %. Furthermore, in a study conducted by Vilela et al. (2007), the concentration of ethanol was below 38 % in approximately 10 % of the samples evaluated. In this sense, it appears that these products are not in accordance with the identity standard established in Brazil.

Bortoletto and Alcarde (2015) evaluated 268 samples of sugarcane spirit collected in the main producing regions of Brazil and found that 50.7 % did not meet the standards of identity and quality in Brazil (Table 2). Contaminants (ethyl carbamate, copper, 1-butanol and 2-butanol), higher alcohols and volatile acidity were the components that showed the greatest irregularities. These results indicated that producers face challenges in adopting good practices for the production of sugarcane spirit, in order to guarantee its quality and standardization. This demonstrates the importance of determining the compounds present in this drink, both to ensure its identity and to prevent damage to the health of consumers due to the presence of contaminants.

Vilela et al. (2021) evaluating the physicochemical quality of 38 samples of sugarcane spirit produced in the state of Paraiba/BR, obtained similar results to those found by Bortoletto and Alcarde (2015).

Table 2
Determination of the quality control of sugarcane spirit.

Substance	Analytical Technique	n	Results	Ref.
Alcohol content	GC-FID	38	10.0% of samples > BL.	Vilela et al., 2021
	GC-FID	268	4.9% of samples > BL.	Bortoletto, and Alcarde, 2015
	GC-FID	21	9.5% of samples lower than BL.	Vilela et al., 2007
Volatile acidity	GC-FID	268	16.4 % of samples > BL.	Bortoletto, and Alcarde, 2015
	GC-FID	38	65.0% of samples > BL.	Vilela et al., 2021
	GC-FID	13	15.4 % of samples > BL.	Mendes Filho et al., 2016
Esters (Ethyl Acetate)	GC-FID	268	1.5% of samples > BL.	Bortoletto, and Alcarde, 2015
	GC-FID	21	15.0% of samples > BL.	Mendes Filho et al., 2016
	GC-FID	38	5.0% of samples > BL.	Vilela et al., 2021
	GC-FID	21	All samples in accordance with BL.	Vilela et al., 2007
Aldehyde	GC-FID	268	6.3 % of samples > BL.	Bortoletto, and Alcarde, 2015
	GC-FID	21	19 % of samples > BL.	Mendes Filho et al., 2016
	GC-FID	38	All samples in accordance with BL.	Vilela et al., 2021
	GC-FID	21		Vilela et al., 2007
Furfural (HMF)	GC-FID	268	2.1 % of samples > BL.	Bortoletto, and Alcarde, 2015
	GC-FID	38	All samples in accordance with BL.	Vilela et al., 2021
Ethyl Carbamate	GC-FID	268	39.1% of samples > BL.	Bortoletto, and Alcarde, 2015
	GC-MS	38	15.0% of samples > BL.	Vilela et al., 2021
	GC-MS	18	5.6 % of samples > BL.	Guerreiro et al., 2018
2-butanol	GC-FID	268	12.5 % of samples > BL.	Bortoletto, and Alcarde, 2015
	GC-FID	21	38.0% of samples > BL.	Mendes Filho et al., 2016
	GC-FID	38	All samples in accordance with BL.	Vilela et al., 2021
	GC-FID	21		Vilela et al., 2007
1-butanol	GC-FID	268	7.7% of samples > BL.	Bortoletto, and Alcarde, 2015
	GC-FID	21	23.0% of samples > BL.	Mendes Filho et al., 2016
	GC-FID	38	All samples in accordance with BL.	Vilela et al., 2021
	GC-FID	21		Vilela et al., 2007
Methyl Alcohol	GC-FID	268	2.6 % of samples > BL.	Bortoletto, and Alcarde, 2015
	GC-FID	38	All samples in accordance with BL.	Vilela et al., 2021
Copper	FAAS	268	26.2% of samples > BL.	Bortoletto, and Alcarde, 2015
	FAAS	38	15.0% of samples > BL.	Vilela et al., 2021
	SWASV	90	25.0% of samples > BL.	Ferreira et al., 2020
	FAAS	21	67.0% of samples > BL.	Vilela et al., 2007
	FAAS	5	All samples in accordance with BL.	Tavares et al., 2012
	SPCPE-SiAt	4		Costa et al., 2011
	FAAS	21		

Table 2 (*continued*)

Substance	Analytical Technique	n	Results	Ref.
				Mendes Filho et al., 2016
Lead	CC	6	All samples in accordance with BL.	Moreira et al. (2012)
	FAAS	38		Vilela et al., 2021
	SWASV	90		Ferreira et al., 2020
	FAAS	21		Mendes Filho et al., 2016
	FAAS	5		Tavares et al., 2012
Arsenic	FAAS	38	All samples in accordance with BL.	Vilela et al., 2021

n: number of samples evaluated.
BL: Brazilian Legislation.
CC: Colorimetric Chemosensor.
FAAS: Flame Atomic Absorption Spectroscopy.
GC-FID: Gas Chromatograph with Flame Ionization Detection.
GC–MS: Gas Chromatograph coupled to a Mass Spectrometer.
SPCPE-SiAt: Solid Paraffin-based Carbon Paste Electrode modified with 2-aminothiazole-silicagel-Anodic Stripping Voltammetry.
SWASV: Square Wave Anodic Stripping Voltammetry.

According to Vilela et al. (2021), only 35 % of the evaluated samples meet the quality criteria in accordance with Brazilian legislation, directly influencing the lack of the certification seal for this product. Miranda et al. (2007) and Ferreira et al. (2020) also observed that 48 % of the evaluated samples were not in compliance with Brazilian legislation concerning at least one evaluated component. With this, it is observed that there is no homogeneity of the products. Furthermore, when it comes to the presence of contaminants, especially those of inorganic origin, few samples have concentrations within the limits established by Brazilian legislation, which can cause health problems for consumers. Several reasons are related to the lack of homogeneity of the evaluated sugarcane spirit samples, which depends mainly on the methods of production, good practices during production, among other factors, which will be described separately (desirable secondary compounds and contaminants) in this review.

3. Desirable secondary compounds

3.1. Organic acids and volatile compounds

3.1.1. Acidity

Organic acids are expressed as total acidity, which is composed of volatile acidity and fixed acidity. Volatile acidity is used to determine the acidity quality control of sugarcane spirit, which is expressed in acetic acid. In addition to acetic and lactic acid, which are normal byproducts of alcoholic fermentation, formic, butyric and propionic acids, among others, may be present. The formation of acetic acid may be caused by contamination of the sugarcane wort by acetic bacteria or even by the yeast itself, as it may produce acetic acid (Cardoso, 2021).

Many other non-volatile acids may also be formed, mostly coming from the natural metabolism of the yeast used in the fermentation process. Examples include oxaloacetic acid, as well as citric, pyruvic, malic, and maleic acids. Another reason as to the formation of acidic compounds during the fermentation of sugarcane spirit is related to the yeast's transition from an aerobic metabolic route (during the exponential growth phase), to an anaerobic one (during the fermentation proper), where many short-chain fatty acids are formed. During the exponential growth phase, yeasts tend to produce long-chain fatty acids, used mostly to create membranes necessary for mitosis to occur. Once the yeast changes into the anaerobic metabolic route, they cease to produce these long-chain fatty acids, but acids containing (Miranda et al., 2007; Ferreira et al., 2020; Mendes Filho et al., 2016 and Costa et al., 2011) carbon atoms, such as butyric, caproic, caprylic, and capric acids, remain inside the yeast cells. Since these acids are no longer used by the cells, they are expelled as secondary metabolites to prevent them from interfering with the permeability of the cell membranes (Maia and Campelo, 2006).

During the distillation process, the initial portions of distillate have increased acidity, which is reduced during the middle stages of distillation and rises once again at the end of the process. The acidity of sugarcane spirit is related to the fermentation process and how it was conducted, with factors such as the predominant yeast strain, fermentation duration, as well as the distillation process temperature and duration being crucial in controlling the final acidity. During the fermentation process, aeration should be kept to a minimum, for an increase in oxygen causes the yeast to convert sugar into acetic acid instead of ethanol. Once the fermentation process is over, distillation should be done as soon as possible, in order to prevent the growth of acetic bacteria (Cardoso, 2021). Increased acidity in sugarcane spirits may be related to contamination of the raw materials or the wort by acetic bacteria, which causes ethanol produced by the yeast to be consumed and converted into acetic acid (Maia, 1994). The recently distilled beverage normally presents aggressive sensory characters and strong alcoholic flavour, aversive attributes that can be attenuated by aging (Bortoletto et al., 2016).

The presence of small amounts of acids in sugarcane spirits, however, is beneficial to its overall quality, for they react with alcohols, forming esters, which are responsible for creating the characteristic aroma of distilled beverages. Thus, it becomes evident that acidity plays a major role in giving sugarcane spirit its traditional flavour and rich aroma (Cardeal and Marriott, 2009)

The volatile acidity in sugarcane spirits is one of the parameters in greatest disagreement with the standards indicated in Brazilian legislation. According to the results shown in Table 2, in all studies in which volatile acidity was evaluated in sugarcane spirits, samples were found outside the limits set by Brazilian legislation.

Very similar results were found by Bortoletto and Alcarde (2015) and Mendes Filho et al. (2016), which found 16.4 and 15.4 %, respectively, of the samples with volatile acidity above 150 mg (100 mL of anhydrous alcohol)$^{-1}$. According to Bortoletto and Alcarde (2015), the lack of standardization and quality of these products is what still influences the low export of the product. In a study conducted on 268 samples of sugarcane spirit from all regions of Brazil, the volatile acidity expressed in acetic acid was performed using GC with flame ionization detection (FID). In this study, 16.4 % of the sugarcane spirit samples evaluated presented volatile acidity above the maximum value allowed by law. In addition to the acidity negatively influencing the sensory quality, it can cause greater solubilisation of metallic copper in distillers, thus increasing the concentration of this contaminant in the final product (Bortoletto and Alcarde, 2015; Boza and Horii, 2000).

3.1.2. Esters

Esters correspond to the majority of aromatic compounds in alcoholic beverages (Moreira et al., 2012), their production is associated with the fat metabolism of the yeast (alcoholysis of Acyl-CoA compounds) or, to a lesser degree, the esterification reaction between fatty acids and alcohols (Serafim and Lanças, 2019). A fragrant aroma, similar to that of ripened fruit is desirable and mostly related to the presence of esters, however, high amounts of these compounds may cause sugarcane spirits to have an overpowering aroma (Moreira et al., 2012).

Ethyl acetate and ethyl lactate are the main esters found in distilled alcoholic beverages (Gao et al., 2014). However, other compounds may also be present, such as isoamyl acetate, isobutyl acetate, 2-phenylethyl acetate, ethyl caproate (Peddie, 1990), ethyl hexanoate, ethyl octanoate, furfuryl acetate, phenyl acetate, diethyl succinate, 2-phenylethyl acetate, phenylethyl acetate, ethyl dodecanoate, ethyl tetradecanoate, and ethyl 9-hexadecenoate (Amorim et al., 2016). Some esters that are also usually found in sugarcane spirit may be responsible for its traditional characteristics, such as ethyl formate, n-pentyl acetate, octyl acetate, ethyl butyrate, and pentyl butyrate (Nascimento et al., 2008). According to Chaves and Povoa (1992), in sugarcane spirits, aromatic esters are formed in large part during the aging process, which gives the product its usual strong but pleasant aroma, contributing to its *bouquet*. A study by Caetano et al. (2021b) has shown that esters were the most prominent chemicals found in sugarcane spirits from the Salinas region (Minas Gerais, Brazil). The authors also suggest that these compounds are an integral part of the regional standard of sugarcane spirits.

According to the studies described in Table 2, it is possible to observe that, in general, the portion of sugarcane spirit samples that are in disagreement with the maximum allowed by the Brazilian legislation for the concentration of esters, expressed in ethyl acetate (200 mg/100 mL of anhydrous alcohol^{-1}) is low. In the work by Mendes Filho et al. (2016), content above the permitted level was found in 15 % of the 13 samples evaluated. Thus, it is observed that, in general, these compounds are present at adequate levels in Brazilian sugarcane spirit.

3.1.3. Aldehydes

Aldehydes are extremely volatile carbonyl based compounds, formed during the fermentation process, they are one of the main components responsible for giving sugarcane spirit its traditional flavour and aroma. Aldehydes can also be formed by oxidation reactions of amino acids, alcohols, or fatty acids (Moreira et al., 2012). Excessive aldehyde concentrations may lead to poisoning, which is related to serious issues in the central nervous system of humans. Aldehydes may display many different aromas, ranging from subtle to overwhelming, based on the presence of specific compounds and their concentration (Cardoso, 2021).

The most common aldehyde generated during alcoholic fermentation is acetaldehyde (Moreira et al., 2012). This compound, like other aldehydes, is produced by yeast cells during the initial stages of the fermentative process. Its concentration declines steadily until the final stages of fermentation, due to it being oxidized into acetic acid (Cardoso, 2021). Acetaldehyde may represent up to 90 % of the total aldehydes found in whiskey, rum, and brandy (Nykänen and Nykänen, 1991).

Aldehydes are usually determined by gas chromatography, as it is an easy-to-use technique and widely available in routine analytical laboratories. In this context, evaluating the results by Bortoletto and Alcarde (2015), Vilela et al. (2007, 2021) and Mendes Filho et al. (2016) by GC-FID observed very distinct results. Vilela et al. (2007, 2021) observed that all samples had aldehyde concentrations below those established by Brazilian legislation, Bortoletto and Alcarde (2015) observed only 6.3 % of samples with levels above the permitted level and Mendes Filho et al. (2016) found aldehyde contents slightly above the permitted level in 19 % of the samples evaluated. The presence of aldehydes above those established by Brazilian legislation can compromise the sensory quality of sugarcane spirits and also affect the consumer's health. Therefore, it is a worrying point to be considered and widely evaluated in sugarcane spirit industries, especially for producers who use the aging process, which is a factor that may be related to the increase in these compounds (Santiago et al., 2017).

3.1.4. Higher alcohols

Higher alcohols are mostly produced during wort fermentation and are important components responsible for giving sugarcane spirit its unique flavour and aroma (Nonato et al., 2001; Brasil, 2014; Teixeira et al., 2019). As a class, it encompasses all organic compounds with an alcohol functional group and more than two carbons in their molecular structure. The main ones found in alcoholic beverages are isoamyl, propyl, isobutyl and amyl alcohols (Piggott et al., 1989; Teixeira et al., 2019).

Their formation is influenced by the fermentation conditions, amount of yeast cells in the wort, fermentation temperature, and final alcohol content of the sugarcane wine. Most higher alcohols come from amino acid degradation that occurs during fermentation. These reactions are the most likely cause for the formation of D-amyl alcohol from D-leucine, isoamyl alcohol from L-leucine, and isobutyl alcohol from valine, which assist in giving alcoholic beverages their traditional aroma (Yokoya and Fabricação de aguardente de cana, 1995). Alcohols containing three to five carbon atoms may be formed in many different ways depending on the yeast strains growing in the wort. The formation of these alcohols is also attributed to some degree to the metabolic pathway used by the yeasts to consume sugars (Maia, 1994).

Cardoso et al. (2003), investigating the influence of the distiller material on the chemical composition of sugarcane spirits, verified that the higher alcohol content decreases in the following order, depending on the composition of the material used in the distillation: porcelain > stainless steel > copper > aluminium. When higher alcohols were evaluated in 268 samples of sugarcane spirit, approximately 26 % had levels higher than the maximum limit in Brazilian law (360 mg/100 mL anhydrous alcohol). This congener was not in compliance for the highest number of samples (Bortoletto and Alcarde, 2015).

3.1.5. Acetals

The 1,1-diethoxy-ethane acetals (acetaldehyde diethyl acetal) and 1-ethoxy-1-pentoxy-ethane (acetaldehyde ethyl pentyl acetal) are formed through reactions between aldehydes and alcohols. Both acetals have already been reported at relatively high levels in sugarcane spirits, 1,1-diethoxy-ethane should contribute to the final aroma of the beverage, either by reducing the pungent odour of the major aldehyde (acetaldehyde) or by providing aroma characteristics such as "refreshing", "fruity" and "green" (Nóbrega, 2003). According to Bortoletto and Alcarde (2013), the balance between free aldehydes, hemiacetal and acetal in sugarcane spirit is influenced by the pH and ethanol content of the product, and even the wood used for the barrel where the aging process is conducted.

3.2. Compounds produced during aging in wooden barrels

Brazilian legislation defines aged sugarcane spirits as a beverage containing at least 50 % sugarcane spirits aged in a wooden cask, with a maximum capacity of 700 L, for a period of at least one year. The legislation also requires phenolic compounds to be present in the beverage (Brazil. Ministério da Agricultura, Pecuária e Abastecimento, 2005).

The aging of sugarcane spirit in wooden casks is paramount to improve the product's overall qualities (Bortoletto et al., 2021; Winstel et al., 2020; Carvalho et al., 2020). Due to its well-known, and valuable sensorial characteristics, oak barrels have been used extensively in the aging process of sugarcane spirits. However, in Brazil, many native species of flora have also been used to produce barrels. Casks made from different species of wood add different sensorial properties to sugarcane spirits, with the wood of choice varying according to regional preference (Serafim and Lanças, 2019). During the aging process compounds found in the wood of the cask migrate to the sugarcane spirits, with the most relevant being volatile oils, phenolic compounds, sugars, glycerol, non-volatile organic acids and tannic substances that modify the flavor, aroma and color of the beverage. The aging process causes a significant increase in the product's dry extract content. This is due to the migration of non-volatile compounds from the wood into the liquid. Volatile acidity and aldehyde concentration are also increased due to the oxidation of ethanol and acetaldehyde. The esterification of alcohols and acids produces esters, which are responsible for the pleasant odor of aged beverages (Cardoso, 2021).

The beverage's maturation level can be determined based on the levels of phenolic compounds extracted from the lignin of the cask (vanillic acid, syringic acid, vanillin, syringaldehyde, coniferaldehyde, and sinapaldehyde, for example), which act as aging markers. The effects of the aging process are also influenced by the wood, charring, and previous use of the cask. The internal conditions of wooden casks are highly relevant to the quality of the spirit and the content of extractable compounds. The use of new barrels that underwent thorough charring, reduced the aging time considerably. The excessive reuse of the casks, however, creates products containing low amounts of lignin-derived products (Silvello et al., 2021).

It is known that low molecular weight phenolic compounds migrate from wood into the spirit during aging. The lignin transformations that occur during this step are among the most important factors that influence the quality of aged sugarcane spirits. Lignin macromolecules have branches of coniferyl and sinapyl alcohols. Coniferyl alcohol generates coniferaldehyde, which is converted into vanillin and, in turn, oxidized to vanillic acid. Sinapyl alcohol generates sinapaldehyde, which is transformed into syringaldehyde and later oxidized to sermic acid as described by Castro et al. (2020). These reactions are described in Fig. 3. Other compounds such as benzoic acid, cinnamic acid, tannins and coumarins are also frequently found in aged beverages. It is worthy of note that coumarins such as 1,2-benzopyrone have a history of being studied due to their relative toxicity to humans (Zacaroni et al., 2011b).

The qualitative characterization of sugarcane spirits during the aging process poses a significant challenge, since it involves subjective decisions and complex cognitive processes carried out by experienced tasters or a sensory panel. These tasters might also be undergoing constant training in order to characterize the spirit and ensure that it is in accordance with the brewer's quality standards (Silvello and Alcarde, 2020). The quantification of total phenolic compounds can be used to continuously monitor the aging process, ensuring the product has been properly aged and to avoid frauds, via the sale of sugarcane spirits of inferior quality (Carvalho et al., 2020).

4. Unwanted secondary compounds

4.1. Ethyl carbamate

Ethyl carbamate (EC), a chemical substance widely present in fermented food products and alcoholic beverages, has been classified as a Group 2A carcinogen by the International Agency for Research on Cancer (IARC) (Gowd et al., 2018). Ethyl carbamate is the most common contaminant in sugarcane spirits, causing severe health problems when consumed by humans, as well as being a major hurdle when exporting the beverage (Labanca et al., 2008).

This compound is potentially carcinogenic and is commonly present in distilled beverages. The precursors of ethyl carbamate are urea, citrulline, N-carbamyl phosphates, and cyanide. The main way of ethyl carbamate formation in sugar cane spirits are related to cyanide ion formed by enzyme degradation of cyanogenic glycosides present in sugar cane. The cyanide is oxidized to cyanate, which in turn reacts with ethanol in the presence of the copper ion forming ethyl carbamate (Aresta et al., 2001). However, the contaminant formation pathway has not yet been elucidated (Karp et al., 2019). In Brazil, as well as in the European Union and the United States of America, the maximum concentration of ethyl carbamate in sugarcane spirits is 150 μg L^{-1} (Brasil, 2005; Andrade-Sobrinho et al., 2002).

Andrade-Sobrinho et al. (2002) evaluated the presence of ethyl carbamate via GC—MS in 126 sugarcane spirit samples and obtained an average concentration of 770 μg L^{-1}, with results ranging from 13 to 5700 μg L^{-1}. Out of the 126 samples, only 21 % were below the established maximum of 150 μg L^{-1}. When tracing back the samples to the province in which they were produced, the group found that samples produced in Ceara had an average ethyl carbamate concentration of 440 μg L^{-1}, in Minas Gerais the average was 1000 μg L^{-1}, followed by São Paulo with 870 μg L^{-1} and Pernambuco with 830 μg L^{-1}. Furthermore, sugarcane spirits distilled in copper stills displayed higher values when compared to distillation columns, with average concentrations of 930 and 630 μg L^{-1}, respectively.

In a study conducted by Bortoletto and Alcarde (2015) ethyl

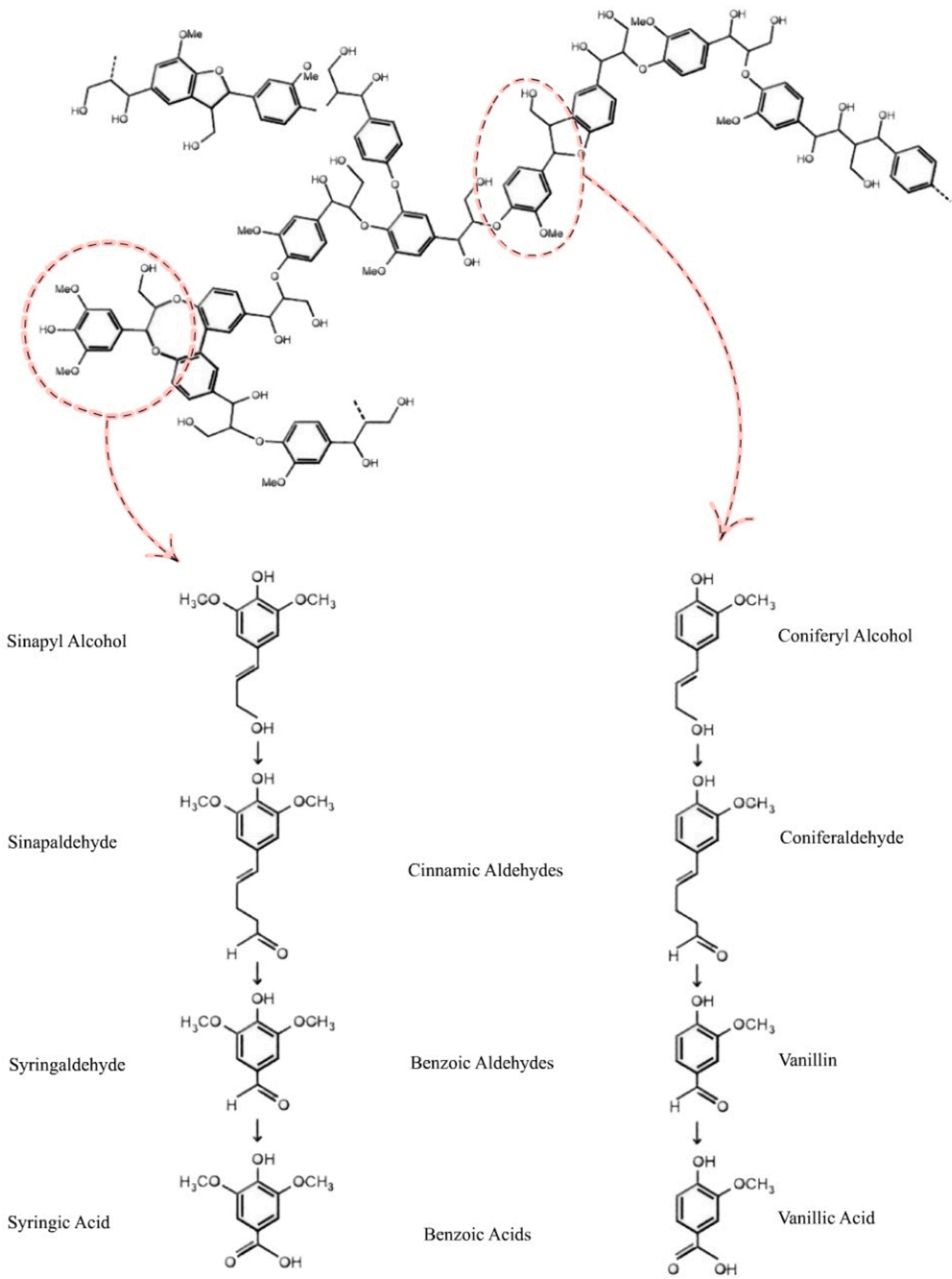

Fig. 3. Transformation of lignin-derived aromatic compounds during the aging of distilled spirits.
Source: Adapted from Castro et al. (2020).

carbamate was not in compliance with the ancient Brazilian law (<150 μg/L) in 39 % of the samples. Vilela et al. (2021) found 15 % of samples in disagreement with Brazilian legislation. A new method for ethyl carbamate determination in sugarcane spirit by QuEChERS and GC–MS Triple-Quadrupole was developed by Guerreiro et al. (2018), providing more robustness and reproducibility of quantitative results. In this work, about 5.6 % of evaluated samples were in disagreement with Brazilian legislation. This shows that the amount of samples in disagreement is high and, since it is a compound that poses a risk to the health of consumers, it is extremely important that it be periodically monitored in the batches produced.

4.2. Furfural and hydroxymethylfurfural

Furfural and hydroxymethylfurfural (HMF) are aldehydes that may also be found in sugarcane spirit, however, their presence is not related to the fermentation process. The presence of furfural and HMF is related to the techniques used to harvest sugarcane, with the pre-harvest burning of sugarcane increasing the chances of formation; how the distillation process was conducted, as sugar and pulp residue may favour HMF and furfural formation; even aging can play a pivotal role in the formation of HMF and furfural, as certain types of wood may increase the chances of these compounds being formed, mostly due to the effect that acids have over pentoses and its polymers, such as hemicellulose (Novaes, 1974; Yokoya and Fabricação de aguardente de cana, 1995; Maia and Campelo, 2006).

The heating of the fermented sugarcane wine during distillation may cause the organic matter present in it to burn, especially hexoses and ketoses, creating furanic aldehydes. This tends to be more common when the distillation is done in copper stills (Nelson et al., 2014). The presence of acids and increased temperatures enhance this reaction, with the concentration of aldehydes formed related to the hexose and ketose content of the wine, as well as the temperature of the distillation process. The formation of furfural and HMF can be minimized by reducing the solids content present in the sugarcane wine. These compounds give the drink an unpleasant taste and have mutagenic potential (Milani et al., 2017).

Zacaroni et al. (2011a) evaluated samples of sugarcane spirit from the southern region of the State of Minas Gerais (Brazil) for furfural concentration. According to the results obtained, 83.33 % of the samples were outside the required quality standards, exhibiting values above those allowed by Brazilian legislation (5 mg/100 mL of anhydrous alcohol). Evaluating 268 samples of sugarcane spirit from all Brazilian regions, Bortoletto and Alcarde (2015) found only 2.1 % of samples with HMF content above what is allowed by law, and Vilela et al. (2021) evaluating 38 samples from Paraiba, found that all were in agreement with the established maximum limits. This demonstrates that the production process of these sugarcane spirits probably does not influence the dehydration of pentoses and hexoses, which originate mainly from thermal degradation (Bortoletto and Alcarde, 2015; Moreira et al., 2012).

4.3. Acrolein

Acrolein (2-propenal) is considered an important aldehyde in distilled beverages. It is formed via the dehydration of glycerol during the distillation, or by *lactobacillus* that might grow in the wort and convert glycerol into β-hydroxypropionaldehyde which, in turn, is converted into acrolein due to the high temperature of the distillation process (Nykänen and Nykänen, 1991). Its presence in sugarcane spirits is highly unwelcome, due to its extreme toxicity and mutagenic characteristics for both humans and animals (Fleet, 2003). Acrolein vapours are lacrimogen and cause irritation to the eyes, nose and throat (Azevêdo et al., 2007).

Masson et al. (2012) evaluated seventy-one samples of sugarcane spirits from small and average size stills produced in the northern and southern Minas Gerais (Brazil) were analysed for acrolein. A total of 9.85 % of the samples tested showed levels of acrolein above the legal limits established by the Brazilian legislation. The analytical method developed for the determination of acrolein in sugarcane spirits involved the formation of a dinitrophenylhydrazone derivative with subsequent analysis by high-performance liquid chromatography.

4.4. 1-butanol and 2-butanol

N-butyl (1-butanol) and 2-butyl (2-butanol) are formed by bacteria and may compromise the quality of sugarcane spirits, when present in high concentrations. It is known that the first is formed in fermentation as a result of contamination by *Clostridium acetobutylicum* (Cardoso, 2021). According to the results shown in Table 2, Vilela et al. (2007, 2021) when analysing samples of sugarcane spirits obtained results in accordance with Brazilian law for all samples evaluated. In contrast, in the studies conducted by Bortoletto and Alcarde (2015) and Mendes Filho et al. (2016) the contaminants 2-butanol and 1-butanol were responsible for 12.5 % and 380% of the irregular samples, respectively. The main factor that causes the occurrence of these compounds in sugarcane spirits is bacterial contamination during production (Souza et al., 2013).

4.5. Methyl alcohol

Methyl alcohol (methanol) is a toxic compound commonly found in alcoholic beverages, albeit in small quantities (Glicksman, 1969). It is formed via the degradation of pectin, a polysaccharide found in sugarcane, which is composed of hundreds of galacturonic acid molecules. These molecules contain methanol fragments, which are released during the fermentative process by enzymes (Maia, 1994).

The presence of methanol in sugarcane spirits is deemed undesirable (Péres et al., 2012), as, despite its low concentration, prolonged exposure may cause blindness and even death (Önder et al., 1998). When ingested by humans, methanol is oxidized into formic acid, and then into carbon dioxide, which can cause severe acidosis (increase in blood acidity), affecting the respiratory system, and potentially causing coma and even death (Maia, 1994). Especially dangerous are sugarcane spirits to which illicit additions of ethanol used as fuel were made, since it may have been adulterated with methanol (Carneiro et al., 2008).

Vilela et al. (2021) evaluated 38 samples of sugarcane spirits and all samples presented methanol concentrations lower than 20 mg (100 mL of anhydrous alcohol)$^{-1}$. Similar results were obtained in the study conducted for evaluating the quality control of 268 samples of sugarcane spirits, methanol was the contaminant responsible for the smallest disagreement with Brazilian law, which was present exceeding the legal limit in only 2.6 % of the evaluated samples. This fact could be related to the absence of adulteration because the raw material sugar cane has low pectin content and therefore methanol content in sugar cane spirits is also relatively low (Bortoletto and Alcarde, 2015).

4.6. Polycyclic aromatic hydrocarbons

Polycyclic aromatic hydrocarbons (PAHs) have been studied in various food products for many years. This is because these compounds are considered highly genotoxic and carcinogenic. Some bodies, such as the Joint Expert Committee on Food Additives (JECFA), which is jointly administered by the Food and Agriculture Organization of the United Nations (FAO/UN) and the World Health Organization (WHO) have already listed 13 PAHs as contaminants in foods, among which, benzo(a) pyrene, benzo(a)anthracene, benzo(b)fluoranthene, and 5-methylchrysene are used as markers of PAH contamination in foods (Official Journal of the European Union, 2006).

PAHs are formed from the pyrolysis of organic compounds in smaller chains, which can occur at high temperature. These compounds with a lower carbon chain are unstable and eventually recombine forming the PAHs, which are stable and toxic to human health. These compounds can be present in smoke from wood-burning, in food processed by frying, drying, cooking, smoking, roasting, baking, among others. Thus, food and beverages are the most common form of transmission of PAHs to humans, either by environmental contamination or even by thermal processing at high temperatures and exposure to combustion gases (Bansal and Kim, 2015).

According to Bettin and Franco (2005), among beverages, distilled types have a higher concentration of PAHs. The presence of these contaminants can be associated with the place where the raw material is grown or with contamination during the production process, whether by the use of lubricant substances, coated tanks, the use of caramel or previously heat-treated aging barrels. Menezes et al. (2015) developed a cold fibre (CF) solid-phase microextraction (SPME) sampling method with gas chromatography-mass spectrometry (GC/MS) to identify 16 PAHs in artisanal sugarcane spirits. The proposed method was attractive as it extracted larger amounts of PAHs in a single extraction procedure compared to conventional approaches. The results obtained from the analysis of 29 sugarcane spirits samples collected have demonstrated the ability of the method to measure trace levels of PAHs.

Foods contaminated with PAHs can cause serious mutagenic problems, causing errors in DNA replication. Furthermore, when consumed, PAHs are metabolized in the liver and can generate carcinogenic metabolites. Nevertheless, Brazilian legislation does not establish a limit for PAHs in sugarcane spirit. Therefore, strict production control must be considered to minimize the problem (Riachi et al., 2014).

4.7. Inorganic contaminants

4.7.1. Copper

Copper is a metal used in the construction of stills that makes a positive contribution to the aroma and flavour of sugarcane spirit and has good thermal properties, however, it requires attention with maintenance in order not to leave residues in its distillates since in high concentrations it can have harmful activity for the organism and catalyses reactions forming carcinogenic ethyl carbamate (Silva et al., 2020b).

Copper is a highly unwanted metal to be present in sugarcane spirits, with its presence being one of the major issues producers face when trying to export the beverage. In Brazil, the maximum amount of copper present in distilled beverages should remain below 5 mg L^{-1} (Brasil, 2005). Other countries, however, have much more stringent requirements, establishing a maximum of 2 mg L^{-1} of copper in distilled beverages. Furthermore, even though copper would not be considered toxic in these concentrations, its presence negatively impacts the sensory characteristics of the beverages, by giving it an acidic flavour (Cardoso, 2021).

Regular consumers of sugarcane spirit claim that artisanally-produced beverages, distilled in copper stills are of better quality than those industrially made. Copper contamination in artisanal sugarcane spirits may be further increased when the production process is inadequate, especially with regards to the cleaning of equipment (Bortoletto and Alcarde, 2015). During the distillation process in copper stills, verdigris may be formed due to oxidation, this is then dissolved into the sugarcane wine and remains even after distillation (Lima Neto and Franco, 1994). The lack of copper in the final product, however, may also negatively impact the product, by giving it a very noticeable sulphite aroma (Nascimento et al., 1998).

In most of the works found in the literature on quality control of sugarcane spirit, copper is one of the most evaluated parameters. It is also possible to observe that several analytical techniques can be used to determine the copper content during quality control of sugarcane spirit, however, most works use Flame Atomic Absorption Spectrometry (FAAS) as an analytical technique. According to the data shown in Table 2, half of the works described indicate that all samples evaluated had copper concentrations lower than the maximum established by Brazilian legislation (Mendes Filho et al., 2016; Costa et al., 2011; Tavares et al., 2012; Moreira et al., 2012).

In the studies by Vilela et al. (2021) and Ferreira et al. (2020), the copper concentration was above that established by Brazilian legislation in 26, 15 and 25 % of the samples evaluated, respectively. In the work conducted by Vilela et al. (2007) evaluating 21 samples from the south of Minas Gerais, a worrying result was found, considering that 67 % of the samples had copper levels above 5 mg L^{-1}. The authors indicate that the possible origin of this metal is due to poor sanitization of the still. This fact is worrying, considering that the product that is reaching the consumer does not have adequate chemical quality for consumption.

4.7.2. Lead and arsenic

Lead and arsenic are toxic compounds that can be found in water, soil, or mechanical equipment. They remain deposited in the human organism for long periods after initial exposure, furthermore, arsenic is highly carcinogenic. They may also be found in sugarcane spirits due to migration from packaging materials or improper soldering in the equipment used to produce the beverage (Cardoso, 2021). In all studies shown in Table 2, samples of sugarcane spirits are in accordance with Brazilian legislation.

4.7.3. Cadmium and manganese

Adequate quality control in the production of alcoholic beverages must be carried out as contamination with heavy metals can pose long-term risks to human health (Dumitriu et al., 2021). Fontes et al. (2020) developed a new method for multi-element determination of Cd and Mn in samples of sugarcane spirits by FAAS using air-assisted dispersive liquid-liquid microextraction (AA-DLLME). The method proved to be rapid (about 6 min for the reagent addition, centrifugation, phase separation, and quantitation are necessary), easy to implement, and good analytical features (precision, limit of detection, and accuracy).

4.8. Pesticides

Pesticides used in agriculture are known to be harmful, having adverse effects on human health (Buckley et al., 2021). In sugarcane crops, several pesticides are applied simultaneously (Vale et al., 2019). Considering this, an analytical method based on a solid-phase microextraction coupled with liquid chromatography and tandem sequential mass spectrometry (SPME-LC–MS/MS) carried out in test tubes was proposed, to simultaneously identify ten multiclass pesticides in sugarcane spirits (Santos et al., 2020). The analyses have shown that five samples contained clomazone, a type of herbicide widely used in sugarcane production. According to Lança and Serafim (2019), sugarcane spirit consumers should be heavily concerned about product safety since pesticides may remain in the product even after distillation, if present in high enough concentrations in the raw sugarcane.

5. Modern tools for determining the chemical and sensory quality of sugarcane spirit

The quality of sugarcane spirits depends on two main factors: sensory properties that are pleasing to the consumer and chemical composition that does not pose health risks (Bortoletto and Alcarde, 2016). More than 30,000 producers produce more than 5000 brands of sugarcane spirits, demanding greater effective control of the production process to ensure the sensory and chemical quality so that the sugarcane spirits meet the national and international standards of identity and quality (Zacaroni et al., 2017). To ensure the safety of the product for human consumption and also to add value to these products, it is imperative to apply quality control techniques. The complexity of food matrices along with the fact that the currently used instrumental techniques have several disadvantages, such as being expensive, laborious and time-consuming, have turned research attention to multivariate analysis techniques. Food fraud and counterfeit products produced to obtain economic advantages have become a growing concern over the last decade. The assessment of food safety and authenticity constitute a powerful tool to mitigate this problem and protect public health. Nevertheless, the growing sophistication of fraudulent practices requires a continuous update and improvement of the analytical methodologies (Medina et al., 2019). In consequence, chemometric techniques have been applied in laboratories around the world aiming at data reduction, pattern recognition, cluster analysis, classification and quantification of data (Oliveira et al., 2019).

The proposed use of GC × GC two-dimensional chromatograms as images for fingerprinting adulterations in products proved to be very useful in authentication problems. This showcases the feasibility of using 2D chromatographic images as a viable fast fingerprint screening of samples. Chemometrics classifiers, such as DD-SIMCA (Data Driven-SIMCA), may be successfully applied to chromatographic data and they have very accurate predictions with few mistakes. Model specificity was determined as 98 % and 100 % for sugarcane spirits adulteration and sugarcane spirits branding distinction, respectively. In both cases, model sensitivity was deemed to be 100 %, with no false negatives found at the 0.05 significance level (Ferreira et al., 2021). An approach using both a Multilayer Perceptron (MLPs) network together with a Back-propagation Algorithm was employed in order to successfully discriminate the physicochemical data of sugarcane spirits produced in two Brazilian regions with Indication of Origin (Cardoso, 2015).

From this perspective, Franco et al. (2021) proposed a novel digital image method for colorimetric determination of reducing sugars in sugarcane spirits employing digital image and a smartphone as the detector. The method was based on the reduction of Cu(II) to Cu(I) by sugars and followed by the formation of a coloured Cu(I)-neocuproine complex. It was observed that the non-aged sugarcane spirits, known for having inferior flavours and aromas, had a reducing sugar content three times higher than the aged sugarcane spirits. Once a common practice among producers was to add sugar to adjust sensory deficits in the final product. Furthermore, the method is simple, does not require complex technical knowledge and could be used as a tool to check possible fraud, adulteration or non-compliance to the law.

Regarding copper quantification, the most used techniques include molecular absorption spectrophotometry, flame and graphite furnace atomic absorption spectrometry, and X-ray fluorescence. These techniques are very sophisticated and expensive, which reduces their applicability and potential use by small producers. The potential to perform copper quantification using a portable device such as a smartphone, in addition to having a lower cost compared to the previously mentioned technique, also has the advantage of consuming fewer chemical reagents, generating less waste and being less harmful to the environment. Furthermore, portable methodologies are usually faster and involve simpler experimental procedures (Böck et al., 2022).

A simple and inexpensive analytical procedure for the determination of Cu(II) in sugarcane spirits was developed. It was based on the colorimetric reaction between Cu(II) and diethyldithiocarbamate (DDTC) performed onto a filter paper surface. The yellow-brownish product was formed, and the measurement of the analytical signal was performed directly on the paper-based device with no need for previous extraction steps. DDTC is a sensitive reagent for Cu(II), however, due to the water-insoluble product, its spectrophotometric determination requires an extraction step by a nonpolar organic solvent. The proposed procedure overcame this inconvenience and combines the high sensitivity of the reaction with the simplicity of the paper device with digital image recording, resulting in a fast, simple, portable, and low-cost method for evaluating sugarcane spirits quality control according to the current legislation (Fernandes et al., 2020). Onça et al. (2020) demonstrated the feasibility of applying the Schiff base 5-bromo-2-salicyl-β-alanine as a colorimetric chemosensor for the spectrophotometric quantification of the copper content in artisanal sugarcane spirits. For this, the experimental conditions were investigated and optimized to understand the behaviour of the complex in solution and, consequently, to obtain an efficient, sensitive, reversible, and highly selective chemosensor to Cu^{2+} ions. Then, a spectrophotometric method was developed and validated following Brazilian legislation, confirming that the proposed method was linear, accurate, precise, selective, and suitable for the target purpose.

Interest in food products with a designation or indication of origin has been growing significantly, incentivizing the research and development of new methodologies related to chemical traceability (Mandrile et al., 2016; Becerra-Herrera et al., 2018). Regarding the verification of sensory quality, Caetano et al. (2021a) evaluated 24 samples of non-aged artisanal sugarcane spirits from the region of Salinas (Minas Gerais, Brazil). It is noteworthy that the region in question has an Indication of Origin for the product and, for the first time, the sensory profile of this type of sugarcane spirits was determined for the aforementioned region. The attributes (23) were divided between aroma (11) and flavour (12) and through the Kohonen artificial neural network, it was possible to group the samples according to their aroma and flavour characteristics into 9 and 10 distinct groups, respectively, constituting a promising tool for future applications. The kurtosis-based projection pursuit coupled with a simple variable selection is a powerful tool for extracting information from the sensory analysis. Selecting variables based on kurtosis highlights the sensory attributes related to taste and smell. This tool was able to show that flavouring can collaborate with sugarcane spirits cost reduction related to the wood barrels by producing some sensory attributes with notes similar to those aged in wood barrels (Cruz et al., 2020). It can be stated that chemometric techniques have a future as a tool for online determination of the overall quality of complex systems, such as sugarcane spirits. The methods have several advantages, being simple, rapid, low-cost, efficient and environmentally friendly (Oliveira et al., 2019).

6. Conclusion

Considering the fact that sugarcane spirit is a widely consumed distilled beverage, Brazilian legislation for the product was presented and the desirable and undesirable secondary compounds were discussed. Contaminants, especially ethyl carbamate, higher alcohols, and volatile acidity were the components that contributed more to the percentage of samples not complying with the law and it caused serious sensory losses in sugarcane spirit. Some results presented in this review suggest that artisanal and industrial production could be not effectively using Good Manufacturing Practices in order to guarantee the quality of the production process aiming to control the quality of the final product. In this sense, data reinforce the need to implement appropriate training for producers in order to suppress their technological difficulties and obtain a product with the best quality. In addition, some modern tools are considered promising to guarantee the quality of this product in order to mitigate fraud and counterfeits, such as chemometrics, which is extremely useful in the interpretation of results, with the dimensionality of the data and safeguarding important information for later applications. In addition, the use of computer vision makes it possible to verify possible fraud, adulteration or non-compliance with legislation.

Data availability

No data was used for the research described in the article.
Data will be made available on request.

CRediT authorship contribution statement

All authors equally contribute to Conceptualization, Methodology, Formal Analysis, Investigation, Writing, and Visualization, under Supervision of the corresponding author J. Simal-Gandara.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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