

Review

Volatile Acidity in Brazilian Cachaça: From Fermentation and Distillation to Sensory Quality and Consumer Acceptance

Amanda A. M. Pereira * and André R. Alcarde

Department of Agroindustry, Food and Nutrition, College of Agriculture “Luiz de Queiroz”, Universidade de São Paulo, Piracicaba 13418-900, São Paulo, Brazil; andre.alcarde@usp.br

* Correspondence: amanda.ribeiro.andrade@usp.br

Abstract

Cachaça is one of Brazil’s most important distilled spirits, and its chemical and sensory quality is strongly influenced by the technological conditions adopted throughout production. Among the physicochemical parameters used to assess quality, volatile acidity has traditionally been regarded as a regulatory criterion; conversely, increasing evidence indicates that its significance extends beyond legal compliance, reflecting microbial control, fermentation performance, distillation practices, storage conditions, and consumer perception. This narrative review critically examines the current knowledge regarding the formation, technological modulation, regulatory relevance, and sensory implications of volatile acidity in Brazilian cachaça. The literature was selected from major scientific databases and official regulatory documents, emphasizing studies addressing fermentation, distillation, aging, chemical quality, and sensory evaluation. The review discusses the biochemical pathways involved in acetic acid formation, the influence of acetic acid bacteria, oxygen availability, hygienic practices, distillation fraction separation, and oxidative processes during storage. It further compares Brazilian regulatory requirements with those adopted for other distilled beverages and examines the relationship between volatile acidity and sensory perception, highlighting the absence of consensus regarding sensory thresholds specific to cachaça and the influence of beverage matrix and volatile interactions on consumer acceptance. Finally, the review proposes volatile acidity as an integrated quality marker capable of reflecting multiple technological stages rather than an isolated analytical parameter. Current knowledge gaps, particularly regarding the integration of chemical, microbiological, and sensory data, are discussed to support future research and contribute to the continuous improvement, standardization, and international competitiveness of Brazilian cachaça.

Keywords: cachaça; volatile acidity; acetic acid; distilled spirits; fermentation; distillation; sensory quality; acetic acid bacteria; quality control; food authenticity

Academic Editor: Alessandra Del Caro

Received: 20 May 2026

Revised: 7 July 2026

Accepted: 13 July 2026

Published: 24 July 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

1. Introduction

Cachaça represents one of the most economically, historically, and culturally significant distilled spirits in Brazil, internationally recognized as a genuinely Brazilian beverage and protected by specific identity and quality legislation. In addition to occupying a prominent position in the national alcoholic beverage market, cachaça shows increasing potential for appreciation in the international market, driven by the growing number of registered producers, the diversification of premium products, and the

recognition of sensory characteristics associated with traditional pot-still production [1,2]. In contrast, despite the sector's growth, challenges related to the standardization of chemical and sensory quality represent significant barriers to the competitiveness of the Brazilian spirit, especially in foreign markets with more restrictive regulatory requirements [3,4].

The chemical and sensory quality of cachaça is influenced by the quality of the raw material and by successive production stages, including must preparation, alcoholic fermentation, distillation, storage, and aging. Each of these factors contributes differently to the formation, transformation, or concentration of volatile compounds throughout production. During these stages, volatile compounds are formed, transformed, and extracted throughout cachaça production and aging, collectively defining the beverage's chemical composition and sensory profile, such as higher alcohols, aldehydes, esters, and organic acids [5,6]. Although many of these compounds contribute positively to the characteristic aromatic bouquet of cachaça, alterations in microbiological control, fermentation conditions, and operational distillation parameters can favor the formation of undesirable compounds and contaminants capable of compromising sensory quality, consumer safety, and product compliance with legislation [7,8].

Volatile acidity is one of the main chemical indicators of technological quality in cachaça production because it reflects fermentation performance, microbiological control, and storage conditions. *Saccharomyces cerevisiae* may produce small amounts of acetic acid as a secondary metabolite associated with cellular metabolism. In contrast, relevant accumulation of acetic acid generally results from the oxidative metabolism of acetic acid bacteria under conditions of oxygen availability, making microbial contamination and aeration meaningful technological factors influencing volatile acidity. Its influence extends beyond regulatory compliance, affecting sensory perception and consumer acceptance. The mechanisms involved in its formation and control are discussed in detail in Sections 2 and 3.

In recent decades, the adoption of Good Manufacturing Practices (GMP) and Hazard Analysis and Critical Control Points (HACCP) systems has contributed substantially to improving the chemical quality of Brazilian cachaça, reducing the occurrence of contaminants and increasing product compliance with the identity and quality standards established by legislation [9]. Despite this, gaps still exist in the literature regarding the integration between chemical parameters and sensory perception of the beverage, especially concerning the influence of volatile acidity on the consumer experience and on the characterization of the sensory quality of cachaça.

Given this context, this review aims to discuss volatile acidity in Brazilian cachaça from an integrated perspective, relating its formation to different stages of the production process, chemical and microbiological control strategies, regulatory aspects, and sensory impacts associated with the quality and acceptance of the distillate. Furthermore, the study proposes volatile acidity as a potential integrated marker of the chemical and sensory quality of cachaça, contributing to future discussions on technological control, product valorization, and competitiveness in the international market.

2. Literature Selection Approach

This narrative review was based on scientific articles, books, official regulations, and technical documents related to cachaça, sugarcane spirits, volatile acidity, fermentation, distillation, chemical quality, and sensory perception. The literature was selected from databases including Scopus, Web of Science, ScienceDirect, PubMed, Google Scholar, and official Brazilian regulatory sources. Priority was given to peer-reviewed studies, review articles, legislation, and technical references published between 2000 and 2026, although classical references were also included when necessary to explain chemical mechanisms,

distillation technology, or sensory thresholds. The search terms included “cachaça”, “sugarcane spirit”, “volatile acidity”, “acetic acid”, “acetic acid bacteria”, “fermentation”, “distillation”, “sensory quality”, and “consumer acceptance”. As this is a narrative review, no meta-analysis or systematic quantitative synthesis was performed [4,6].

Although considerable advances have been achieved in understanding volatile acidity in cachaça, the available scientific evidence remains fragmented. Most published studies investigate individual production stages, such as fermentation, distillation, or aging, whereas comparatively few studies evaluate volatile acidity as the cumulative outcome of the entire production chain. Moreover, differences in raw materials, production scale, analytical methodologies, and sensory protocols make direct comparisons among studies difficult and often limit the extrapolation of their findings. These methodological differences partly explain the absence of a universally accepted framework relating volatile acidity to chemical quality, sensory perception, and technological performance. Consequently, beyond summarizing the available evidence, the present review relevantly discusses current limitations of the literature and highlights research gaps that should be addressed to strengthen future quality assessment strategies for Brazilian cachaça.

Recent reviews and methodological advances published over the last few years have further reinforced that distilled beverage quality should be interpreted through an integrated framework encompassing microbiological dynamics, volatile compound formation, processing conditions, and sensory perception rather than isolated analytical parameters. This broader perspective has motivated increasing efforts to combine chemical characterization with microbial ecology, process engineering, and sensory science, providing a more comprehensive understanding of quality development throughout distilled spirit production. Accordingly, the present review adopts this integrative approach to discuss volatile acidity as a technological quality marker rather than merely a regulatory parameter [10].

3. Cachaça: Identity, Production and Quality Challenges

3.1. Identity and Regulatory Standards

Brazilian legislation defines cachaça as the typical and exclusive name for sugarcane brandy produced in Brazil, obtained by distilling the fermented must of sugarcane juice, with an alcoholic strength between 38 and 48% *v/v* at 20 °C [1]. These regulatory standards establish the identity of the beverage and provide the basis for chemical quality control discussed throughout this review. In contrast, despite the international recognition of cachaça as a genuinely Brazilian product, its competitiveness in the foreign market still faces challenges related to the standardization of chemical quality and compliance with more restrictive international legislation [3,4].

Recent data reinforce that cachaça quality standardization remains a strategic issue for the consolidation of the beverage in both domestic and international markets. The *Anuário da Cachaça 2024* indicates continued expansion and diversification of registered producers, while recent discussions on exportation emphasize that chemical consistency, regulatory compliance, and sensory identity are central challenges for the international positioning of Brazilian cachaça [2,4].

The chemical composition of cachaça results from the interaction between raw materials, fermentation, distillation, storage, and aging, when applicable. During these stages, various volatile compounds are formed or extracted, responsible for the physicochemical and sensory characteristics of the beverage, including higher alcohols, aldehydes, esters, organic acids, and phenolic compounds [5,6]. Even minor alterations in process control can markedly influence the chemical profile of the distillate, favoring both the formation of desirable compounds and undesirable contaminants and congeners. Therefore, the final

quality of cachaça is directly associated with the adoption of appropriate production practices, hygiene, and technological control throughout the entire production chain.

Among the chemical parameters used to assess the quality of cachaça, volatile acidity deserves special attention due to its strong relationship with the microbiological and operational conditions of the production process. Volatile acidity is mainly expressed by the concentration of acetic acid present in the beverage, and its formation is influenced by factors such as bacterial contamination, excess oxygen during fermentation, prolonged fermentations, inadequate hygiene conditions, and oxidative processes during storage and aging [5,11]. Unlike other contaminants whose formation may occur sporadically, an increase in volatile acidity generally reflects integrated failures across different production stages, making this parameter particularly relevant for monitoring the technological quality of the beverage.

During alcoholic fermentation, the chemical composition of the fermented wine results from complex interactions between fermentative yeasts, bacterial populations, and technological management of the process. Although *Saccharomyces cerevisiae* drives ethanol production and contributes to the formation of desirable volatile compounds, inadequate hygienic practices and excessive oxygen availability favor the proliferation of acetic acid bacteria, promoting ethanol oxidation to acetic acid. These microbiological imbalances reduce fermentative efficiency and modify the volatile composition of the fermented wine, with direct consequences for the chemical and sensory quality of the distilled spirit [10,12].

Furthermore, inadequate practices related to yeast reuse, temperature control, and equipment sanitization can intensify the formation of acidic compounds and other undesirable metabolites such as acetaldehyde, excessive higher alcohols, volatile sulfur compounds, and organic acids. In the distillation stage, volatile acidity also plays a significant role due to the higher concentration of acetic acid in the final distillation fractions, especially in the “tail” fraction, making the control of the distillate cut an relevant factor for maintaining the quality of cachaça [5,6]. Distillation does not directly promote acetic acid formation; rather, it determines the distribution and concentration of acidic compounds among the head, heart, and tail fractions, thereby influencing the volatile acidity of the final distillate.

During batch distillation, the distillate is conventionally divided into three sequential fractions, commonly referred to as the head, heart, and tail fractions. These fractions are collected according to the progressive decrease in alcohol content throughout distillation and differ markedly in their chemical composition owing to the distinct volatility of individual compounds. The head fraction is obtained at the beginning of distillation and is characterized by a high concentration of highly volatile compounds, including aldehydes, esters, methanol, and acetaldehyde. The heart fraction constitutes the central portion of the distillate and is considered the most suitable for beverage production because it contains the highest ethanol concentration and the most balanced chemical composition. Conversely, the tail fraction is collected at the end of the process, when the alcoholic strength decreases, and is enriched with less volatile compounds, such as higher organic acids, furfural, heavy alcohols, and other high-boiling congeners that may negatively affect the chemical and sensory quality of cachaça [5,6].

The distribution of volatile acidity during distillation is closely associated with the physicochemical properties of acetic acid and its interactions with ethanol and water. Although acetic acid is classified as a volatile organic acid, its relatively high boiling point and greater affinity for the aqueous phase favor its progressive concentration in the later stages of distillation. Consequently, the tail fraction generally contains higher concentrations of volatile acidity than the heart fraction. Appropriate fraction cutting is therefore essential to prevent excessive incorporation of the tail fraction into the final beverage, as this may lead to marked increases in acetic acid concentration, compromising both regulatory compliance and sensory quality. Conversely, excessively early separation of the heart fraction

may reduce beverage yield without proportionally improving chemical quality, highlighting the importance of optimizing operational cut points during distillation [4,5].

The selection of fraction cut points represents one of the most relevant technological decisions during cachaça production because it directly determines the balance between desirable and undesirable volatile compounds in the final distillate (Figure 1). Proper separation minimizes the carryover of compounds associated with off-flavors while preserving the volatile constituents responsible for the characteristic aroma and flavor of cachaça. Therefore, fraction cutting should not be viewed solely as a strategy for controlling volatile acidity but rather as an integrated quality control measure that simultaneously influences ethanol concentration, congener profile, sensory acceptance, and compliance with regulatory standards. Recent studies emphasize that the optimization of distillation parameters contributes substantially to the production of chemically balanced and sensorially acceptable cachaças, reinforcing the central role of distillation in determining overall beverage quality [6,8].

Beyond fraction separation, recent studies have highlighted that distillation should be regarded as a process responsible for shaping the overall volatile profile of distilled beverages. Process variables such as heating rate, reflux intensity, equipment design, and interactions among volatile compounds influence not only the concentration of acetic acid but also the preservation of aroma-active constituents that determine sensory complexity. Consequently, optimization of distillation conditions contributes simultaneously to chemical stability, regulatory compliance, and sensory quality, reinforcing the importance of integrated process control throughout distilled spirit production [13].

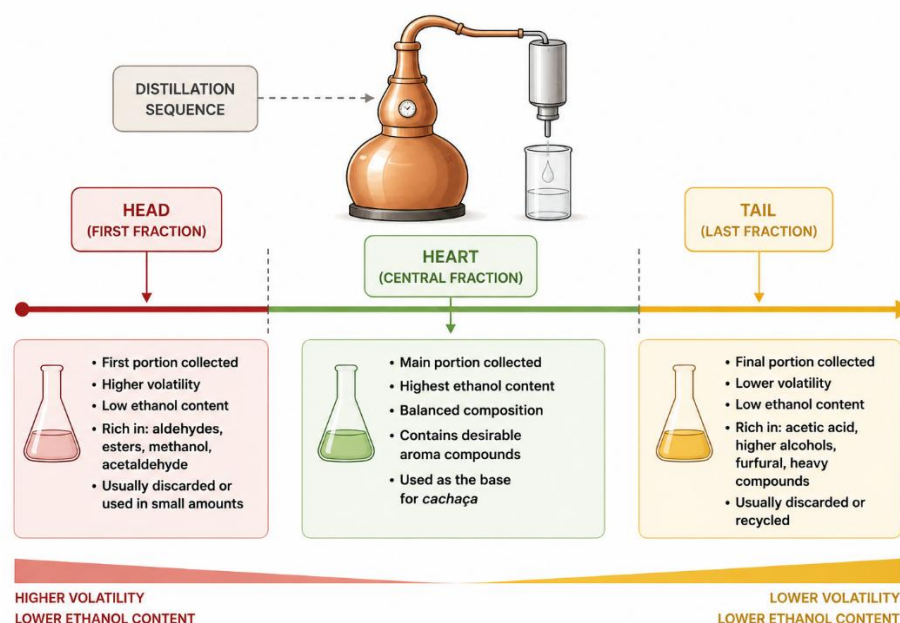


Figure 1. Schematic representation of the head, heart, and tail fractions obtained during batch distillation of cachaça. Source: Created by the authors based on [1,4–6,14].

The relevance of volatile acidity is also associated with the limits established by Brazilian legislation for cachaça and sugarcane spirit. Ordinance No. 539/2022 establishes a maximum limit of 150 mg of acetic acid per 100 mL of anhydrous alcohol for volatile acidity [1]. Although this regulatory threshold aims to ensure minimum standards of identity and quality, elevated acetic acid concentrations generally reflect deficiencies in microbiological control, fermentation management, or distillation practices, while also compromising the chemical stability of the distillate. Beyond compliance with Brazilian legislation, ef-

fective control of volatile acidity has become increasingly important for strengthening the international competitiveness of cachaça, as export markets place growing emphasis on product consistency, chemical quality, authenticity, and regulatory compliance (Table 1) [8,10].

Table 1. Comparison of regulatory provisions related to volatile acidity and quality requirements for cachaça and selected distilled spirits.

Country/Region	Distilled Beverage	Expression of Limit	Maximum Permitted Limit	Legal Basis/Reference
Brazil	Cachaça	Mg acetic acid/100 mL of anhydrous alcohol	150	MAPA Normative Instruction No. 13, of 29 June 2005 [1]
European Union	Fruit Spirits	Mg acetic acid/L of anhydrous alcohol	2000	Commission Regulation (EC) No. 110/2008, of 15 January 2008 [15]
United States	Whiskey	Mg acetic acid/100 mL of anhydrous alcohol	100	TTB—Alcohol and Tobacco Tax and Trade Bureau. Standards of Identity for Distilled Spirits [16]
Mexico	Tequila	Mg acetic acid/100 mL of anhydrous alcohol	300	NOM-006-SCFI-2012: Alcoholic Beverages—Tequila—Specifications [17]
Peru	Pisco	Mg acetic acid/100 mL of anhydrous alcohol	200	NTP 211.001:2016—Pisco. Requirements [18]
Australia/ New Zealand		Mg acetic acid/100 mL of anhydrous alcohol	150	Australian New Zealand Food Standards Code—Standard 2.7.3 [19]

Note: Volatile acidity limits are expressed as acetic acid. Because international regulations adopt different analytical criteria and reporting units (e.g., mg acetic acid/100 mL anhydrous alcohol, mg/L anhydrous alcohol, or g/hL pure alcohol), direct numerical comparison should be interpreted with caution. The table is intended to provide a regulatory overview rather than an analytical equivalence among distilled beverages. Source: [1,15–19].

In recent decades, the implementation of Good Manufacturing Practices (GMP) and Hazard Analysis and Critical Control Points (HACCP) systems has contributed to improvements in the chemical quality of Brazilian cachaça by reducing the occurrence of contaminants and increasing the compliance of commercial products with regulatory standards [11]. In this context, volatile acidity assumes a strategic role as it directly reflects the efficiency of the control measures adopted throughout the production process. Thus, understanding the factors involved in its formation and control represents a production step for the technological improvement of the cachaça production chain and for strengthening the quality of the Brazilian spirit in national and international markets.

3.2. Production Stages Affecting Volatile Composition

Recent reviews on sugarcane spirits have reinforced that chemical quality should be interpreted as the result of multiple interacting variables rather than as the isolated effect of a single production step. In this context, volatile acidity should be considered together with other congeners, including aldehydes, esters, higher alcohols, methanol, copper, and ethyl carbamate, since the overall chemical profile is what ultimately defines both compliance and sensory quality [6,15].

3.2.1. Sugarcane Quality and Must Preparation

The quality of the sugarcane raw material plays a fundamental role in determining the chemical composition of cachaça and the formation of compounds associated with volatile acidity. Delays between harvesting and milling, together with the use of deteriorated or overripe sugarcane, promote microbial proliferation and favor undesirable biochemical changes that compromise the quality of the must even before alcoholic fermentation begins. Consequently, the initial microbiological condition of the raw material directly influences fermentation performance and the formation of volatile compounds throughout the production process [5,10]. Furthermore, inadequate agricultural practices, such as pre-harvest burning, may accelerate the physicochemical and microbiological deterioration of sugarcane, increasing the availability of undesirable microorganisms and substrates that negatively affect fermentation stability and the chemical quality of the resulting distillate [5].

Inadequate wort preparation is another critical factor contributing to increased volatile acidity. The presence of impurities, including soil particles, bagasse, and plant residues, favors microbial contamination and creates conditions that facilitate the proliferation of acetic acid bacteria and other spoilage microorganisms [10]. Likewise, inadequate wort composition, characterized by inappropriate sugar concentrations, unfavorable pH, nutrient imbalance, or insufficient assimilable nitrogen, impairs yeast metabolic performance and fermentation efficiency, increasing the susceptibility of the process to microbiological contamination and undesirable metabolic deviations. Under these conditions, acetic acid bacteria can proliferate more readily, promoting ethanol oxidation and increasing volatile acidity. Consequently, inadequate hygienic practices, contaminated equipment, poor sanitation procedures, and oxygen availability represent the main technological factors associated with excessive acetic acid formation. Conversely, prolonged fermentation conducted under adequate sanitary conditions and effective microbiological control do not necessarily result in elevated volatile acidity [12,20].

Recent studies have reinforced that the microbiological dynamics of cachaça fermentation extend beyond the isolated activity of *Saccharomyces cerevisiae* or acetic acid bacteria. The composition and stability of the fermentative microbiota are influenced by raw material quality, yeast selection, cell recycling practices, hygienic conditions, and technological management, all of which affect fermentation performance and the formation of volatile compounds. Native and selected yeast strains differ substantially in their metabolic behavior, leading to distinct congener profiles and sensory characteristics of the final distillate. Consequently, volatile acidity should be interpreted as the outcome of complex microbiological and technological interactions throughout fermentation rather than solely as an indicator of acetic acid bacteria proliferation, reinforcing the importance of microbiological monitoring and process control for producing chemically balanced and sensorially acceptable cachaças [10,12,20,21].

3.2.2. Fermentation and Formation of Volatile Acidity

Alcoholic fermentation represents the most critical stage in determining the chemical composition and technological quality of cachaça, as it governs not only ethanol produc-

tion but also the formation of volatile congeners that define the sensory identity of the final distillate. During this process, *Saccharomyces cerevisiae* converts fermentable sugars into ethanol while simultaneously producing secondary metabolites, including higher alcohols, esters, aldehydes, and organic acids. Under appropriate microbiological and technological conditions, these compounds contribute positively to the aromatic complexity of the beverage. However, when microbial balance is disrupted, particularly by the proliferation of acetic acid bacteria under aerobic conditions, ethanol is oxidized to acetic acid, leading to increased volatile acidity and alterations in both the chemical composition and sensory quality of cachaça [5,10,12,20,21].

Several technological variables influence the formation of volatile acidity during alcoholic fermentation, including fermentation temperature, fermentation time, sugar concentration, oxygen availability, inoculum management, and hygienic conditions throughout the process. These factors directly affect yeast metabolic activity and the microbiological stability of the fermentation, thereby influencing the formation of ethanol and secondary metabolites. Inadequate control of fermentation conditions may reduce the predominance of *Saccharomyces cerevisiae*, favor microbial competition, and facilitate the establishment of oxidative microorganisms capable of increasing acetic acid formation. Likewise, inappropriate reuse of starter cultures or successive recycling without adequate microbiological control may alter the microbial population, compromising fermentative performance and the chemical quality of the wine destined for distillation [10,20,22].

The excessive presence of oxygen during fermentation also deserves specific attention due to its relationship with the activity of AAB. Although small amounts of oxygen are required for the initial development of yeasts, excessively aerobic conditions favor the oxidation of ethanol to acetic acid, leading to marked increases in the volatile acidity of the fermented wine [11]. Therefore, rigorous control of fermentation conditions represents one of the main strategies for preventing excessive acidity formation in cachaça production.

Although current evidence consistently demonstrates that microbial contamination, oxygen availability, and fermentation management influence volatile acidity, direct comparisons among studies remain challenging due to the inherent variability of cachaça production systems. Differences in sugarcane cultivar and quality, indigenous or selected yeast populations, starter management, fermentation scale, recycling practices, and analytical approaches contribute to considerable heterogeneity in reported results. Consequently, the relative contribution of each technological or microbiological factor to acetic acid accumulation cannot be interpreted independently. Instead, volatile acidity should be regarded as the outcome of dynamic interactions between microbial ecology, fermentation conditions, and process management throughout cachaça production [6,12,20,22].

3.2.3. Distillation and Fraction Separation

Distillation plays a central role in the concentration and separation of volatile compounds present in fermented wine, directly influencing the final chemical composition of cachaça. Among the compounds related to volatile acidity, acetic acid exhibits characteristic behavior during distillation due to its greater affinity for water and lower volatility compared to other congeners, concentrating predominantly in the final fractions of the distillate, known as the “tail” [5,6].

In this context, proper distillation fractionation is an necessary step in controlling volatile acidity in pot-still cachaça. Inadequate cuts between the “heart” and “tail” fractions can favor the excessive incorporation of acetic acid into the final product, compromising its chemical quality. Furthermore, practices such as indiscriminate recirculation of distillation fractions can contribute to the progressive accumulation of acidic compounds throughout the production process [5].

Differences between distillation systems also influence the acid composition of the beverage. Studies show that cachaças produced in pot stills often have higher concentrations of acetic acid compared to those produced in column stills, mainly due to the operational particularities of discontinuous distillation and the higher concentration of congeners present in these distillates [23]. Therefore, monitoring the distillation process and properly defining the cuts play a decisive role in controlling volatile acidity and standardizing the quality of cachaça.

Although pot-still distillation is frequently associated with higher concentrations of volatile acidity than continuous column distillation, this characteristic should not be interpreted exclusively as evidence of inferior quality. Batch distillation generally preserves a broader spectrum of volatile compounds, contributing to the chemical complexity and sensory identity that distinguish traditional cachaças from industrially produced spirits. Consequently, moderate increases in volatile acidity may coexist with desirable sensory characteristics when accompanied by balanced concentrations of esters, higher alcohols, and other aroma-active compounds. This observation reinforces that quality assessment should not rely solely on volatile acidity values but rather on an integrated interpretation of the complete chemical profile, production practices, and sensory performance of the beverage [6,21,24].

Nevertheless, the higher volatile acidity frequently reported in pot-still cachaças should not be interpreted exclusively as an indicator of inferior quality. Traditional batch distillation generally produces beverages with a more complex volatile composition than continuous column distillation, reflecting differences in copper contact, fraction separation, and process dynamics. When volatile acidity remains within balanced concentrations and is accompanied by desirable levels of esters and other aroma-active compounds, it may contribute to the sensory identity and authenticity of artisanal products rather than representing a technological defect. Therefore, quality assessment should consider not only the absolute concentration of volatile acidity but also the overall chemical profile, sensory characteristics, and production style of the beverage [6,21,24].

In contrast, higher concentrations of congeners or volatile acidity in pot-still distillates should not automatically be interpreted as a defect. In traditional distilled beverages, batch distillation may produce a more complex chemical profile than continuous distillation, and this complexity can contribute positively to sensory identity when compounds remain within balanced concentration ranges. Recent evidence from other distilled beverages also shows that fermentation and distillation conditions can modify the distribution of volatile aroma compounds and influence sensory preference. For example, Choi et al. (2024) [24] reported that co-fermentation in distilled soju increased several volatile aromatic compounds and improved odor and overall preference, illustrating that changes in volatile composition may enhance or impair quality depending on the matrix, compound balance, and sensory context. Therefore, in cachaça, the determining issue is not simply whether volatile acidity is higher in a given production system, but whether it remains compatible with chemical stability, regulatory compliance, and desirable sensory complexity [6,21,24].

3.2.4. Storage and Aging Effects

Additionally to the fermentation and distillation stages, during storage and aging, cachaça undergoes progressive chemical transformations resulting from oxidation reactions, extraction of wood-derived compounds, evaporation phenomena, and interactions between the beverage and the barrel. These processes continuously modify the volatile composition and consequently influence both the chemical quality and sensory profile of the final product [11]. In wooden containers, this process can be even more intense due to the material's permeability to oxygen and the extraction of phenolic compounds and organic acids from the wood.

Aging in barrels also promotes complex chemical changes related to esterification, oxidation, and degradation of volatile compounds, modifying the chemical balance of the beverage over time [5]. Although some of these transformations contribute positively to the aromatic complexity of cachaça, an excessive increase in acidity can compromise its chemical stability and indicate inadequate storage conditions or prolonged aging.

Wooden barrels behave as semi-permeable systems that simultaneously allow oxygen ingress and the gradual loss of volatile compounds through evaporation. Oxygen diffusion promotes oxidative reactions, whereas the evaporation of water, ethanol, and volatile aroma compounds modifies the concentration and equilibrium of the remaining constituents. Therefore, the final concentration of volatile acidity reflects not only acetic acid formation but also the dynamic balance between oxidative processes and volatile losses occurring during storage [11].

The extent of these compositional changes depends on several technological variables, including barrel species, wood porosity, barrel age, storage temperature, relative humidity, oxygen transfer rate, and storage duration. These factors influence oxidation kinetics, esterification reactions, and the extraction of phenolic compounds from the wood, ultimately affecting the balance between acidity, aroma complexity, and overall sensory quality [5].

Furthermore, factors such as improper reuse of barrels, poor hygiene, and the use of deteriorated containers can promote secondary microbiological contamination and accelerate the formation of acidic compounds. Therefore, controlling storage and aging conditions is an determining step in maintaining the chemical quality of cachaça and preventing excessive increases in volatile acidity throughout the distillate's shelf life.

Although oxidative reactions during storage and aging are recognized as relevant contributors to changes in volatile acidity, the magnitude of these effects remains highly dependent on storage conditions and production practices. Factors such as barrel species, wood porosity, storage temperature, relative humidity, aging time, and oxygen transfer rates vary considerably among studies, making direct comparisons difficult. Furthermore, most investigations evaluate aging under specific experimental conditions, which limits the extrapolation of their findings to commercial production systems. Future studies integrating chemical characterization, sensory evaluation, and chemometric approaches under standardized aging conditions would contribute to a better understanding of how storage influences volatile acidity and the overall quality of cachaça [6,21,25].

4. Volatile Acidity in Cachaça: Chemical Mechanisms and Technological Modulation

Volatile acidity in cachaça arises from a complex network of microbiological, biochemical, and physicochemical reactions occurring throughout fermentation, distillation, and subsequent processing stages. Although acetic acid represents the predominant constituent of volatile acidity, its accumulation reflects the dynamic balance between ethanol oxidation, microbial metabolism, organic acid formation, esterification reactions, and process-related oxidative phenomena. Consequently, the concentration of volatile acidity is modulated by multiple technological variables, including fermentation management, oxygen exposure, distillation practices, and storage conditions, rather than by a single isolated mechanism. Therefore, understanding the chemical pathways involved in acetic acid formation provides a broader interpretation of volatile acidity as an integrated indicator of technological performance and beverage quality, rather than merely a regulatory parameter [10,21,26].

During alcoholic fermentation, *Saccharomyces cerevisiae* naturally produces small amounts of acetic acid as a secondary metabolite associated with central carbon metabolism and intracellular redox balance. Under adequate fermentation conditions, this phys-

iological production remains limited and has little influence on the final volatile acidity of the distillate. In contrast, when oxygen becomes available and AAB, particularly species belonging to the genera *Acetobacter* and *Gluconobacter*, proliferate, ethanol oxidation becomes the predominant pathway for acetic acid accumulation. Consequently, excessive volatile acidity is generally associated with bacterial activity rather than with yeast metabolism itself.

This distinction is particularly relevant because the origin of acetic acid is not exclusively microbiological contamination, but rather the balance between yeast metabolism and bacterial oxidation. While *S. cerevisiae* may contribute to basal acetic acid formation during alcoholic fermentation, significant accumulation is generally associated with the activity of acetic acid bacteria under oxygen availability. Therefore, recent interpretations of distilled beverage quality emphasize the need to evaluate volatile acidity as a marker of microbial ecology, fermentation management, and oxidative control rather than simply as an endpoint chemical parameter [14].

Environmental and technological conditions strongly modulate the biochemical pathways involved in volatile acidity formation. Factors such as oxygen availability, fermentation temperature, fermentation duration, nutrient availability, and yeast physiological status directly influence microbial metabolism and the production of volatile compounds. Under unfavorable fermentation conditions, reduced yeast performance and increased microbial competition facilitate ethanol oxidation and alter the formation of aroma-active congeners, including acetaldehyde, higher alcohols, esters, and organic acids. These compositional changes may persist throughout distillation, ultimately affecting both the chemical composition and the sensory quality of cachaça [12,22,26,27].

After fermentation, the concentration of volatile acidity may continue to change due to physicochemical phenomena occurring during distillation and storage. Because acetic acid exhibits relatively high affinity for the aqueous phase and lower volatility than many aroma compounds, its distribution during distillation differs from that of alcohols and esters, contributing to its preferential concentration in later distillation fractions. During storage and aging, oxidative reactions involving ethanol and acetaldehyde may further increase acetic acid concentration, particularly under conditions of excessive oxygen exposure or inadequate storage. Consequently, volatile acidity should be interpreted as the cumulative result of biochemical and chemical reactions occurring throughout the entire production chain rather than as the consequence of a single processing stage.

Recent studies have reinforced that the formation of organic acids and other volatile compounds in cachaça results from the combined influence of microbial activity and technological management throughout the production process. Factors such as yeast strain selection, fermentation conditions, oxygen availability, and process hygiene determine the metabolic performance of fermentative microorganisms, directly affecting the formation of volatile congeners and the chemical composition of the final distillate. These findings support the interpretation that volatile acidity should be regarded as the outcome of integrated microbiological and technological processes rather than the product of a single metabolic pathway (Figure 2) [10,12,20,21,28].

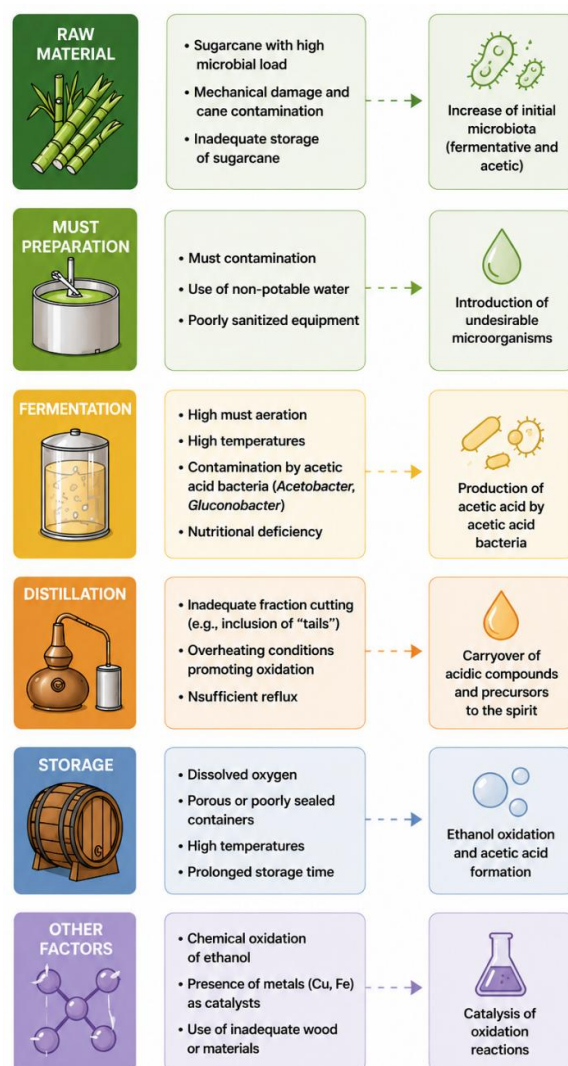


Figure 2. Technological factors contributing to volatile acidity formation throughout cachaça production. Source: Created by the authors based on [1,4–6,14].

5. Regulatory Limits Versus Sensory Perception

5.1. Legal Limits for Volatile Acidity in Brazilian Cachaça

The physicochemical parameters established by Brazilian legislation for cachaça have the main objective of guaranteeing the identity, standardization, and safety of the marketed product. Among these parameters, volatile acidity occupies a prominent position as it represents a reliable indicator of the microbiological and technological conditions of the production process. According to Ordinance No. 539 of 2022 from the Ministry of Agriculture and Livestock (MAPA), the maximum permitted limit for volatile acidity in cachaça and sugarcane brandy is 150 mg of acetic acid per 100 mL of anhydrous alcohol [1]. This limit seeks to ensure adequate levels of chemical quality and prevent fermentation, distillation, or storage failures from compromising the stability of the distillate.

Despite the existence of well-defined regulatory limits, several studies demonstrate that volatile acidity remains among the parameters with the highest frequency of non-compliance in cachaça produced in Brazil, especially in artisanal and small-scale productions [3,9]. This scenario is frequently associated with deficiencies in Good Manufacturing Practices, difficulties in microbiological control, and a lack of operational standardization throughout the production process. Furthermore, the high variability observed between

batches of cachaça reinforces the importance of continuous monitoring of volatile acidity as a parameter of quality and legal compliance.

In the international context, the chemical composition of distilled beverages also represents a determining factor for commercial acceptance and export. Although specific limits for acidity vary between different legislations and categories of distillates, international markets frequently adopt rigorous criteria related to the presence of contaminants and the chemical stability of the product [8]. Therefore, controlling volatile acidity assumes strategic relevance not only for complying with Brazilian legislation, but also for strengthening the competitiveness of Brazilian cachaça in foreign markets with higher technical and sensory demands.

5.2. Sensory Impact of Volatile Acidity

Additionally, to its regulatory importance, volatile acidity exerts a relevant influence on the sensory characteristics of cachaça. Acetic acid, the main component associated with volatile acidity, makes a high contribution to the aromatic and gustatory attributes of the distillate, and can alter the sensory balance of the beverage when present in high concentrations [29]. Although small concentrations of acidic compounds participate in the natural chemical complexity of cachaça, excess acidity is associated with the intensification of sensory characteristics considered undesirable.

Among the main sensory impacts related to increased volatile acidity are a vinegary aroma, excessive pungency, an irritating mouthfeel, and an imbalance between alcoholic, sweet, and fruity notes [30]. Increased acetic acid concentration can also mask desirable aromatic compounds from fermentation and aging, reducing the sensory complexity of the beverage. Furthermore, high acidity levels are often associated with the perception of an aggressive or technologically poor quality beverage, especially in unaged spirits.

The influence of acidity on the sensory profile of cachaça also depends on the interaction between different congeners present in the beverage. Compounds such as esters, higher alcohols, and aldehydes can modulate the perception of organic acids, altering the intensity and quality of the aromatic and gustatory sensations perceived by the consumer [5,28]. Therefore, the evaluation of volatile acidity should not be interpreted in isolation, but rather as part of a complex set of chemical interactions responsible for the formation of the sensory profile of cachaça.

Contemporary studies on distilled beverages increasingly recognize that sensory perception cannot be explained by the concentration of individual compounds alone. Instead, aroma perception emerges from complex interactions among volatile constituents, matrix composition, and consumer experience. Consequently, the sensory impact of volatile acidity should be interpreted within the broader context of the complete volatile profile, supporting multidimensional approaches that integrate chemical analysis with descriptive and consumer sensory evaluation [28,31].

5.3. Thresholds, Sensory Descriptors, and Consumer Rejection

The sensory perception of volatile acidity is directly related to individual thresholds for detecting and accepting acetic acid in the beverage. Although Brazilian legislation establishes maximum limits for chemical compliance, sensory studies suggest that negative changes in quality perception can occur even at concentrations below the legal limits, depending on the overall composition of the distillate and the consumer's sensitivity [30]. This demonstrates that regulatory compliance does not always correspond to maximum sensory acceptance of the product.

The sensory perception of acetic acid is also strongly influenced by the ethanol concentration of the beverage. Ethanol modifies aroma volatility, oral perception, and trigeminal sensations, which may alter both the detection threshold and the perceived intensity

of acetic acid. Consequently, the same acetic acid concentration may produce distinct sensory responses in beverages with different alcoholic strengths, making threshold values obtained in hydroalcoholic model solutions or other distilled beverages not directly transferable to cachaça [30].

Reported detection thresholds for acetic acid vary considerably depending on the beverage matrix and experimental methodology. In hydroalcoholic model solutions, threshold values have been reported within the low hundreds of milligrams per liter, whereas substantially different values may be observed in fermented and distilled beverages due to matrix complexity and sensory interactions. Therefore, no universally accepted sensory threshold has been established specifically for cachaça, reinforcing the need for additional studies relating chemical composition to sensory perception and consumer acceptance [3,30]. Reported acetic acid thresholds range from approximately 200 mg/L in simple aqueous systems to values exceeding 1 g/L in alcoholic beverages, depending on ethanol concentration, beverage matrix, and sensory methodology [7].

The sensory perception of volatile acidity should also be interpreted as the result of complex interactions among multiple volatile compounds rather than the isolated effect of acetic acid. Esters may partially mask acidic notes by contributing fruity and sweet aromas, whereas aldehydes, higher alcohols, volatile phenols, and wood-derived compounds can modify, enhance, or suppress the perception of acidity depending on their concentration and relative proportions. Consequently, the sensory impact of volatile acidity depends on the overall volatile composition of the beverage, reinforcing that chemical analyses should be interpreted together with sensory evaluation to better predict consumer perception and acceptance [4,6,7,14,32].

Recent studies on distilled spirits reinforce that sensory quality results from the combined effect of numerous aroma-active compounds rather than from isolated chemical parameters. Barnes et al. (2022) [21] identified a broad diversity of volatile compounds in distilled spirits, including alcohols, esters, lactones, carbonyls, fatty acids, phenols, furans, aromatics, terpenoids, alkenes, and alkanes, highlighting the complexity of these matrices and the need for analytical approaches capable of capturing this diversity. This evidence supports the interpretation that the sensory impact of volatile acidity in cachaça should be evaluated together with the complete volatile profile of the beverage, since acetic acid perception may be modulated by fruity esters, aldehydes, wood-derived compounds, and other aroma-active molecules present in the distillate [6,14,21].

Although acetic acid detection thresholds have been reported for hydroalcoholic model solutions and other alcoholic beverages, there is currently no universally accepted sensory threshold specifically established for cachaça. The perception of volatile acidity depends not only on acetic acid concentration but also on ethanol content, beverage matrix, interactions with volatile congeners, and consumer experience. Consequently, regulatory limits should not be interpreted as sensory thresholds, reinforcing the need for further studies relating chemical composition to sensory perception in cachaça.

Sensory descriptors associated with high volatile acidity include terms such as “vinegary,” “aggressive,” “burning,” “fermented,” and “unbalanced,” frequently linked to negative evaluations in descriptive analyses and hedonic acceptance tests. Conversely, beverages with moderate and balanced acidity tend to exhibit greater harmony between aromatic and gustatory attributes, favoring the perception of quality and sensory complexity. Thus, the intensity of perceived acidity depends not only on the absolute concentration of acetic acid but also on the interaction of this compound with the other volatile constituents of the beverage.

The increasing appreciation for premium and aged cachaças has amplified the importance of sensory parameters related to the overall quality of the spirit, increasing interest in studies that integrate chemical composition and consumer perception. In this

context, understanding the effects of volatile acidity on the sensory experience of cachaça represents a meaningful step in developing quality control strategies more aligned with the expectations of the contemporary market. Furthermore, the integration of chemical analyses and sensory evaluations can contribute to greater standardization of the beverage and to strengthening the image of Brazilian cachaça on the international stage.

Recent studies on distilled spirits have reinforced that sensory quality should not be interpreted as the consequence of isolated volatile compounds but rather as the result of complex interactions among multiple aroma-active substances. Barnes et al. (2022) [21], while developing a comprehensive analytical method for distilled spirits, emphasized that distilled beverages contain compounds belonging to numerous chemical classes—including alcohols, esters, aldehydes, fatty acids, phenols, furans, terpenoids, and lactones—which are formed or modified throughout fermentation, distillation, and aging. The authors further highlighted that many aroma-active compounds occur at concentrations below their individual odor thresholds but still contribute to the overall sensory profile through synergistic interactions. This evidence reinforces that the sensory impact of volatile acidity in cachaça cannot be interpreted solely based on acetic acid concentration, but rather within the context of the complete volatile composition of the beverage. Consequently, future investigations should integrate physicochemical analyses with sensory evaluation to better understand how volatile acidity interacts with other aroma compounds and influences consumer perception.

It is relevant to note that sensory conclusions regarding volatile acidity depend on the type of sensory test applied. Detection or recognition thresholds are generally obtained through discrimination tests or threshold methodologies, frequently using trained or semi-trained assessors, whereas consumer rejection is more appropriately evaluated through hedonic or acceptability tests with naïve consumers. Therefore, sensory thresholds should not be directly interpreted as consumer rejection limits. This distinction is particularly relevant for cachaça, since the perception of acetic acid may be modulated by ethanol content, volatile congeners, aging-derived compounds, and consumer familiarity with the beverage.

Despite the growing interest in volatile acidity as a quality parameter, relevant limitations remain in the available literature. Most published studies involve relatively small sample sets, evaluate beverages produced under specific technological conditions, or investigate volatile acidity together with multiple quality attributes, making it difficult to isolate its individual contribution to sensory perception. Furthermore, methodological differences in sensory protocols, panel composition, analytical techniques, and beverage matrices limit direct comparisons among studies and hinder the establishment of universally accepted sensory thresholds for cachaça. These limitations reinforce the need for multicenter studies integrating microbiological, chemical, sensory, and chemometric approaches to improve the understanding of volatile acidity and its practical application in quality assessment.

6. Volatile Acidity as a Quality Marker

Volatile acidity can be interpreted as an integrated quality marker because it reflects the cumulative effects of raw material quality, microbial ecology, fermentation management, distillation efficiency, and storage stability. Unlike isolated contaminants that may be associated with specific processing failures, volatile acidity integrates several technological and sensory dimensions of the product. This interpretation is consistent with recent approaches to cachaça and sugarcane spirits quality control, which emphasize the need to combine chemical composition, regulatory compliance, and sensory perception to support product standardization and market differentiation [4,14].

Recent advances in spectroscopy and chemometric tools have expanded the possibilities for quality control in sugarcane spirits by allowing rapid, non-destructive, and multivariate assessment of chemical parameters. Oliveira et al. (2023) [25] demonstrated that near-infrared spectroscopy combined with chemometric models could classify commercial cachaça samples according to geographical origin and predict alcohol content and density, reinforcing the potential of integrated analytical approaches for authentication and quality monitoring. Although volatile acidity was not the primary target of that study, its findings support the broader concept that quality markers in cachaça should be interpreted within multivariate analytical frameworks rather than as isolated parameters. In this context, volatile acidity may be more useful when combined with alcohol content, density, volatile congeners, sensory descriptors, and production records, allowing more robust interpretation of technological deviations and product quality [14,25].

Emerging analytical approaches published recently have reinforced the value of integrating advanced instrumental techniques with multivariate data analysis for quality assessment of fermented and distilled beverages. Such strategies improve the identification of quality markers, facilitate authentication, and provide a more comprehensive understanding of the relationships among processing variables, chemical composition, and sensory attributes. Within this context, volatile acidity may be interpreted as one component of a broader analytical framework for quality monitoring rather than as an isolated indicator [12].

Furthermore to its technological relevance, volatile acidity is closely related to the chemical stability of the beverage during storage and aging. The progressive increase in acetic acid concentration may indicate an intensification of oxidative processes capable of altering the chemical composition of the distillate and compromising its standardization [29]. In aged beverages, the interaction between oxygen, wood, and volatile compounds makes acidity monitoring even more relevant, especially considering the need for chemical balance in higher value-added products.

The use of volatile acidity as a quality indicator is also strategically relevant for the commercial valuation of Brazilian cachaça. The growth of the premium market and the increase in international requirements related to the chemical composition of alcoholic beverages reinforce the need for parameters capable of reflecting not only legal compliance, but also technological efficiency and product stability [4]. In this scenario, rigorous control of volatile acidity can contribute to greater standardization between batches, reduction of production losses, and strengthening the competitiveness of cachaça in foreign markets.

Recent studies demonstrate that production systems with higher levels of microbiological and operational control tend to exhibit lower concentrations of volatile acidity and greater chemical stability of the distillate [3]. Thus, the incorporation of volatile acidity into integrated quality control programs represents a relevant tool for monitoring production efficiency and preventing technological deviations. Furthermore, the association between chemical analyses and preventive control strategies can contribute to the continuous improvement of the cachaça production chain.

Therefore, volatile acidity should be understood as a multifactorial parameter associated with microbiological dynamics, operational conditions, and the chemical stability of the beverage. Its integrated interpretation allows for the identification of production failures, the evaluation of the efficiency of technological control, and the direction of strategies aimed at improving the quality of Brazilian cachaça. Thus, monitoring volatile acidity plays an relevant role in consolidating more consistent quality standards and strengthening the image of cachaça as a distillate of excellence in the national and international markets.

Although volatile acidity represents a valuable integrated quality marker, it should not be interpreted as a standalone diagnostic parameter. Similar volatile acidity values may arise from distinct technological scenarios, including microbial contamination during

fermentation, excessive oxygen exposure, inappropriate distillation cut points, or oxidative changes during storage and aging. Consequently, the interpretation of volatile acidity requires complementary analytical information capable of identifying its most probable origin. Parameters such as volatile congener profiles, ethanol concentration, aldehyde and ester contents, sensory evaluation, and production records may substantially improve the diagnosis of technological deviations. Therefore, volatile acidity should be interpreted within a multidisciplinary quality assessment framework rather than as an isolated regulatory parameter (Figure 3) [6,21,25].

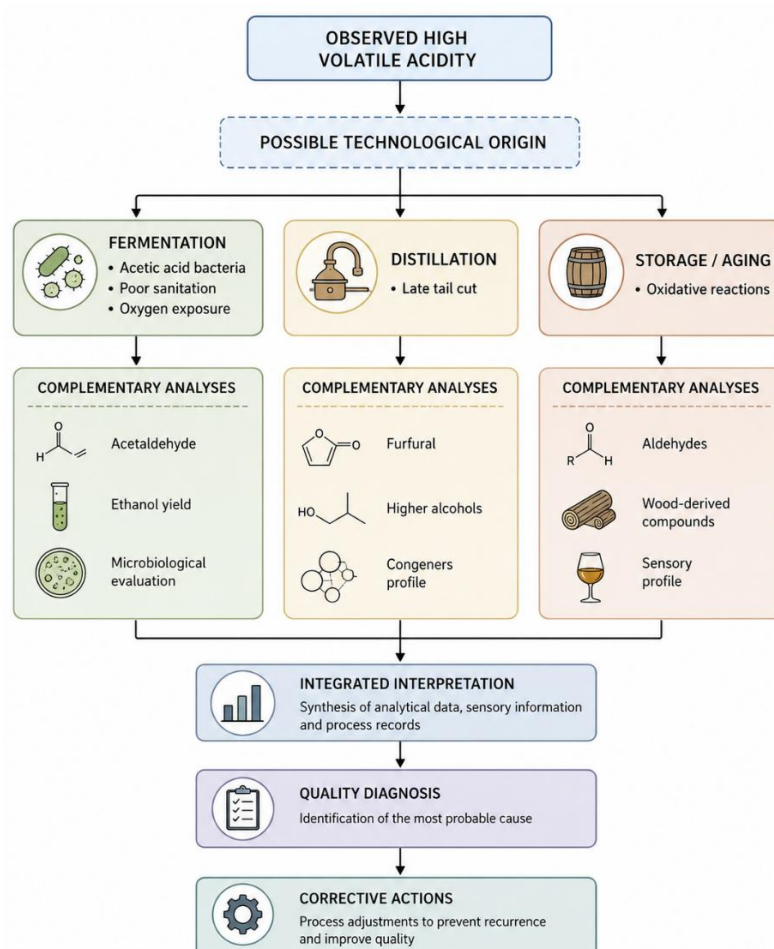


Figure 3. Conceptual framework for interpreting high volatile acidity through complementary chemical, sensory, and technological analyses. Source: Prepared by the authors based on the literature [1,6,11,21,24,25].

Although considerable progress has been achieved in understanding volatile acidity in Brazilian cachaça, several scientific challenges remain. Current knowledge is largely based on studies investigating isolated stages of production or individual analytical parameters, whereas integrated approaches simultaneously considering microbiological, chemical, technological, and sensory factors are still scarce. This fragmentation limits the establishment of robust cause-and-effect relationships and reduces the practical applicability of volatile acidity as a standalone quality indicator [6,21,25].

Future research should prioritize multidisciplinary approaches combining advanced analytical techniques, chemometric tools, sensory science, and production data to better distinguish the different technological origins of volatile acidity. Furthermore, establishing sensory thresholds specific to cachaça, validating predictive quality models, and investigating consumer perception across different production styles represent important

research priorities that may strengthen quality control strategies and support the international competitiveness of Brazilian cachaça [7,24,25].

7. Future Perspectives: From Volatile Acidity to Integrated Quality Prediction

Although volatile acidity has historically been regarded as an individual physico-chemical parameter for regulatory compliance, recent advances in analytical chemistry, food microbiology, chemometrics, and artificial intelligence suggest that its role should be interpreted within a broader framework of integrated quality assessment. Rather than serving solely as an indicator of excessive acetic acid formation, volatile acidity may contribute to predictive models capable of describing fermentation performance, process consistency, sensory quality, authenticity, and consumer acceptance. The convergence of emerging analytical technologies with multivariate data analysis has created new opportunities for rapid, non-destructive, and high-throughput monitoring throughout distilled spirit production, representing an important perspective for future research on cachaça [33,34].

7.1. Current Limitations and Future Challenges

Recent advances in analytical chemistry have considerably expanded the possibilities for quality evaluation of distilled beverages beyond conventional chromatographic techniques. While gas chromatography remains the reference method for quantifying volatile compounds, emerging analytical platforms have demonstrated significant potential for rapid, non-destructive, and high-throughput assessment of spirit quality.

Near-infrared spectroscopy (NIR) has become one of the most promising technologies because it enables rapid determination of alcohol content, acidity, esters and other quality parameters without sample preparation. When combined with multivariate calibration, NIR allows simultaneous prediction of several physicochemical variables and supports authentication, geographical origin discrimination and process monitoring, making it particularly attractive for industrial applications [33,35].

Similarly, Fourier-transform infrared spectroscopy (FTIR) has shown excellent performance for rapid determination of chemical markers in alcoholic beverages. Recent studies demonstrated that FTIR associated with chemometric models can accurately quantify alcohol content, acidity and other relevant compositional parameters while substantially reducing analytical time and operational costs. Such approaches represent promising alternatives for routine quality control in cachaça production [36].

More recently, metabolomics has emerged as a powerful strategy for comprehensive characterization of distilled beverages. Unlike targeted analytical methods, metabolomic approaches simultaneously evaluate hundreds of metabolites, allowing a more complete understanding of fermentation dynamics, raw material characteristics and flavor development. These techniques have substantially improved the identification of chemical markers associated with product quality and technological performance [37,38].

7.2. Chemometrics and Artificial Intelligence

The increasing complexity of chemical datasets generated by modern analytical platforms has stimulated the incorporation of chemometric methods and artificial intelligence into beverage quality assessment. Principal component analysis, partial least squares regression, discriminant analysis, random forest algorithms and artificial neural networks have become valuable tools for interpreting multidimensional datasets generated by spectroscopy, chromatography and metabolomics.

Beyond exploratory analysis, machine learning algorithms have demonstrated remarkable performance in beverage classification, authenticity assessment, geographical

origin discrimination and prediction of sensory quality. Recent studies using ATR-FTIR associated with artificial neural networks successfully classified different distilled spirits with excellent predictive performance, demonstrating the potential of artificial intelligence to reduce subjectivity in quality assessment and sensory evaluation [39].

Similarly, the integration of NIR spectroscopy with chemometric modeling has enabled simultaneous prediction of alcohol content, acidity, flavor compounds and aging characteristics, indicating that future quality control systems may rely on predictive models rather than isolated physicochemical analyses [33].

7.3. Integration of Microbiology, Chemistry and Sensory Science

Current evidence indicates that beverage quality cannot be fully explained by isolated chemical parameters. Instead, it emerges from the interaction between microbial ecology, metabolic pathways, volatile compound formation and sensory perception. Fermentation microbiota determine the production of numerous aroma-active compounds, while subsequent technological steps modulate their persistence and sensory relevance.

Metabolomic studies have demonstrated that different yeast species and fermentation strategies produce distinct metabolite profiles capable of altering aroma complexity and consumer perception. Likewise, recent research in distilled beverages emphasizes that flavor quality depends on the interaction among volatile compounds rather than on the concentration of individual analytes. Consequently, volatile acidity should be interpreted as one component within a broader network of quality markers integrating microbiological performance, chemical composition and sensory acceptance [38,40].

The development of electronic nose technologies further reinforces this integrated approach. Modern sensor arrays combined with pattern-recognition algorithms have demonstrated high accuracy in discriminating distilled spirits, identifying aroma profiles and supporting rapid quality assessment. Recent advances include portable systems coupled with deep-learning algorithms and low-cost electronic noses capable of classifying spirits according to aroma profile, aging conditions or botanical origin, suggesting considerable potential for future applications in cachaça production [41,42].

7.4. Future Research

Future investigations should move beyond the traditional evaluation of volatile acidity as an isolated regulatory parameter and prioritize integrated approaches capable of describing the complexity of cachaça production. The combination of rapid spectroscopic techniques, metabolomics, microbiological characterization, chemometric modeling and artificial intelligence is expected to improve process monitoring, authenticity assessment and prediction of sensory quality.

Another important challenge is the development of standardized analytical protocols capable of integrating chemical, microbiological and sensory information into predictive quality models. Such approaches may facilitate real-time decision-making during fermentation and distillation, reduce production variability and support the establishment of more comprehensive quality criteria for Brazilian cachaça.

Ultimately, volatile acidity should be considered not only as an indicator of technological deviations but also as part of a multidimensional quality framework that integrates microbial ecology, chemical composition, sensory perception and process management. This perspective may contribute to the development of more robust quality control strategies, strengthen the international competitiveness of cachaça and stimulate future innovations in distilled beverage science.

8. Conclusions

Volatile acidity has emerged as one of the most informative indicators for evaluating the quality of Brazilian cachaça because it reflects the combined influence of microbiological, biochemical, technological, and oxidative processes occurring throughout production. Rather than representing an isolated analytical parameter, its concentration integrates the cumulative effects of raw material quality, fermentation management, distillation practices, oxygen exposure, storage conditions, and aging, thereby providing valuable insight into the overall efficiency and consistency of the production process.

Although Brazilian legislation establishes maximum permissible limits for volatile acidity, the evidence compiled in this review demonstrates that its importance extends well beyond regulatory compliance. Elevated concentrations of acetic acid are consistently associated with undesirable sensory attributes and may negatively affect consumer acceptance even when legal requirements are fulfilled. These findings emphasize that compliance with legislation alone cannot fully guarantee product quality and reinforce the importance of interpreting volatile acidity together with complementary chemical analyses and sensory evaluation.

The literature further indicates that the implementation of Good Manufacturing Practices, microbiological monitoring of fermentation, optimized distillation procedures, and appropriate storage and aging conditions constitutes the most effective strategy for controlling excessive acetic acid accumulation. Collectively, these measures contribute to improved batch-to-batch consistency, enhanced chemical stability, and greater standardization of cachaça, while preserving the sensory characteristics that define product identity and authenticity.

Beyond synthesizing the current state of knowledge, this review proposes an integrated framework for interpreting volatile acidity as a multidimensional quality marker that connects production practices, chemical composition, regulatory requirements, and sensory perception. Such an approach provides a more comprehensive basis for quality assessment than reliance on regulatory limits alone and may support decision-making by producers, quality control laboratories, and regulatory agencies.

Despite the substantial advances achieved in recent years, important scientific challenges remain. The limited availability of multidisciplinary studies simultaneously integrating microbiological dynamics, volatile composition, sensory science, and chemometric approaches continues to restrict a comprehensive understanding of volatile acidity and its practical application as a predictive quality marker. Future research should therefore prioritize integrated analytical strategies capable of distinguishing the technological origins of elevated volatile acidity, establishing robust sensory thresholds specific to cachaça, and developing predictive models that strengthen quality assurance and support the international competitiveness of Brazilian cachaça.

Author Contributions: Conceptualization: A.A.M.P.; Data curation: A.A.M.P.; Formal analysis: A.A.M.P.; Funding acquisition: A.R.A.; Investigation: A.A.M.P.; A.R.A.; Methodology: A.R.A.; Project administration: A.A.M.P.; Resources: A.R.A.; Software: A.A.M.P.; Supervision: A.R.A.; Validation: A.R.A.; Visualization: A.A.M.P.; Writing—original draft: A.A.M.P.; Writing—review and editing: A.A.M.P.; A.R.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partly financed by the Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP)—2022/08674-0, 2022/15790-6.

Institutional Review Board Statement: Not applicable. This study is a narrative review and did not involve human participants or animals.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: The authors are grateful to Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES)—Finance Code 88887.916645/2023-00.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Brazil. Ministry of Agriculture and Livestock. *MAPA Ordinance No. 539 of 26 December 2022: Establishes the Identity and Quality Standards for Cachaça and Sugarcane Spirit*; Official Gazette of the Federative Republic of Brazil: Brasília, Brazil, 2022. Available online: <https://mapadacachaca.com.br/wp-content/uploads/2023/07/024-2022-PORTARIA-MAPA-No-539-DE-26-DE-DEZEMBRO-DE-2022-MAPA.pdf> (accessed on 30 June 2026).
2. Ministry of Agriculture and Livestock. *Cachaça Year Book 2024*; MAPA: Brasília, Brazil, 2024.
3. Bortoletto, A.M.; Alcarde, A.R. Assessment of chemical quality of Brazilian sugar cane spirits and cachaças. *Food Control* **2015**, *54*, 1–6. <https://doi.org/10.1016/j.foodcont.2015.01.030>.
4. Nascimento e Silva, F.; Oliveira, E.S.; Cardeal, Z.L.; Souza, P.P. Exportation and quality challenges of Brazilian cachaça. *Beverages* **2020**, *6*, 68. <https://doi.org/10.3390/beverages6040068>.
5. Alcarde, A.R. *Cachaça: Ciência, Tecnologia e Arte*; Edgar Blücher: São Paulo, Brazil, 2017.
6. Bortoletto, A.M.; Alcarde, A.R. Congeners in sugar cane spirits and cachaça. In *Cachaça and Other Sugarcane Spirits*; Academic Press: London, UK, 2020; pp. 181–197. <https://doi.org/10.1016/B978-0-12-815873-6.00010-1>.
7. Lawless, H.T.; Heymann, H. *Sensory Evaluation of Food: Principles and Practices*, 2nd ed.; Springer: New York, NY, USA, 2010.
8. EFSA Panel on Contaminants in the Food Chain. Ethyl carbamate and hydrocyanic acid in food and beverages. *EFSA J.* **2007**, *551*, 1–44. <https://doi.org/10.2903/j.efsa.2007.551>.
9. Bortoletto, A.M.; Silvello, G.C.; Alcarde, A.R. Good manufacturing practices and hazard analysis and critical control point plan proposal for distilleries of cachaça. *Sci. Agric.* **2018**, *75*, 432–443. <https://doi.org/10.1590/1678-992X-2017-0040>.
10. Ratkovich, N.; Esser, C.; Machado, A.M.R.; Mendes, B.A.; Cardoso, M.G. The Spirit of Cachaça Production: An Umbrella Review of Processes, Flavour, Contaminants and Quality Improvement. *Foods* **2023**, *12*, 3325. <https://doi.org/10.3390/foods12173325>.
11. Reazin, G.H. Chemical mechanisms of whisky maturation. *Am. J. Enol. Vitic.* **1981**, *32*, 283–289.
12. Costa, G.H.G.; Boldrin, M.V.D.; Rocha, L.P.; Castilhos, M.B.M.; Ferreira, O.E.; Corrêa, T.A.; Bragança, C.R.S. Impact of autochthonous yeasts on the volatile profile and sensory acceptance of artisanal cachaça: A multivariate approach. *Eur. Food Res. Technol.* **2026**, *252*, 237. <https://doi.org/10.1007/s00217-026-05173-x>.
13. Bortoletto, A.M. Rum and Cachaça. In *Distilled Spirits*; Bryce, D.W., Ed.; Academic Press: Cambridge, MA, USA, 2023; pp. 61–74. <https://doi.org/10.1016/B978-0-12-822443-4.00013-X>.
14. Lima, C.M.G.; Benoso, P.; Pierozan, M.D.; Santana, R.F.; Hassemer, G.S.; Rocha, R.A.; Dalla Nora, F.M.; Verruck, S.; Caetano, D.; Simal-Gandara, J. A state-of-the-art review of the chemical composition of sugarcane spirits and current advances in quality control. *J. Food Compos. Anal.* **2022**, *106*, 104338. <https://doi.org/10.1016/j.jfca.2021.104338>.
15. European Parliament; Council of the European Union. Regulation (EC) No. 110/2008 of 15 January 2008 on the definition, description, presentation, labelling and the protection of geographical indications of spirit drinks. *Off. J. Eur. Union* **2008**, *L39*, 16–54.
16. United States. Alcohol and Tobacco Tax and Trade Bureau (TTB). *Standards of Identity for Distilled Spirits. Code of Federal Regulations, Title 27, Part 5*; U.S. Government Publishing Office: Washington, DC, USA, 2026.
17. NOM-006-SCFI-2012; Alcoholic Beverages—Tequila—Specifications. Ministry of Economy: Mexico City, Mexico, 2012.
18. NTP 211.001:2016; Pisco. Requirements. INACAL: Lima, Peru, 2016.
19. Standard 2.7.5; Spirit Drinks. FSANZ: Canberra, Australia, 2019.
20. Farias, F.C.; Alcarde, A.R.; Oliveira Filho, J.H. Spontaneous fermentation and selected yeast fermentation for the production of cachaça by cell-recycle batch process. *Bol. Cent. Pesqui. Process. Aliment.* **2019**, *36*, 1–12.
21. Barnes, Q.; Vial, J.; Thiébaud, D.; De Saint Jores, C.; Steyer, D.; Contamin, M.-A.; Papaiconomou, N.; Fernandez, X. Characterization of flavor compounds in distilled spirits: Developing a versatile analytical method suitable for micro-distilleries. *Foods* **2022**, *11*, 3358. <https://doi.org/10.3390/foods11213358>.
22. Paolini, M.; Tonidandel, L.; Larcher, R. Development, validation and application of a fast GC-FID method for the analysis of volatile compounds in spirit drinks and wine. *Food Control* **2022**, *136*, 108873. <https://doi.org/10.1016/j.foodcont.2022.108873>.

23. Reche, R.V.; Franco, D.W. Distinction between cachaça produced in pot still and column still by chemometric analysis. *Quim. Nova* **2009**, *32*, 332–336. <https://doi.org/10.1590/S0100-40422009000200016>.
24. Choi, K.-T.; Lee, S.-H.; Kim, Y.-J.; Choi, J.-S.; Lee, S.-B. Improvement of volatile aromatic compound levels and sensory quality of distilled soju derived from *Saccharomyces cerevisiae* and *Wickerhamomyces anomalus* co-fermentation. *Food Chem. X* **2024**, *22*, 101368. <https://doi.org/10.1016/j.fochx.2024.101368>.
25. Oliveira, S.; Duarte, E.; Gomes, M.; Nagata, N.; Fernandes, D.D.S.; Veras, G. A green method for the authentication of sugarcane spirit and prediction of density and alcohol content based on near infrared spectroscopy and chemometric tools. *Food Res. Int.* **2023**, *170*, 112830. <https://doi.org/10.1016/j.foodres.2023.112830>.
26. Coelho, T.J.S.; Alcarde, A.R. Behaviour of volatile aromatic compounds during distillation of cachaça in a three-body pot still. *J. Inst. Brew.* **2026**, *132*, 29–48. <https://doi.org/10.58430/jib.v132i1.91>.
27. Spaho, N.; Urošević, I.; Urošević, T.; Mihaljević Žulj, M. Application of distillation in alcoholic beverage production. In *Mass Transfer Operations in the Food Industry*; Elsevier: Amsterdam, The Netherlands, 2025; pp. 237–282. <https://doi.org/10.1016/B978-0-12-819536-9.00007-2>.
28. Briceno, J.C.C.; Rabelo, P.N.; Belo, L.; Mendes, D.; Caliar, M.; Silva, F.; Morgado, C.; Oliveira, T.F. Kinetics of volatile aromatic compound production during the aging of cachaça in different types of wood. *Food Sci. Technol.* **2025**, *45*, e00455. <https://doi.org/10.5327/fst.00455>.
29. Nykänen, L.; Suomalainen, H. *Aroma of Beer, Wine and Distilled Alcoholic Beverages*; Springer: Dordrecht, The Netherlands, 1983.
30. Bortoletto, A.M.; Silvello, G.C.; Alcarde, A.R. Chemical and microbiological quality of sugar cane juice influences the concentration of ethyl carbamate and volatile congeners in cachaça. *J. Inst. Brew.* **2015**, *121*, 251–256. <https://doi.org/10.1002/jib.213>.
31. Alvarenga, G.F.; Machado, A.M.R.; Barbosa, R.B.; Ferreira, V.R.F.; Santiago, W.D.; Teixeira, M.L.; Nelson, D.L.; Cardoso, M.G. Correlation of the Presence of Acrolein with Higher Alcohols, Glycerol, and Acidity in Cachaças. *J. Food Sci.* **2023**, *88*, 2078–2088. <https://doi.org/10.1111/1750-3841.16523>.
32. Meilgaard, M.C.; Civille, G.V.; Carr, B.T. *Sensory Evaluation Techniques*, 5th ed.; CRC Press: Boca Raton, FL, USA, 2016.
33. Qi, W.; Jiang, Q.; Ma, T.; Tan, Y.; Yan, R.; Erihemu, E. Near-Infrared Spectroscopy Combined with Chemometrics for Liquor Product Quality Assessment: A Review. *Foods* **2025**, *14*, 2992. <https://doi.org/10.3390/foods14172992>.
34. Li, J.; Zhang, Q.; Sun, B. Chinese Baijiu and Whisky: Research Reservoirs for Flavor and Functional Food. *Foods* **2023**, *12*, 2841. <https://doi.org/10.3390/foods12152841>.
35. Fulgêncio, A.C.C.; Resende, G.A.P.; Teixeira, M.C.F.; Botelho, B.G.; Sena, M.M. Combining Portable NIR Spectroscopy and Multivariate Calibration for the Determination of Ethanol in Fermented Alcoholic Beverages by a Multi-Product Model. *Talanta Open* **2023**, *7*, 100180. <https://doi.org/10.1016/j.talo.2023.100180>.
36. da Silva, G.F.; Botelho, B.G. Simultaneous Quantification of Alcoholic Content and Acidity in Brazilian Commercial Kombuchas by FTIR Spectroscopy and Chemometric Analysis. *J. Food Sci.* **2025**, *90*, e70433. <https://doi.org/10.1111/1750-3841.70433>.
37. Fan, Y.; Qiu, C.; Chen, P.; Zhao, Y.; Feng, X.; Jiang, S.; Liu, D.; Cao, Y.; Liu, S.; Liu, Y. Differential Non-Volatile Metabolomics in High- and Low-Alcohol Strong-Flavor Baijiu by Non-Targeted Approach. *Foods* **2026**, *15*, 37. <https://doi.org/10.3390/foods15010037>.
38. Chen, Y.; Huang, H.; Yin, R.; Wang, S.; Hong, J.; Wu, Y.; Guo, L.; Song, Y.; Zhao, D.; Sun, J.; et al. Exploration of Key Flavor Quality Factors in Beer and Its Distilled Spirits Based on Flavor Metabolomics. *LWT* **2025**, *224*, 117832. <https://doi.org/10.1016/j.lwt.2025.117832>.
39. Lopez-Rosas, A.E.; Gomez-Navarro, C.S.; Warren-Vega, W.M.; Zarate-Guzmán, A.I.; Romero-Cano, L.A. Advancements towards the Development Artificial Intelligence for Sensory Analysis: Integrating Pattern Recognition and Signal Processing in ATR-FTIR Analysis of Spirits. *J. Food Compos. Anal.* **2024**, *131*, 106224. <https://doi.org/10.1016/j.jfca.2024.106224>.
40. Ellis, D.J.; Kerr, E.D.; Schenk, G.; Schulz, B.L. Metabolomics of Non-*Saccharomyces* Yeasts in Fermented Beverages. *Beverages* **2022**, *8*, 41. <https://doi.org/10.3390/beverages8030041>.
41. Li, Y.; Yang, K.; He, Z.; Liu, Z.; Lu, J.; Zhao, D.; Zheng, J.; Qian, M.C. Can Electronic Nose Replace Human Nose?—An Investigation of E-Nose Sensor Responses to Volatile Compounds in Alcoholic Beverages. *ACS Omega* **2023**, *8*, 16356–16363. <https://doi.org/10.1021/acsomega.3c01140>.
42. da Silva, A.A.; Vieira, B.R.; Yamauchi, E.Y.; Li, R.W.C.; Gruber, J. Low-Cost Electronic Nose for Identification of Wood Species in Which Brazilian Sugar Cane Spirit Was Aged. *Chemosensors* **2025**, *13*, 172. <https://doi.org/10.3390/chemosensors13050172>.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.