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Review

Relationship between Representative Trace Components and Health Functions of Chinese Baijiu: A Review

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Abstract: Baijiu is a traditional fermented Chinese beverage with a history of hundreds of years. The notable characteristics of Baijiu include diverse raw materials, complex technology, and the co-fermentation of multiple strains. Complex brewing technology has created different aromas and contributes to complex trace component formation in Baijiu. Among the different components, the alcohol, ester, and acid contents are the highest in Baijiu, constituting its aroma skeleton. Nitrogen compounds significantly constitute the aroma compounds of Baijiu and affect human health. Although present in low concentration, sulfur compounds significantly contribute to the taste and positively impact human health. We provide a systematic review of domestic and international reports on the trace components in Baijiu. The review introduces their sources, types, and effects on Baijiu aroma, describes their content and existence in mainstream aromas of Baijiu, such as the strong-, jiang-, and light-aromas, and discusses their health effects. Furthermore, this article summarizes and proposes several feasible research ideas. The systematic review of these trace components will possibly facilitate studies on Baijiu, particularly on its relationship with health.

Keywords: Baijiu; trace components; health benefits; fermentation; functional foods

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Citation: Du, P.; Jiao, G.; Zhang, Z.; Wang, J.; Li, P.; Dong, J.; Wang, R. Relationship between Representative Trace Components and Health Functions of Chinese Baijiu: A Review. *Fermentation* **2023**, *9*, 658. https://doi.org/10.3390/fermentation9070658

Academic Editor: Chih Yao Hou

Received: 1 July 2023
Revised: 8 July 2023
Accepted: 12 July 2023
Published: 13 July 2023

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1. Introduction

Chinese Baijiu (referred to as Baijiu) is a transparent, strong alcoholic beverage, which is highly consumed worldwide [1]. Baijiu appeared in China during the second century BC. During the Yuan Dynasty, the Chinese invented solid-state fermentation and distillation processes, which were recorded in the traditional Chinese medical book Compendium of Materia Medica [2]. Baijiu is a distilled alcoholic beverage primarily produced from grains [3]. The fermentation process of Baijiu is unique and more complex than the fermentation of whisky and brandy. During natural fermentation, saccharification occurs quietly [4]. "Jiuqu" (a mixture of wheat and many microorganisms) is the fermentation starter, and sorghum, wheat, corn, rice, glutinous rice, and rice husks are the raw materials [1]. The entire Baijiu brewing process can be divided into jiuqu production, raw material saccharification, fermentation, solid distillation, aging, and blending [4]. Each process impacts the quality of Baijiu and the content and types of its trace components.

Temperature, air humidity, and microbial composition differ among brewing regions. Baijiu aroma differs according to the brewing technology and "jiaochi" (the container for solid Baijiu fermentation) in different regions and according to the brewing materials and proportions [5]. Originally, Baijiu aroma was classified into 12 different types: Strong, jiang, light, rice, zhima, fuyu, laobaigan, chi, herbal (dong aroma baijiu), te, mixed, and feng [6]. These aromas are related and interdependent. Strong-, jiang-, light-, and rice-aromas are the four primary aroma types and are the bases for the development and evolution of the remaining eight (Figure 1A) [7]. Technological innovations have alleviated

the Baijiu constraints associated with the aroma types, causing the evolution of more aromas [8]. For example, the "Hexiang aroma" (produced by adding lotus leaves during fermentation and aging) has attracted many consumers; however, the 12 Baijiu aromas dominate the market.

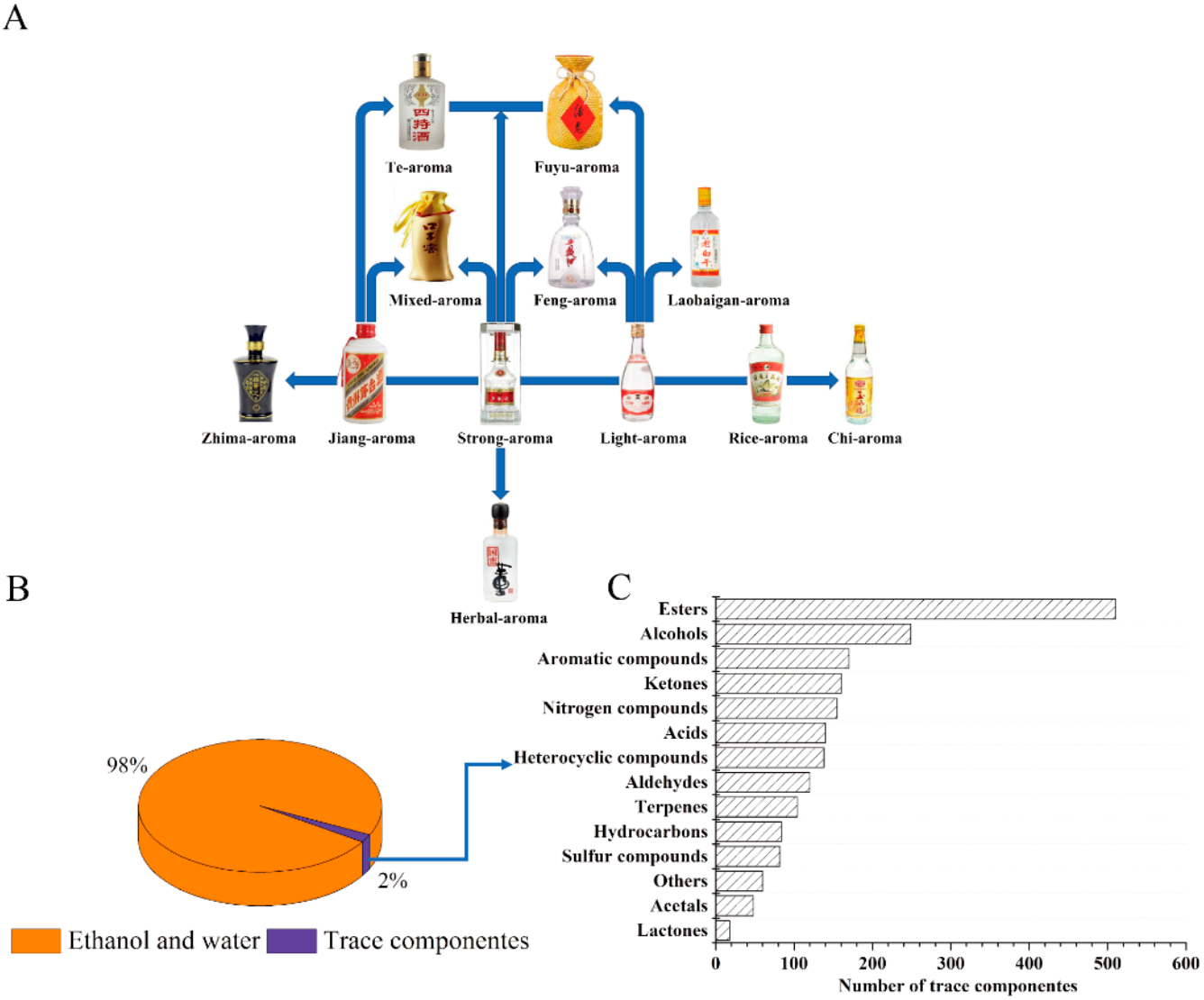


Figure 1. (**A**) Development relationship among 12 Baijiu aroma types; (**B**) types of trace components in Baijiu; and (**C**) quantity.

Complex brewing processes create different Baijiu aromas and endow the beverage with complex trace components. Approximately 98% of the Baijiu components are ethanol and water, and approximately 2% are trace components (Figure 1B). Although sparsely present, these components are crucial for Baijiu aromas [6]. Baijiu aromas classified based on their characteristics are determined by trace component composition. In Baiju, 2020 trace ingredients, including 510 esters, 249 alcohols, 140 acids, 18 lactones, 102 aldehydes, 160 ketones, 48 acetals, 82 sulfur compounds, 155 nitrogen compounds, 138 heterocycles, 170 aromatics, 84 hydrocarbons, 104 terpenes, and 60 others have been reported (Figure 1C) [6]. These trace components can be divided into volatile and non-volatile components. Volatile components determine the aroma of Baijiu, whereas the non-volatile affect its taste. Several sources of Baijiu aroma have been identified; the aroma of grain in raw materials is an example. The rice hull in "jiupei" contains more pentosan and furfural and is a "zaoxiang" source in Baijiu. Similarly, jiuqu is a significant source of Baijiu aroma. Another factor is

the container jiaochi, which provides a stable environment for microbial metabolism to generate various aroma components [9]. The production of volatile components is primarily influenced by microorganisms. Alcohols are the precursors for other volatile compounds, which are primarily derived through microbial decomposition and metabolism of sugars and amino acids in raw materials [3]. Metabolic pathways, such as alcohol oxidation, keto-acid decarboxylation, amino acid deamination, and amino acid decarboxylation are the primary sources of volatile aldehydes and ketones [3,10]. Volatile esters have two sources: The metabolic production of yeast and the esterification reaction between acids and alcohols at a specific temperature [3]. Acids are essential components of Baijiu aromas. They can balance the aroma and primarily originate from the metabolic processes of acetic and lactic acid bacteria [6]. In a study of jiang-aroma Baijiu, benzaldehyde and 4-ethyl guaiacol were found as essential aromatic compounds [11]. Pyrazine is a common nitrogen-containing compound. Nuts and roasted aromas are typical aroma characteristics of pyrazine, significantly contributing to the zhima-aroma Baijiu [12]. Apart from the volatile components, non-volatile components are crucial to determining whether Baijiu is mellow. Appropriate amounts of glycerol, 2,3-butanediol, and mannitol are used as Baijiu buffers, making it sweet and mellow [9].

With living standard improvements, requirements beyond aroma, such as the health attributes have been sought for. Due to the many chemical components present in it, Baijiu is not considered an ethanol solution [13]. Alcohol consumption is a double-edged sword, whose abuse harms human health and can cause adverse health outcomes [14]. It is considered the primary cause of hepatitis and neurocognitive impairment [15–17] and a contributing factor to certain cancers [18]. In contrast, moderate alcohol consumption has many positive effects. Baijiu trace components are believed to be vital for its health attributes [6,7]. In ancient China, Baijiu was a drug rather than an alcoholic drink. For example, it is recorded in the Compendium of Materia Medica that: Baijiu can dispel cold and wet phlegm in the skeleton, stop stagnation, and treat cholera, malaria, asphyxia, and heartache [6]. Modern medical research has shown that proper Baijiu consumption can reduce serum uric acid concentration [19] and the risk of Alzheimer's disease [20]. The trace components in Baijiu can improve blood lipid levels and reduce the risk of cardiovascular diseases [2]. A recent study showed that moderate consumption of strong-aroma Baijiu reduced liver injury [21,22]. Therefore, moderate drinking without excess consumption is encouraged.

Alcohols and esters are the most abundant and essential trace components in determining Baijiu aromas [23]. Esters account for over 60% of the total trace components [24], while alcohols account for approximately 12% of the total trace components [9]. Similarly, the acidic compound content of Baijiu is high [7]. Alcohols, esters, and acids constitute the aromatic skeleton of Baijiu. Nitrogenous compounds are substances that significantly affect the aroma compounds of Baijiu. For example, pyrazine (a nitrogenous compound in Baijiu) has significant health effects [25]. Sulfur compounds are substances with low aroma thresholds, small amounts, and unique aroma characteristics; however, their contribution to the taste and aroma of Baijiu is notable [26,27]. These five trace components are essential in the aroma of Baijiu and positively affect health [7,8,25,28,29].

Therefore, this review focuses on these five representative trace components in Baijiu, as well as summarizes their sources, types, and effects on Baijiu aroma. Furthermore, it describes their content and existence in mainstream Baijiu with strong-, jiang-, and light-aromas; discusses their relationship with health; and proposes several feasible research ideas to expand the existing knowledge base.

2. Sources of Baijiu Trace Components

Baijiu is characterized by complex raw materials, special processes, co-fermentation of multiple strains, and a complex product composition [3]. The aroma characteristics and Baijiu quality are determined by the trace components, which account for only 2% of the total. Research shows that Chinese Maotai (a type of jiang-aroma Baijiu) does not harm

the liver since its trace components are balanced [30]. Therefore, the control and balance of trace components are worth studying, and understanding their sources is the foundation of this study. The sources of the trace components in Baijiu are shown in Figure 2.

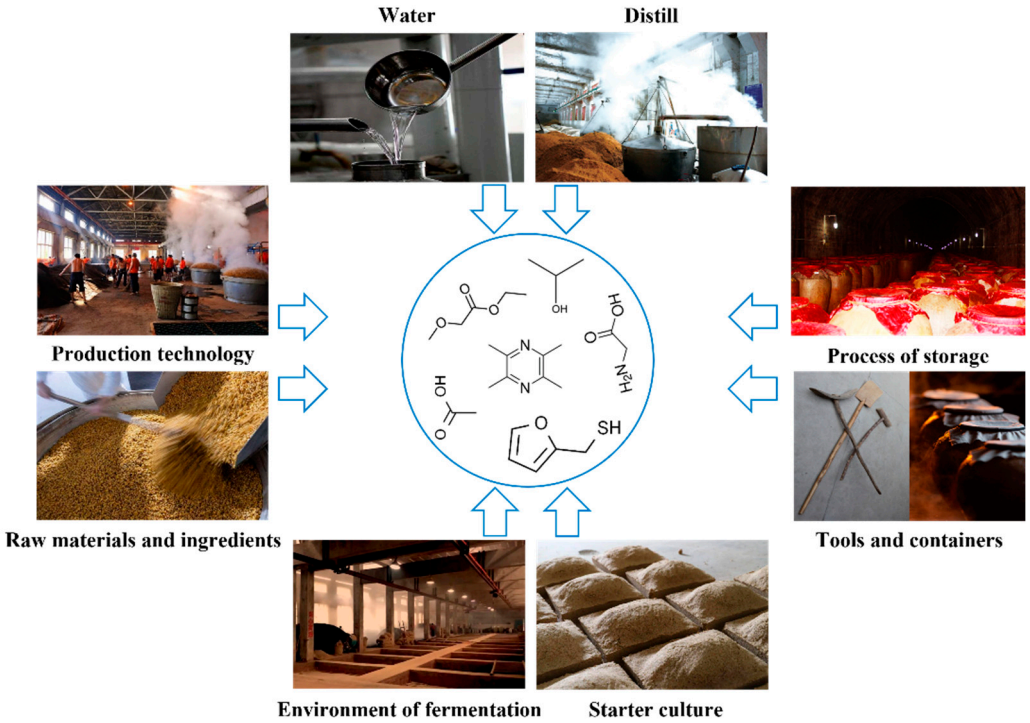


Figure 2. Source of trace components in Baijiu.

2.1. Production Technology

Different production processes produce different aromatic components. The 12 aroma types are processed differently; therefore, the aroma components of the produced Baijiu differ and are a feature of Baijiu technology [10]. Baijiu production is a complex process involving many microorganisms. The metabolic activity of microorganisms is influenced by many factors. For example, during the production of jiang-aroma Baijiu, the high temperature generated by stacking fermentation destroys many microorganisms; however, their metabolic activities adapt to high temperatures [31]. Many physical and chemical reactions are also associated with microorganism metabolites. For example, some pyrazines are products of the Maillard reaction, which utilizes metabolites, such as reducing sugars and amino acids produced by microorganisms as their precursors [32]. Therefore, the differences in each step may cause differences in the trace components. The production process includes the factors described below [9].

2.2. Raw Materials and Ingredients

Different raw materials produce various trace components during fermentation. Some trace components in the raw materials are introduced into Baijiu, some are transformed by microorganisms as precursors of other substances, and some diffuse into the air and disappear [3]. Sorghum has high amylopectin and phosphorus contents, suitable tannin content, and induces a mellow taste after fermentation. Wheat has a high protein content and is the primary "Chenxiang" flavor source. Corn fermentation can produce higher alcohols, which eases Baijiu drinking [33]. Amongst excipients, rice husk is the most suitable; others produce an unpleasant odor to Baijiu. The primary purpose of rice husks in the fermentation process is to form a properly sized spatial structure around the raw materials, which helps in regulating the temperature and facilitating oxygen flow [34]. Phenolic compounds released by microbial corrosion of rice husks are essential trace components [35].

Different qualities of rice husks affect Baijiu differently. Rice husks with high freshness, low impurity, low moisture content, and large particles are the best choices [9].

2.3. Environment of Fermentation

The fermentation environment usually includes the fermentation container, surrounding temperature, air humidity, and the number and abundance of microbial populations within a certain spatial range. Many types of fermentation containers are available for Baijiu, including cellars, stone cellars, brick cellars, and wooden barrels. Different fermentation containers significantly affect the growth, reproduction, and metabolites of microorganisms [2]. The trace components contained in the container penetrate the jiupei. The brewing of strong Baijiu aroma has always been associated with the saying "A thousand year old jiaochi and a thousand year old distiller's grains". This indicates that old cellars and long-term aging distiller grains are indispensable for brewing high-quality strong-aroma Baijiu [36]. Similarly, this phrase illustrates the significance of microorganisms in fermentation environments. Porcelain jars and stone cellars are used for fermenting light- and jiang-aroma Baijiu, respectively. Different fermentation container materials produce different Baijiu types [9].

2.4. Starter Culture

The fermentation starter significantly influences the formation of trace components in Baijiu [2,8]. The raw materials used in the fermentation starter, its microorganisms and esterifying enzymes, and its production process affect the trace components in Baijiu. This fermentation starter is known as jiuqu. Wheat and barley are commonly used raw materials in fermentation starters. Notably, Chinese herbal medicine is added to the fermentation starter used in fermenting the herbal Baijiu aroma, and some researchers believe that terpenes are introduced in this process [8,37]. The significance of fermentation starters is not negligible. The application of cell immobilization technology (including immobilized enzymes and bacteria) enables direct altering of the trace component content [9].

2.5. Tools and Containers

In traditional Baijiu production, the used tools and utensils comprise iron, copper, tin, aluminum, wood, bamboo, slate, brick, and yellow mud. The most commonly used are wood and bamboo, which gradually enter the jiupei after continuous wear, tear, and fermentation. Through the corrosion of acids and alcohols and their interaction with microbial metabolites, these materials release aroma components indispensable for high-quality Baijiu and may be a source of its phenolic compounds. In addition, the wear of tools comprising iron, slate, or other materials during use enters the Baijiu fermentation system directly or indirectly, and thus affects its trace components [2].

Fermentation and storage containers are used for fermenting Baijiu. We have described the fermentation container in the "Environment of fermentation", in which storage containers have a history of long usage. Tile jars, pottery jars, and "jiuhai" (a large Baijiu container), made of rattan, pig blood, lime, and other materials, are the common storage containers. Modern storage containers, such as aluminum barrels and stainless-steel cans have emerged. According to the traditional concept, a long Baijiu storage in tile jars, pottery jars, and jiuhai produces a better aroma. These containers have microporous and breathable structures, and the participation of oxygen induces slow chemical reactions in Baijiu, generating more trace components. Trace metal elements in tile and pottery jars, rattan, pig blood, lime, and other components in jiuhai infiltrate into Baijiu and increase its trace components [2,9].

2.6. Process of Storage

The trace components in Baijiu undergo physical and chemical reactions and produce new trace components during storage. Therefore, storage is essential for determining the source and changes in trace components in Baijiu. The storage time, conditions, and methods affect the storage process. Practical experience indicates that quality of Baijiu increases

with longer duration of storage. Jiang- and light-aroma Baijiu have a storage period of over 3 years [38], and that of strong-aroma has a storage period of over 1 year [36]. This period is known as the Baijiu maturation period. Similarly, storage conditions and methods promote the formation of trace components in Baijiu. Storing in a constant temperature and humidity environment, such as basements and natural caves, modifies the quality slowly, and the loss is minor. However, when stored indoors at room temperature, its quality changes rapidly, and the loss is enormous. Addition of tiles and pottery chips to the storage process have been found to accelerate the ripening of Baijiu, with a positive effect. X-rays, magnetic fields, ultrasonics, and other technologies have also been used to accelerate Baijiu maturation [9].

2.7. Distillation

Distillation is the primary method for extracting ethanol and trace components from jiupei. During fermentation, many beneficial and a few harmful components are generated. The primary purpose of distillation is to substantially extract beneficial components [2]. It is conducted at high temperatures, and the acids and alcohols in jiupei undergo spontaneous esterification to generate esters. The glycoside precursors on wheat skin and the tannins on sorghum skin decompose and are converted into phenolic compounds, which enter Baijiu with alcohol vapor, increasing the trace aroma components in Baijiu. The amino acids in Baijiu are supposed to be originating primarily from distillation, and controlling the temperature and time during the process is key to ensuring the amino acid content [39]. We believe that the "zhaijiu" (technology for removing the Baijiu flowing out at the beginning and the end of distillation while retaining only that in the middle) can affect the trace components in Baijiu. Due to their different boiling points, the trace components in jiupei flow out sequentially, with low-boiling-point alcohol-soluble components appearing first. Similarly, low-boiling-point olefins and aldehydes were distilled, followed by high-boiling-point trace components. A high component retention by zhaijiu produces rich trace components in Baijiu [9].

2.8. Water

The water mentioned in this section refers to fermentation and blending water. The trace components contained in the water used for fermentation can be directly introduced into Baijiu and may affect microbial metabolism. The jiang-aroma Baijiu originated from the Maotai town. The water for fermenting the traditional jiang-aroma Baijiu is obtained from the Chishui river. The water is rich in iron ions [40] and can affect the biological activity of many enzymes [41], possibly a secret of the jiang-aroma Baijiu fermentation. Water accounts for more than half of the Baijiu, and blending water is the primary source of trace components in Baijiu. Purified water is the common blending water and is the basis of the clean Baijiu taste [9].

3. Trace Components in Baijiu

3.1. Alcohol Components in Baijiu

Alcohols are crucial for enhancing the sweetness and aroma of Baijiu and are precursors of esters. The alcohol with the highest content in Baijiu is ethanol, and other alcohols present include methanol, propanol, n-propanol, 2-butanol, isobutanol, n-butanol, isoamyl alcohol, n-hexanol, n-pentanol, hexanol, heptanol, octanol, glycerin, and 2,3-butanediol β-phenethyl alcohol [9]. Alcohols containing more than three carbon atoms per molecule are higher alcohols. Higher alcohols and other aroma components produced by yeasts in brewing are byproducts of ethanol fermentation. These alcohol types and contents vary with yeasts. Among higher alcohols, isobutanol has a strong bitter taste; n-butanol and n-propanol are slightly bitter. Tyrosol, produced by yeast fermentation of tyrosine, has an elegant aroma and a bitter and long-lasting taste. Amyl and isoamyl alcohols account for many higher alcohols and are bitter. Therefore, for optimal taste, Baijiu should contain an appropriate amount of higher alcohols [28,42].

All alcohols in Baijiu account for 12% of total trace elements. Owing to the lower boiling points of alcohols than those of other components, they are prone to volatilization. Release of other components with the alcohols during volatilization also enhance the aroma. In Baijiu, the alcohol content of the low-carbon chains is the highest. When the carbon atoms in the molecule are increased, the odor gradually transits to fruit and fat odors, which are more persistent [9].

In strong-aroma Baijiu, the total content of all alcohols except for ethanol is second only to the organic acid content, which is the second largest component. Isoamyl alcohol, n-propanol, isobutanol, 2-butanol, n-hexanol, 2,3-butanediol, isopropanol, n-pentanol, and β-phenethyl alcohol are the primary alcohols in strong-aroma Baijiu, of which isoamyl alcohol has the highest content [36]. Isoamyl alcohol and isobutanol significantly impact the appearance and taste of Baijiu, and their contents in high-quality strong-aroma Baijiu have a golden ratio of 3:1 [9]. Similarly, 2-butanol, isobutanol, and n-butanol taste bitter, and their contents are very high, damaging the typical characteristics of strong-aroma Baijiu. Contrary to strong-aroma Baijiu, light-aroma Baijiu has the highest alcohol proportion in various components. Methanol, propanol, 2-butanol, isobutanol, isoamyl alcohol, n-butanol, and 2,3-butanediol are reportedly the primary alcohols in light-aroma Baijiu. Among these, n-propanol and isobutanol were the two most abundant alcohols. The taste characteristics of light-aroma Baijiu, primarily related to the alcohol content and proportion, are slightly sweet, with strong stimulation and a certain refreshing bitter taste [43]. The jiang-aroma Baijiu contains n-propanol, 2-butanol, isobutanol, n-butanol, isoamyl alcohol, n-amyl alcohol-phenethyl alcohol, 2,3-butanediol, n-hexanol, heptanol, and octanol, among others, and n-propanol has the highest content, which is strongly related to its taste [6].

Sugar, pectin, and amino acids are the used alcohol sources. The precursor of methanol is pectin, which is a condensate of galactose uronic acid. The carboxyl group often combines with methyl or calcium groups to form an ester [8], which generates acids of methanol and pectin via pectin esterase. As the most abundant ethanol in Baijiu, pectin primarily originates from the Embden–Meyerhof pathway in yeast [7,8]. Protein decomposition in raw materials or microbial cell protein hydrolysis generates amino acids that are further hydrolyzed to generate the corresponding alcohols, which are the primary sources of medium and high alcohols in Baijiu [9]. Glycerol is an intermediate product of yeast ethanol fermentation. In addition, 2,3-butanediol-producing bacteria produce glycerol when oxygen is sufficient. Mannitol is produced by molds and lactic acid bacteria, which produce lactic acid using hexose [28].

Therefore, alcohols in Baijiu significantly impact its aroma characteristics. As mentioned before, moderate alcohol consumption is associated with improved health [44]. However, research on the relationship between small molecular weight alcohols (excluding ethanol) and health is limited. Methanol is a common pollutant in Baijiu that negatively impacts human health [45]. Therefore, controlling its content is essential. Propanol is a common solvent in the pharmaceutical field. It may have a relaxing effect on local analgesics. Similarly, propanol is an antioxidant since it can scavenge free radicals; however, this property may be relatively weak [46]. An antibacterial experiment of n-butanol extract from maple leaves showed that n-butanol strongly inhibits bacteria; 50 mg/100 mL of n-butanol extract from maple leaves can reduce the decay and quality loss of citrus and slow the decrease in fruit hardness; this preservation ability is related to its antioxidant activity [47]. Furthermore, n-butanol, n-propanol, and isobutanol enhance the efficacy of traditional antibiotics against antibiotic resistance. The bactericidal effect of n-butanol and aminoglycosides on *Staphylococcus aureus* was greatly improved after mixing for 1 min [48]. The role of higher alcohols in alcohol intoxication remains controversial. Some studies have suggested that the interaction between ethanol and higher alcohols increases the possibility of drunkenness [49]. Another study showed that alcohol dehydrogenase 3 (ADH3) is crucial in the process of acute alcohol intoxication (AAI) [50], and ADH3 is the only ADH detected in the brain tissue [51]. Therefore, ADH3 may prevent AAI by reducing the harmful effects of ethanol on the brain. The hydrophobic higher alcohols in Baijiu (such as trifluoroethanol and tert-butyl alcohol) can promote ADH3 activation [52],

accelerate ethanol elimination, and reduce the drunkenness reaction [53]. Isoamyl alcohol is highly cytotoxic. Isoamyl alcohol-induced alcohol intoxication inhibits ethanol and acetaldehyde metabolisms [54]. Glycerol is usually present in normal mammalian foods and can be catabolized and absorbed in the intestine and stomach, making it harmless. However, excessive intake of glycerol can pose health threats, such as vomiting, loss of balance, and death [55]. An in vitro study found that β-phenethyl alcohol inhibits DNA and RNA syntheses, and that at a certain concentration, it inhibited cell division in mouse lymphoma cells by 50% [56]. Notably, many alcoholic substances have been proven to be cytotoxic and reduce the content of those with negative effects, while balancing taste is challenging.

3.2. Acid Components in Baijiu

Acids are essential aromatic compounds in Baijiu. A low acid content produces a light-aroma Baijiu, while excess acids induce rough tastes in Baijiu. An appropriate amount of acid is a buffer and slowly forms esters with alcohols during storage [9]. Baijiu contains many acid types. Table 1 describes the aroma characteristics of different organic acids in Baijiu. Volatile compounds include formic, acetic, propionic, butyric, caproic, and octanoic acids. Formic acid produces the strongest stimulation; however, its concentration was low. Acetic acid is highly irritating and high in content, bringing a pleasant aroma and sour taste to Baijiu; however, its excess makes Baijiu taste sharp and sour. Propionate has a sharp and sweet odor, with a soft and astringent taste when consumed in excess. Butyric acid has a "jiaoni" aroma and a slight sweetness. Caproic acid has a spicy taste and is present at a certain concentration in Baijiu with strong aromas containing a certain amount of caproic acid; it causes a fatty odor when in excess. Octylic acid and fatty acids with longer carbon chains have an oily odor, and their content is not high [7,57].

Table 1. Aroma characteristics of different acid components in Baijiu.

Aroma Compounds	Aroma Threshold (μg/L)	OAV	Aroma Characteristics	References
Formic acid	1000	—	It smells sour, with irritation and bitterness in the mouth.	[9]
Acetic acid	160,000	1–11.4	It has a sour, refreshing, sweet taste and pungent feeling.	[7]
Propionic acid	18,100	0.59–3	It smells sour and tastes mild and astringent.	[7]
butanoic acid	964	30–410.94	It smells of oil and mud.	[7]
Valeric acid	389	3–447	It has a fatty odor similar to that of butyric acid.	[7]
Caproic acid	2520	6.95–146	The taste is soft, with a strong fatty odor in excess.	[7]
Heptanoic acid	13,800	0.59–2	It has a strong fatty odor and a pungent taste.	[7]
Octanoic acid	2700	1–10	It has a fatty odor and a faint pungent smell.	[7]
Lauric acid	9154	—	It has an aroma of laurel oil and a slightly sweet taste in the mouth.	[9]
Lactic acid	350,000	—	It smells sour and astringent in excess.	[9]
Succinic acid	3	—	It smells sour and umami.	[9]
Citric acid	6	—	It has a citrus aroma.	[9]
Oleic acid	1000	—	It has a rancid smell.	[9]
Linoleic acid	—	—	It has an odor of soybean oil and cottonseed oil.	
Cinnamic acid	—	—	Almost no smell.	

OAV indicates odor activity value.

Non-volatile acids give Baijiu a mellow taste. Lactic, malic, gluconic, tartaric, citric, and succinic acids are found in Baijiu [58]. Lactic acid is relatively soft, and its faint aroma can make Baijiu mellow and thick, impacting Baijiu with a special aroma. Succinic acid is a blending agent for the taste of Baijiu. An appropriate amount of succinic acid will make Baijiu full and mellow. Citric and tartaric acids taste strong, giving Baijiu a refreshing taste [7,59]. An appropriate proportion of non-volatile acids in Baijiu eases stimulation and balances taste, causing a fresh, soft, and happy feeling after tasting Baijiu.

The acid contents and types in Baijiu with different aromas differ, which is a vital indicator of their different styles. Acetic, propionic, butyric, caproic, valeric, heptanoic, phenylpropanoic, 2-methylpropionic, 4-methylvaleric, and 2-methylbutanoic acids are present in Baijiu with various aromas [7]. Jiang-aroma Baijiu has the highest acid content among all aroma types of Baijiu, with acetic, lactic, caproic, butyric acids, and amino acids accounting for 94.3% of the total acid content. High amino acid content is an essential feature of the jiang-aroma Baijiu, distinguishing it from other aroma types of Baijiu [9]. The caproic, acetic, lactic, and butyric acid contents in strong-aroma Baijiu account for 94% of its total acid. The prominent feature of the strong-aroma Baijiu is that its caproic acid content exceeds those of Baijius of other aromas. In contrast to the jiang-aroma and strong-aroma Baijius, the light-aroma Baijiu has low acid content, primarily acetic and lactic acids, and the acetic acid content is high, making this Baijiu unique [7,9]. Although the acid types in Baijiu are up to 100, most exist only in certain Baijius with aroma, which may be the unique secret of different aromas of Baijiu. Chlorogenic, 3-methoxy group butyric, gallic acid β-nitropropionic, and 3,4-di hydroxycinnamic acids only exist in the strong-aroma Baijiu. Geranic, 2-ethyl-2-hydroxybutyric, 9-decenoic, and 17-octadecycloic acids are unique ingredients of the jiang-aroma Baijiu. Undecenoic, 5-hexenoic, ethoxyacid, 3-decenoic, 4-heptenoic, and 2-hydroxydecanoic acids are primarily detected in the light-aroma Baijiu. In addition to the above three aromas of Baijiu, the characteristic acids in others with aroma are relatively simple, and only methyltartronic acid has been detected in the fragrance-aroma Baijiu [7,24].

Development of advanced molecular biology techniques has enabled the rapid tracking of the acid sources in Baijiu [60]. Some studies have suggested that most acids in Baijiu originate from microbial fermentation, consistent with our view [7]. Acids are products of incomplete sugar oxidation; however, sugars are not their only substrates. Many noncarbohydrate compounds can also form acids. Notably, many microorganisms can consume and transform acids, which are produced and consumed during fermentation. Different acids can also transform into each other [9].

Acetic acid is an inevitable product of ethanol fermentation present in Baijiu with various aromas and is an essential precursor of butyric and caproic acids and their esters. Acetic acid is primarily produced via three methods. Acetobacter oxidizes ethanol to acetic acid, which is a noticeable challenge in Baijiu production. Some yeasts with strong ester production capacity can produce acid less efficiently than the acetic acid bacteria. Normal ethanol fermentation is often accompanied by acetic acid and glycerol formation. Similarly, acetic acid can be produced by fermenting sugars to produce acetaldehyde, which is oxidized to acetic acid. All three conditions produce acetic acid; however, controlling acetic acid production is a critical challenge [7]. Lactic acid is primarily derived from bacteria. Baijiu is produced in an open environment [2]. Many lactic acid bacteria inevitably become infectious during brewing. Lactic acid bacteria enter the cells for fermentation, giving Baijiu a unique aroma. Lactic acid bacteria have two fermentation types: Homogeneous (with lactic acid as the only fermentation product) and heterotypic (with acetic acid, ethanol, carbon dioxide, and hydrogen as the fermentation products) lactic acid fermentation. Lactic acid bacteria use sugar to generate pyruvic acid through glycolysis, which is reduced to lactic acid by lactate dehydrogenase [61,62]. Ethanol and acetic acid are the primary raw materials in caproic and butyric acid syntheses. Ethanol and phosphoric acid combine with acetic acid to form butyric acid in the presence of acetyl and acetyl phosphates. When butyric acid and phosphoric acid co-exist, they are oxidized to form acetylphosphates [9]. Fermentation generally involves decomposing large molecules into smaller ones, whereas hexanoic acid fermentation involves the conversion of two carbon atoms of ethanol into six hexanoic acids, which is a rare example of fermentation [9]. The formation of valeric acid is complex. Propionibacteria carboxylate pyruvic acid forms oxaloacetate, which is reduced to malate. The malate is reduced to succinate, which is converted to propionate. Propionyl-CoA is generated by the enzyme coenzyme A (CoA). Finally, propionic acid is converted into valeric acid through a synthesis pathway similar to those of butyric and

caproic acids [63]. Valproic acid is a precursor in heptanoic acid synthesis. In addition to its reduction from malic acid, a precursor of propionic acid, succinic acid can be obtained through deaminating amino acids. The amino acids in Baijiu can be obtained via protein decomposition [9,63].

Sour substances affect the aroma and taste of Baijiu and the health of the consumer [7]. The aroma and function of Baijiu are related, and many studies have shown that sour substances contribute to the association [7]. Short-chain fatty acids in Baijiu primarily include acetic, butyric, lactic, and caproic acids, which can affect the gut microbiota and health of the host by stimulating bifidobacterial growth and inhibiting Gram-negative facultative and anaerobic bacteria [64–66]. Acetic acid and ethyl acetate can significantly reduce the damage caused by alcohol intoxication by altering ethanol metabolism and have an active protective effect against acute alcoholic liver injury [67]. In a study on the effects of long-term ethanol consumption on gastrointestinal metabolites in mammals, acetic acid reportedly had a significant protective effect against ethanol-induced liver injury [64]. Propionic and butyric acids reportedly regulate calorie intake and energy expenditure to control weight and reduce plasma cholesterol levels [68]. Butyric acid inhibits colon cancer cells. It antagonizes histone deacetylases, keeps chromatin open, and has high transcriptional activity. Increasing P21 gene expression stops the cell cycle in the G0 phase [7]. Lactic acid can stabilize the natural microbalance in the body, maintain an acidic environment in the stomach, and inhibit the growth of pathogenic bacteria while promoting bifidobacterial growth [69]. Malic acid relieves cough and asthma [70]. Linoleic acid is a long-chain fatty acid in Baijiu, which can combine with cholesterol to promote cholesterol efflux, reduce the levels of low-density lipoprotein and triglycerides in the blood, and increase the level of high-density lipoprotein [71]. Similarly, phenolic acids are important components in Baijiu. Gallic acid has antioxidant, anti-apoptotic, cardioprotective, neuroprotective, and anticancer properties, and most studies have shown that it can affect the signal network of reactive oxygen species (ROS) through its antioxidant properties [72]. Furthermore, gallic acid inhibits the growth of pathogenic microorganisms. In vitro antibacterial experiments have shown that it has a strong inhibitory effect on *S. aureus* and *Pseudomonas aeruginosa* [73]. Ferulic acid and its derivatives have antioxidant, free radical scavenging, anti-inflammatory, analgesic, and anti-ultraviolet radiation effects, and corresponding drugs have been gradually developed. For example, sodium ferulic acid injection is used for treating ischemic cardiocerebrovascular diseases [74,75]. In this review, we have covered only monomeric acidic substances, and the coordination of multiple acidic substances in Baijiu has not been dealt with herein.

3.3. Ester Components in Baijiu

The results of the aroma analysis showed that esters were the primary aromatic components of Baijiu. They account for over half of all aroma components in Baijiu, and most have a low odor threshold, which significantly impacts the typical aroma of Baijiu [24]. Esters have pleasant aromas. Their types and concentrations in different Baijiu samples give the product unique aroma characteristics. The total ester content of high-quality Baijiu is generally high, which is an intuitive indicator for identifying the advantages and disadvantages of Baijiu [8]. Ethyl hexanoate, ethyl lactate, and ethyl acetate are the three major esters in Baijiu, and ethyl lactate and ethyl acetate are simultaneously present in all kinds of Baijiu with the 12 basic aromas. Changes in the contents of the three esters have a decisive impact on the aroma of Baijiu. Different concentrations of ethyl acetate produce different aromas, with apple and banana aromas at high concentrations and those of pear and pineapple at low concentrations [76]. A similar trend is observed for ethyl hexanoate. When the concentration is high, it presents a spicy and foul smell and emits a pleasant pineapple-like aroma at low concentrations, making the aroma of strong-aroma Baijiu unique [77]. The aroma threshold of ethyl lactate is low, and its primary function is to make Baijiu taste strong; however, when the concentration is excessively high, it causes Baijiu to taste like green grass or bitter [78]. Notably, another component, ethyl butyrate, affects the primary

aroma. It is similar to the fragrance regularity of ethyl hexanoate. With decreased concentration, there are changes from an unpleasant sweat odor to a rum aroma. Ethyl butyrate is a component of the old cellar aroma in Baijiu, and its content should not be excessively high, as this introduces the odor of fat corruption into Baijiu [8,9].

The aroma strength of ester components is related to the number of carbon atoms in their structural formula and shows a certain pattern. Ester components containing 1–2 carbon atoms have a weak aroma of a short duration of aroma. Esters containing 3–5 carbon atoms have a fatty odor, and their content in Baijiu should not be excessively high. Ester compounds containing 6–12 carbon atoms exhibit strong and long-lasting aromas. Those containing beyond 13 carbon atoms exhibit almost no aroma. The ester content of Baijiu with different aroma types and that of Baijiu with the same aroma type and different qualities differ. The total ester content of high-quality Baijiu is high. According to previous reports, among the 12 aroma types of Baijiu, the strong-aroma Baijiu has the highest total ester content, reaching over 600 mg/100 mL. Rice-aroma Baijiu has the lowest total ester content (approximately 120 mg/mL). The total ester contents of other aromas of Baijiu decrease in the following order: Light, jiang, feng, and herbal [9].

Ethyl hexanoate is a characteristic component of strong-aroma Baijiu [36]. The ethyl hexanoate content in the strong-aroma Baijiu is high, approximately 200 mg/100 mL, accounting for approximately half of the total ester content. Ethyl hexanoate has a low aroma threshold and is the primary aroma component of the strong-aroma Baijiu [36,77]. Similarly, its proportion in the total ester content of the herbal-aroma Baijiu is high; however, its absolute content value is lower than that in the strong-aroma Baijiu [8,37]. The style of the jiang-aroma Baijiu shows that it cannot contain excess ethyl hexanoate [39]. The rice-aroma Baijiu does not contain ethyl hexanoate [5]. The above descriptions show that the ethyl hexanoate content in various aroma types of Baijiu varies greatly and is essential in the differentiation of aroma types and highlighting of styles.

Ethyl acetate is the material basis for the style of light-aroma Baijiu. Taking fenjiu (a light-aroma Baijiu) as an example, ethyl acetate accounts for approximately 53% of its total esters and is the primary ester component of light-aroma Baijiu [5,9]. Similarly, ethyl acetate exists in other aromas of Baijiu; however, it is not the primary ester component. For example, in the jiang- and strong-aroma Baijius, the ethyl acetate contents are similar, between 20% and 38% of the total ester content. The rice-aroma Baijiu has a lower content of ethyl acetate, accounting for only approximately 17% of the total esters, while Dongjiu is the representative herbal-aroma Baijiu, with ethyl acetate content only accounting for approximately 8% of the total esters [9].

Ethyl lactate is significant in maintaining the integrity of the Baijiu style; however, it damages the style when it is in excess or inadequate. Whether there is a balance in the content of the different esters is worth noting. Research on the ester composition of different aroma types of Baijiu shows that to maintain the style of strong-aroma Baijiu, the ethyl lactate content should be lower than that of ethyl hexanoate [36]. Similar rules exist for the jiang-aroma Baijiu. The ethyl lactate content should be higher than that of ethyl hexanoate and lower than that of ethyl acetate [39]. In light-aroma Baijiu, the ethyl lactate content should be greater than that of ethyl hexanoate and less than that of ethyl acetate, and a great difference between the two ester contents is better [5,9], which is an attractive phenomenon. In contrast to the strong-, jiang-, and light-aroma Baijius, ethyl lactate content in herbal-aroma Baijiu is less than that in ethyl hexanoate and more than that in ethyl acetate [9]. In other aroma types of Baijius, this was not observed. For example, the difference in the contents of ethyl lactate and other esters in rice-aroma Baijiu is not evident, possibly since it contains fewer types of original esters.

The ethyl butyrate content is less than that of the above-mentioned esters, and it is almost undetectable in the light-, medicinal-, and rice-aroma Baijius. Ethyl butyrate has a special function in the strong-aroma Baijiu. Baijiu is rich in aroma and taste when its ethyl hexanoate content is within the range of 1/10 to 1/15 [39].

Baijius have other trace esters, and ethyl pentanoate exists in the strong-, jiang-, and light-aroma Baijius. Isoamyl acetate was detected only in the strong- and jiang-aroma Baijius. Ethyl heptanoate and ethyl octanoate exist only in Baijius of specific aromas. Although these esters, primarily comprising ethyl acetate, ethyl lactate, and ethyl hexanoate, are present in minor proportions, their presence contributes to the aroma frame and makes the beverage full and delicate. Table 2 describes the aroma characteristics of different ester components of Baijiu [9].

Table 2. Aroma characteristics of different esters in Baijiu.

Aroma Compounds	Aroma Threshold (μg/L)	OAV	Aroma Characteristics	References
Ethyl Formate	150,000	—	Has a peach-like aroma with a spicy and astringent taste on the palate.	[9]
Ethyl acetate	32,600	1–105	It has banana and apple aromas and tastes spicy and bitter.	[8]
Isoamyl acetate	230	—	It has an aroma similar to that of pear, apple, and banana.	
Ethyl propionate	19,000	115	It has a pineapple aroma and a slightly bitter taste in the mouth.	[8]
Ethyl Butyrate	82	21–7634	It has a pineapple and jiaoni aroma and excessive fat odor.	[8]
Isoamyl butyrate	—	—	It has a pineapple-like aroma.	
Ethyl valerate	27	0.1–5369	It has a pineapple-like aroma and tastes spicy.	[8]
Ethyl nonanoate	3150	1	It has a fruity aroma and a sweet taste in the mouth.	[8]
Ethyl caprate	1120	1–7	It has a rose-like fragrance.	[8]
Ethyl lactate	128,000	1–167	It has a faint fragrance and a slightly sweet taste and will have a bitter taste in excess.	[8]
Ethyl laurate	500	1–4	It has a strong fruit aroma.	[8]
Ethyl myristate	500	1	It tastes like celery or butter.	[8]
Ethyl palmitate	140,000	—	It has the sour smell of fat.	[9]
Ethyl oleate	1000	—	It has the sour smell of fat.	[9]

OAV indicates odor activity value.

Esters in Baijiu are formed by enzyme-catalyzed alcohols and organic acids. In addition, esters are generated through chemical reactions during distillation and storage. They appear as byproducts in ethanol fermentation, and their synthesis is catalyzed by esterases. Research has shown that esterases within yeast cells catalyze the binding of fatty acid acyl-CoA with alcohols to form esters. Yeast is not the only microorganism that can produce esterases and has been detected in molds and bacteria [79]. The synthetic pathway for ethyl lactate is similar to that of most fatty acid ethyl esters. Lactic acid generates lactyl-CoA, catalyzed by transacylase, followed by ethyl lactate synthesis from ethanol via esterase catalysis [80]. Notably, most organic acids have a certain inhibitory effect on eukaryotic cells, while that of esters is little on these cells. Converting fatty acids into their corresponding esters is an effective detoxification method [81].

Xu et al. [8] summarized the effects of ester compounds in Baijiu on health from two perspectives. Ester compounds, such as ethyl acetate, ethyl propionate, ethyl butyrate, ethyl isobutyrate, ethyl valerate, and ethyl caproate regulate human mood by enhancing the response of γ-aminobutyric acid (GABA) receptors. Previous studies have shown that esters with shorter carbon chains have more significant effects on GABA type A (GABAA) receptors. The GABAA receptor can bind to GABA in a very short period by opening a transmembrane channel and inhibiting neuronal activity in the brain, affecting human emotions. Ester compounds enhance the response of GABAA receptors, which can have relaxing effects and significantly alleviate the side effects caused by alcohol consumption. Moderate concentrations of acetic acid and esters can induce the synthesis of certain longevity proteins by activating the AMPK signaling pathway in the liver to protect the cardiovascular system

and reduce hyperglycemic effects [82]. However, the ester compounds in Baijiu have negative effects on human health. Phthalates (PAEs) are endocrine disruptors that can cause abnormal lipid metabolism, childhood obesity, interference with immune responses, neuropsychological diseases, and reproductive toxicity. PAEs are plasticizers in the environment, and plant growth can enrich PAEs, which can be introduced into brewing materials. This is a significant health threat [8].

3.4. Nitrogen Compounds in Baijiu

Nitrogen compounds are compounds containing nitrogen elements. The nitrogenous compounds in Baijiu include proteins, amino acids, polypeptides, pyrazines, and pyridines. They are essential raw materials for microorganisms in fermentation and are significant aroma sources and precursors of aroma components in Baijiu [28]. Nitrogenous compounds are also classified into volatile and non-volatile compounds. Amino acids and peptides are two essential non-volatile nitrogen compounds, whereas pyrazine, which has a nutty aroma, is a volatile nitrogen compound [9,28].

The unique "baked" and "nut" aroma of Baijiu is primarily contributed by pyrazine compounds, which constitute an essential aroma component in soy sauce- and sesame-aroma Baijius [83]. Twenty-six types of pyrazine compounds are currently detected in Baijiu, and those with high content include pyrazine, 2-methylpyrazine, 2,5-dimethyl pyrazine, 2,6-dimethylpyrazine, 2,3-dimethylpyrazine, 2-ethyl-6-methylpyrazine, 2-ethyl-5-methylpyrazine, 3-methylpyrazine, 2,6-diethylpyrazine, 3-ethyl-2, 5-dimethylpyrazine, 2-ethyl-3, 5-dimethylpyrazine, 4-methylpyrazine (TMP), 2-methyl-3, 5-diethylpyrazine, 3-isobutyl-2,5-dimethylpyrazine, 2-ethyl-3-isobutyl-6-methylpyrazine, 3-isoamyl-2,5-dimeth ylpyrazine, and 3-propyl-5-ethyl-2,6-dimethylpyrazine [83–86]. Among the pyrazine compounds in most Baijiu samples, TMP and 3-methylpyrazine have the highest contents. Baiyunbian (a Baijiu with a mixed aroma) is dominated by 2,6-dimethylpyrazine. The TMP content in the jiang-aroma Baijiu is relatively high, with an average of approximately 10 mg/L. Analyzing a jiang-aroma Baijiu that has been stored for many years showed that the total amount of pyrazine compounds can reach 63.6 mg/L, a content that is not seen in Baijius of other aromas [25]. The sources of pyrazine can be the Maillard reaction, Bacillus metabolism, or abiotic reaction [87–89]. During the high-temperature stacking fermentation stage of the jiang-aroma Baijiu, pyrazine content increased rapidly, indicating that pyrazine compounds were produced via the Maillard reaction [25]. After inoculation of daqu with Bacillus, the content of aromatic and pyrazine compounds in strong-aroma Baijiu significantly increased [90], indicating that Bacillus metabolism is related to the pyrazine content. Tracking was conducted on jiang-aroma Baijiu during storage. The alcohol, acid, and ester contents decreased with age, while the 2, 3, 5-trimethylpyrazine content increased, indicating that certain pyrazines originated from non-biological reactions [25].

Although the amino acid content of Baijiu is low, they are essential. Amino acids are precursors of macromolecular organic acids during Baijiu fermentation, and some alcohols are produced by their microbial metabolism. During high-temperature fermentation, free amino acids or dipeptides, reducing sugars, triglycerides, and their derivatives undergo a Maillard reaction that produces many pyrazines and furans [25]. Aldehydes and ketones (i.e., carbonyl compounds) are decomposed from amino acids and are essential aromatic components of Baijiu. Twenty-five amino acid types are found in Baijiu, including glycine, alanine, tyrosine, serine, aspartic acid, lysine, threonine, valine, leucine, isoleucine, arginine, histidine, methionine, and glutamic acid [3]. Polypeptides contained in Baijiu include cyclic dipeptide, dipeptide, tripeptide, and tetrapeptide [1,39,91,92]. Amino acids and peptides may be related to the unique production process of Baijiu. The unique high-temperature stacking process of the jiang-aroma Baijiu promotes aspergillus growth, and the proteins are more easily hydrolyzed into amino acids and peptides [39]. Wheat is the primary raw material of jiuqu, which is rich in microorganisms, enabling protein hydrolysis into amino acids and peptides [28]. The composition analysis for bran and rice husks also indicates that they may be partial sources of amino acids and peptides [93,94].

Pyrazines are compounds related to the aroma of Baijiu and have unique pharmacological effects [25]. TMP is currently the most studied pyrazine. Lin et al. summarized the various physiological effects of TMP: (1) TMP (5–150 mg/kg) can reduce the oxidation of low-density lipoprotein, alleviate inflammatory reactions, inhibit smooth muscle cell migration, inhibit platelet activation, reduce myocardial ischemic injury, and have an active therapeutic effect in patients with cardiovascular disease. (2) TMP (10–200 mg/kg) can penetrate the blood–brain barrier, promote angiogenesis, and participate in cerebrovascular disease and neuroprotection through anti-apoptosis, anti-inflammation, antioxidation, and other mechanisms. TMP is therapeutic against Alzheimer's disease, Parkinson's disease, and depression. (3) TMP (30–500 mg/kg) can induce anti-tumor effects and reduce neuronal apoptosis in the injured spinal cord, as well as inhibit neuronal apoptosis to alleviate neuropathic pain. (4) TMP (15–200 mg/kg) can improve systemic insulin resistance and has an active therapeutic effect on diabetes complications. (5) TMP (20–200 mg/kg) can regulate lipid metabolism, resist lipid peroxidation and tissue fibrosis, and protect the liver, kidneys, and other organs. (6) TMP (50–150 mg/kg) can ameliorate degenerative diseases [25,95]. The concentration of TMP in jiang-aroma Baijiu within the above range can be significant in healthcare. Notably, research on the efficacy of TMP has mostly focused on animal and cell models, with limited clinical trial data. Therefore, evaluating the clinical efficacy of TMP requires large-scale clinical trials [25].

Amino acids are essential in Baijiu fermentation and are present in Baijiu. However, due to its poor volatility, the amino acid content of Baijiu is low. Research on amino acids in Baijiu is relatively comprehensive, and their relationship with health has been studied for many other fermented foods [28]. Peptides can be directly absorbed by human small-intestinal cells, and the absorption efficiency of peptides in the small intestine is higher than that of amino acids [96]. After absorption, peptides exhibit physiological functions, such as antitumor, antiviral, anti-inflammatory, analgesic, protein structure protection, and regulation of blood sugar and blood lipids, highlighting the enormous medicinal potential of small peptides. Most studies on peptides in Baijiu currently focus on tripeptides and tetrapeptides and remain in their initial stages. Yuan Li et al. [39] reviewed the physiological functions of tripeptides and tetrapeptides; RNH (Arg Asn His) and PHP (Pro His Pro) are the tripeptides; and AKRA (Ala Lys Arg Ala) and DRAR (Asp Arg Ala Arg Arg Arg Arg Arg) are the tetrapeptides found in Baijiu. RNH reduces the reactive oxygen species content in human liver cancer cells (HepG2) by increasing the activity of antioxidant enzymes and reducing the level of oxidized glutathione in cells. RNH can inhibit the levels of malondialdehyde and lipid peroxidation induced by 2,2′-azobis (2-methyl-propionamidine) dihydrochloride (AAPH) and enhance the antioxidant defense ability of cells. PHP protects HepG2 cells from AAPH-induced oxidative stress by inhibiting the production of reactive oxygen species, malondialdehyde, and oxidized glutathione, reducing the expression level of the Keap1 protein, and improving those of antioxidant enzymes and Nrf2 protein. Similarly, AKRA exhibits antioxidant activity. AKRA can reduce AAPH-induced oxidative stress in HepG2 cells, reduce the consumption of reduced glutathione, and prevent an increase in the concentrations of oxidized glutathione and malondialdehyde. Research on DRAR in health remains inadequate, and its description in open literature shows that it inhibits the volatility of aromatic compounds, particularly esters and alcohols. However, certain challenges are associated with the study of polypeptides in Baijiu. Studies on polypeptides are limited. Cyclic dipeptides, dipeptides, and other structural polypeptides should be investigated. Research on polypeptides and their health effects is insufficient, and no polypeptides with great health value have been identified. The discovery of a more valuable polypeptide in Baijiu will form the basis for future research on its biological activity and synthesis mechanisms. Research on peptide metabolism after ingestion is lacking, and whether spatially active peptides can maintain their integrity and smoothly enter the small intestine in gastric acid remains unresolved.

3.5. Sulfur Compounds in Baijiu

Many studies have shown that alcohols and esters are crucial factors affecting the aroma of Baijiu; however, trace compounds, such as those of sulfur, which have a low aroma threshold, also contribute significantly to Baijiu aroma [23]. The types of sulfur compounds in Baijiu aromas vary greatly. Fifty-eight sulfur compounds were detected in the jiang-aroma Baijiu, 20 in the light, 12 in the strong, only dimethyl trisulfide and methyl in the rice, 11 in the zhima, and 37 in the herbal, of which 12 are unique to them. We speculate that this is related to its unique brewing process. Other Baijius contain a few sulfur compounds. For example, methylthiol alcohol has only been detected in the soybean-aroma Baijiu [29]. In addition to the aforementioned aromas of Baijiu, sulfur compounds in other aromas of Baijiu are rarely studied.

The ingredients in the jiang-aroma Baijiu are the most abundant among all Baijiu aromas, which is a reason for the recent "Jiang aroma hot" phenomenon [11]. Recent research has found that sulfur compounds, such as furfuryl mercaptan, dimethyl trisulfide, ethanethiol, and methyl mercaptan, are vital components of the overall aroma of the jiang-aroma Baijiu [97]. In a study of wine aroma, methyl mercaptan was considered a compound with negative effects; however, it may benefit the aroma in the jiang-aroma Baijiu [98]. Studies on dimethyl disulfide and dimethyl trisulfide have found that they may increase the aroma of the jiang-aroma Baijiu [99]. The test showed that dimethyl trisulfide and 3-mercaptohexyl ester are relatively essential sulfur compounds in the light-aroma Baijiu [100]. Another study by Gao et al. [101] showed that dimethyl trisulfide was the primary aromatic compound in fenjiu and erguotou Baijius. Song et al. [102] detected 65 odor-active compounds in the light-aroma Baijiu through headspace solid-phase microextraction technology and found that benzyl mercaptan, dimethyl trisulfide, 2-methyl-3-furan mercaptan, and furfuryl mercaptan greatly impacted its overall aroma. Dimethyl trisulfide is considered the only common sulfur compound in strong- and jiang- aroma Baijius [11], and the sulfur compounds in the strong-aroma Baijiu are significantly less abundant than those in the jiang-aroma Baijiu. This phenomenon may be related to technology. Bromocresol, 3-methylindole, and methylthiophenol are the primary sources of soil aroma in the strong-aroma Baijiu [103]. The conversion or consumption of sulfur compounds during fermentation is considered the primary reason for the low sulfur content in the rice-aroma baijiu [29]. According to the Chinese national standard "GB/T 20824-2007", the content of methyl mercaptan in high-alcohol zhima-aroma Baijiu should not be less than 0.5 mg/L, and the methyl mercaptan should be fixed in the form of indicators. Through aroma recombination and omission experiments, it was proven that methyl mercaptan, ethyl hexanoate, ethyl pentanoate, and 3-methylbutanol are the essential aroma components of the zhima-aroma Baijiu [104]. Another study proved that furfuryl mercaptan was a vital factor in aroma production [105]. The herbal-aroma Baijiu is unique since Chinese herbs are added to the jiuqu production process. According to a report, there are 12 components in the herbal-aroma Baijiu that are unique to it, and it is speculated that these components may originate from Chinese herbal medicines [29]. Methylthiophenol detected in the soy-aroma Baijiu was verified through an aroma recombination experiment, which showed that it was not a vital aroma component [106].

Microorganisms significantly contribute to sulfur compound metabolism. Sulfur compounds closely related to the aroma of Baijiu primarily originate from peptides and amino acids generated by the microbial hydrolysis of proteins [29]. Hydrogen sulfide is primarily converted from cysteine and its precursor, sulfur-containing protein. The sulfur-containing protein content in the raw materials and the amount of hydrogen sulfide generated after fermentation vary. Studies have shown that hydrogen sulfide production by yeast and bacteria is higher than that by molds. *Saccharomyces sphaeroides* and Hansen's yeast can convert cysteine into hydrogen sulfide. When cystine is present in jiupei, hydrogen sulfide is generated during high-temperature distillation in the presence of furfural and acetaldehyde [107]. Some studies have speculated that sulfur-containing amino acids and sugars generate sulfur compounds via the Maillard reaction. For example, furfuryl

mercaptan is derived from the Maillard reaction between l-arabinose and sulfur-containing amino acids in protein hydrolysate [108].

Sulfur compounds have health benefits. For example, 3-methylthiopropylamine is a sulfur compound with antioxidant activity generated by the decarboxylation of methionine. Its antioxidant activity is attributed to the synergistic effect of the amino and methyl thiohydroxyl groups in 3-methylthiopropylamine [109]. Dimethyl trisulfide reportedly has detoxifying effects. In animal experiments, it can transform highly toxic cyanide-like compounds into less toxic organic thiocyanate esters and is considered a potential cyanide antidote [110]. Furfuryl mercaptan is a food additive that extends shelf life owing to its antioxidant activity. Similarly, methylmercaptan and 3-methylthio ethyl propionate are antioxidants [29]. Owing to the low content of sulfur compounds in Baijiu, it has not been the focus of significant research, and research on the relationship between sulfur compounds and health is limited. This substance, which has a low content but significantly impacts taste, should be given special attention.

4. Summary and Future Perspectives

Alcohols, acids, and esters are the three trace components with the highest contents in Baijiu. Nitrogen compounds are presently the most promising components in Baijiu. Sulfur compounds, although present in minority, significantly impact aroma. We selected these five representative trace components, analyzed their sources, summarized their types, discussed their role in the aroma of Baijiu, described their existence and characteristics in the mainstream aroma of Baijiu, such as jiang-, strong-, and light-aromas, and discussed their relationship with health.

Research on Baijiu fermentation technology, the aroma of finished products, and other aspects is relatively common. Influenced by the concept that excessive drinking harms health, many researchers have been unwilling to explore the health benefits of Baijiu. No food intake can bypass dose complications; therefore, research on Baijiu and its health effects should be conducted correctly. We propose several feasible research ideas to address the weaknesses of research on Baijiu and health.

Existing research has focused on the impact of all trace components in Baijiu, except for ethanol on health, and the impact of each type of trace component on health should also be the focus of attention. Classification research can clarify their contribution to health. Improving the content of trace components through microbial fortification technology without changing the original aromatic characteristics is worth considering.

The relationship between trace components and microorganisms in Baijiu and the traceability of these components are challenges worthy of attention. The sources of many trace components in Baijiu are currently unclear. Are they derived from raw materials, microorganisms, or chemical reactions during fermentation? Applying microbial fortification technologies can be successful only when these are understood. Research on this topic can guide the brewing processes. PAEs, ethyl formate, and biogenic amine are potential health threats in Baijiu. Traceability can prevent the involvement of pollutants in the brewing process and minimize the content of harmful substances in the product.

The relationship between trace components in Baijiu and health should be the focus of future studies. The study of the correlation between gut microbiota and trace components should be prioritized, as it is the basis for explaining their inherent connections from a mechanistic perspective. Trace components in Baijiu can be used to study alcoholic liver injuries. Currently, there are many studies on alcoholic liver injury. There is a high possibility of success in verifying alcoholic liver injury based on the trace components in Baijiu. Given that ethanol causes significant liver damage, if other components can be proven to counteract the negative effects of ethanol, this will be a matter to look forward to.

Finally, considering "structure-effect" without "dose-effect" seems inappropriate. Exploring the relationship between trace components and health should prioritize the dose effect, as the effect can be produced only when the dosage reaches a certain level. Therefore, accurate quantification of all trace components in Baijiu should also be given precedence.

Author Contributions: Conceptualization, P.D.; methodology, G.J.; investigation, J.W.; writing—original draft preparation, P.L.; writing—review and editing, Z.Z. and J.D.; supervision, P.D.; funding acquisition, R.W. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Focus on Research and Development Plan in Shandong Province (2021ZDSYS10 and 2022CXGC020206).

Institutional Review Board Statement: Not applicable.

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

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

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