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Investigate the mystery of Baijiu production region – Environmental factors for Luzhou (Sichuan, China)

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Abstract: With a long tradition of brewing history, Chinese strong-flavour Baijiu (SFB) developed prosperously in the southwest, especially in Luzhou, and has existed for more than 300 years building craftwork and brewing techniques. As a product of the distillation of fermented grains, its production involves many microbial communities. During this time, microbial communities within production have burgeoned and evolved throughout the development history, enhancing unique texture and flavour. Meanwhile, environmental factors are critical constituents in the production, which provide the optimal conditions for processing procedures and various microorganisms, including externally controlled macro-environment and micro-environment of fermentation. By studying the correlation with environmental factors from macro and micro perspectives, we illustrated the bond with environmental symbiotic and holistic patterns of the intrinsic microbial community and fermentation characteristics. This review is essential to study and control the whole ecological conditions of the Baijiu fermentation process, aiming to gain insight into the dynamics of the microorganisms and ensure a traditional fermentation environment for quality control.

Keywords: production region; macro-environmental factor; micro-environmental factor; microbiota; strong-flavour Baijiu

Fermented foods often possess specific geographical indications, with their uniqueness usually only produced in specific regions. Chinese Baijiu has a long history and rapid progression in the spontaneous fermentation beverage (Jin et al. 2017; Wu et al. 2021). Based on characteristic flavour (Wei et al. 2020), Chinese Baijiu is classified into 12 types, including strong-flavour Baijiu (also known as Luzhou-flavour Baijiu), sauce-flavour Baijiu, mild-flavour Baijiu, rice-flavour Baijiu, jian-flavour Baijiu, feng-flavour Baijiu, te-flavour Baijiu, fuyu-flavour

Baijiu, sesame-flavour Baijiu, chi-flavour Baijiu, lao-baigan-flavour Baijiu, and herbal-flavour Baijiu (Zheng and Han 2016; Xu et al. 2017; Pang et al. 2018; Wang et al. 2018b). The majority of previous research has focused on the aroma composition of various flavour types of Baijiu as well as the precursors to the aroma (Wang et al. 2022). Recently, more and more studies have recognised that the quality of Baijiu must be traced back to the dynamically changing conditions of the overall environment (De Filippis et al. 2021). Microorganisms

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Table 1. The embodiment of environmental factors in Baijiu

Baijiu flavour	Location	Sample	Environmental factors	References
Strong-flavour	Sichuan	fermented grain, Zaopei	indoor environment outdoor environment contact surface	Li et al. 2022
Jiang-flavour	Guizhou	fermented grain, Daqu	temperature moisture acidity reducing sugar	Hao et al. 2021 Zhu et al. 2022
Light-flavour	Shanxi	fermented grain	tools staffs air	Pang et al. 2018
Fuyu-flavour	Hunan	fermented grain	summer winter (seasonal temperature)	Kang et al. 2022
Rice-flavour	Wuhan	fermented grain	temperature acidity	Hu et al. 2021

are the primary contributors to flavour, and their growth is influenced by the local environment (Lax et al. 2014; Wang et al. 2018a). There is a close relationship between the dynamic transformation of microorganisms with the local ecological environment and the co-occurrence pattern that determines the final flavour metabolites (Bokulich et al. 2014; Williams et al. 2014). Researchers are investigating the critical environmental factors for different flavour types of Baijiu, as shown in Table 1.

According to the research data, strong-flavour Baijiu (SFB) had occupied more than 70% of the market share for the past decade. The unique fermentation technique and soft taste of SFB remained popular among con-

sumers, allowing SFB to grow quickly and establish several central production regions. Geographically, it can be divided into Northwest, Southwest, North China, and the Jianghuai region (Hong et al. 2021). As revealed by Figure 1, the southwest region, particularly Luzhou in Sichuan, accounts for more than half of the market share in all regional comparisons. In the Luzhou region, more than 300 distilleries (Luzhou Natural Resources and Planning Bureau 2022) produce SFB, serving as the industrial base for nationwide production.

At the same time, distinguishing from other regional Baijiu, Luzhou-flavour Baijiu (Luzhou-flavour Liquor) (Hong et al. 2021) is produced through a dou-

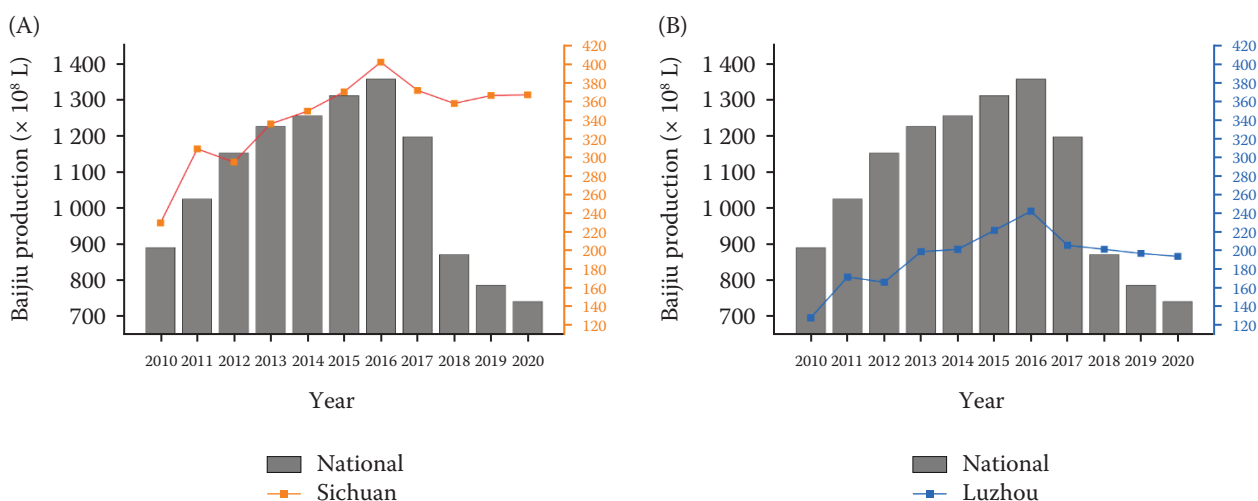


Figure 1. Baijiu production in (A) Sichuan Province, (B) Luzhou, and nationwide

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ble-round fermentation process with single grain and multiple steaming, which necessitates more stringent raw materials and environmental factors (Qian et al. 2021b). As a result, there is significant regional variation in SFB production. The environmental perturbation in the processing of Baijiu blossom is needed for scientific interpretation (García-Ulloa et al. 2022). However, existing data and research are insufficient. We obtained and processed meteorological data from the National Meteorological Information Center, as well as summering local environmental data from Luzhou, and conducted regional analysis of the integrated fermentation environment. In addition, we compared and analysed climatic conditions and geographical environments (Zhao et al. 2017) to address the relationship between fermentation and environmental factors (Zhao et al. 2017). From both macro and micro perspectives, we sorted out the national brewing environment and the internal environmental changes in brewing, highlighting their totality and differences, to gain a comprehensive understanding of the environmental characteristics of Baijiu fermentation and ultimately provided a perspective that addressed intended construction and regional uniqueness.

MACRO ECOLOGICAL ENVIRONMENT ANALYSIS

Comparison of the four production regions. As illustrated in Figure 2A, the environment plays an essential role in Baijiu fermentation, and Baijiu with different flavours are produced in different regions due to their various ecological conditions. Wind, precipitation, atmospheric pressure, and temperature are all crucial factors when controlling the fermentation and storage

of Baijiu (Xiao et al. 2017; Zhang et al. 2021). China is a vast territory with a general topographic trend of elevation in the west and declination in the east. However, there is a great deal of individual variation between regions. Based on the main origins of SFB, we selected four major producing areas (Xinjiang, Sichuan, Hebei, Jiangsu province) to represent the four regions and further take local climate data for comparison (Figure 2B). These production areas of SFB exhibit distinct quality and flavour, showcasing a unique regional dependency.

The data comparison reveals significant differences between the four regions (Figure 3). In terms of wind, precipitation, atmospheric pressure, and temperature, the southwest region differs considerably from the other three regions, with regular variations in air pressure due to topography and altitude. Regarding wind speed, the North China and Jianghuai regions are in the eastern plains and exhibit distinctly strong wind (Yang and Sun 2018; Wu et al. 2020). Due to the narrow tube effect of the terrain and the monsoon, the wind is fierce in the northwest in spring (Cheng 2005). There are significant differences in precipitation across regions. The annual precipitation in the Jianghuai region peaks in the summer, followed by the southwest and North China. Because of the continental climate, annual precipitation in northwest China is low. Temperature in the southwest is higher throughout the year, with significant differences from other regions in spring, autumn, and winter.

Previous research had also shown that the temperature (Wang et al. 2020a) and wind (Siller et al. 2021) had an impact on the temporal microbial community and metabolome changes in Baijiu, so we inferred that a low wind speed and a warm, humid climate were concerned with Baijiu fermentation. Utilising meteorological data from four different regions, we dis-

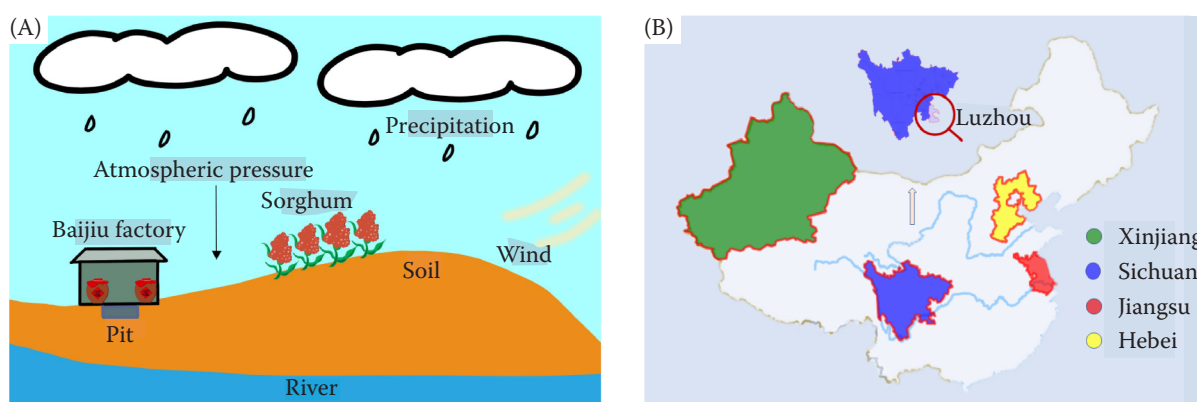


Figure 2. (A) Environmental factors and (B) major producing areas of Baijiu brewing

Green – macro-ecological environment analysis of major producing areas, including northwest region (Xinjiang); blue – southwest region (Sichuan), yellow – the north China region (Hebei); red – Jianghuai region (Jiangsu)

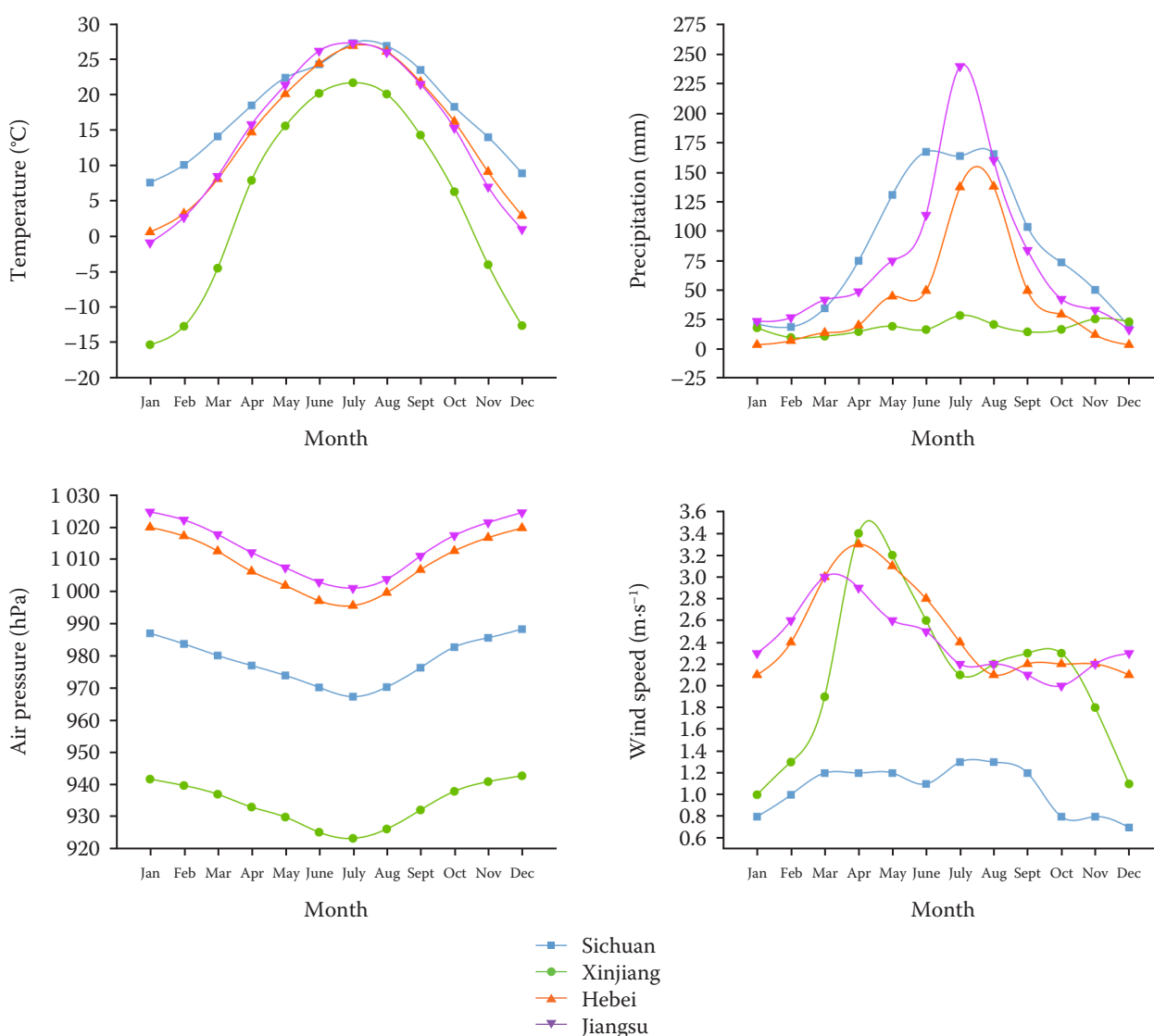


Figure 3. Macro-ecological environmental data analysis of four major producing areas, including northwest region (Xinjiang), southwest region (Sichuan), north China (Hebei), and Jianghuai region (Jiangsu)

covered that the southwest has a markedly different climate, with higher temperatures and humidity than other regions, particularly in winter, when the average temperature remains around ten degrees with frost-free periods. Moreover, the wind speed is dramatically lower in comparison to other regions. The traditional fermentation custom of 'winter break and summer break' (Pang et al. 2018) demonstrated the importance of brewing temperature based on temperature changes. Therefore, the climatic characteristics of the southwest region may have critical links to the growth of micro-organisms in production, providing good production conditions for the entire brewing process.

Comparison of producing areas in southwest China. Southwest China is the leading producer of Baijiu,

and the triangle consisting of Luzhou (Sichuan), Yibin (Sichuan), and Zunyi (Guizhou) is known as the Golden Triangle of Chinese Baijiu, with Luzhou and Yibin producing the majority of SFB. Regarding terrain and climatic conditions, Luzhou has inherent superiority in developing Baijiu over other cities in the southwest.

The average maximum temperature in Luzhou is not more than 30 °C, and the average minimum temperature is not less than 5 °C, as shown in Figure 4A. Data show that the average number of days with monthly precipitation of 10.0 mm is more than 10 days, and 25.0 mm also exists from April to October 2022. The plentiful precipitation provides sufficient moisture and influences the growth conditions of the local Baijiu fermentation. In comparison to the same latitude, the

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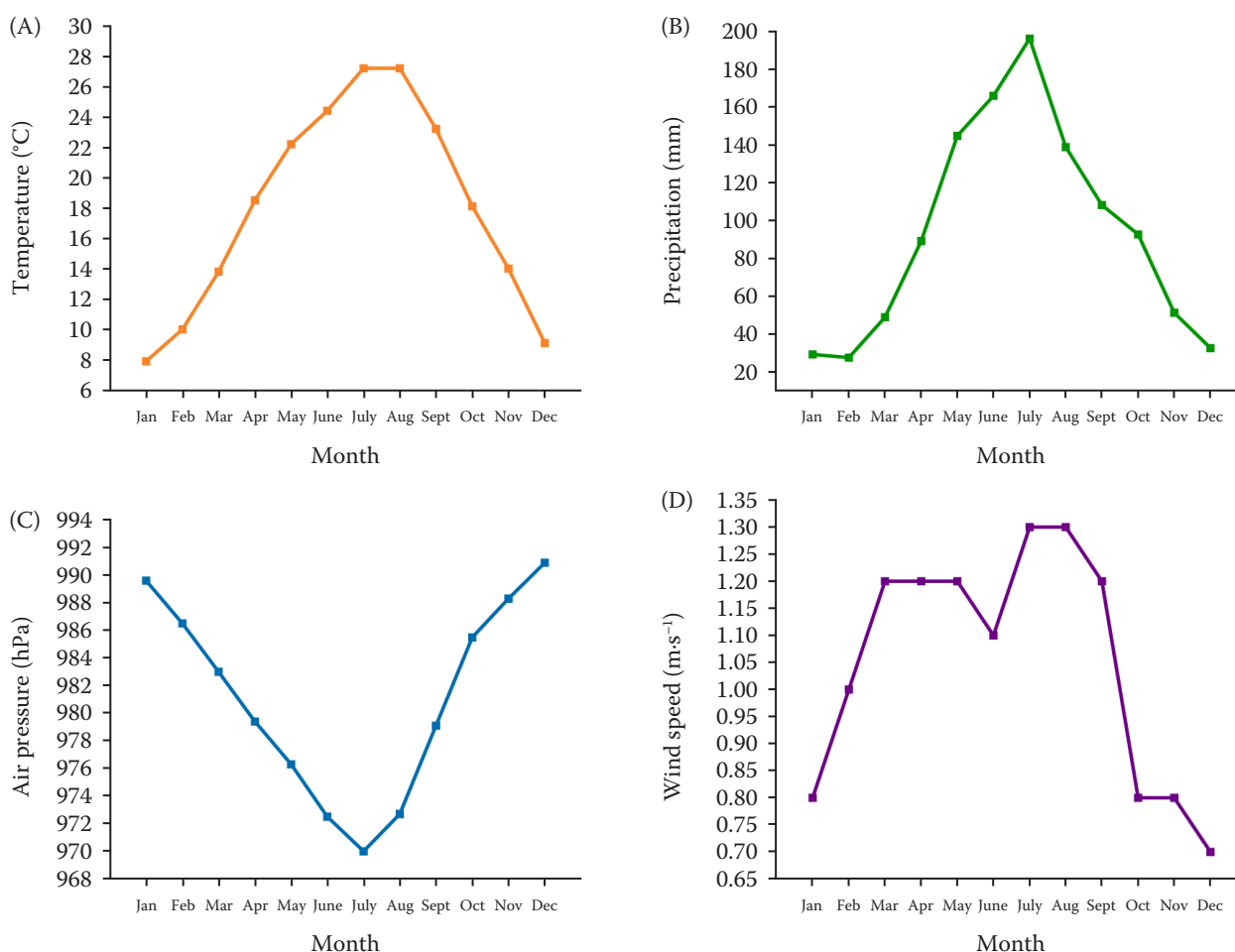


Figure 4. Environmental data of Luzhou producing area: (A) temperature, (B) precipitation, (C) air pressure, and (D) wind speed

overall climate in Luzhou is warm and moist, with rare instances of extreme weather, providing favourable conditions for the stable growth of microorganisms during whole fermentation. Previous research has also shown that the appropriate temperature and humidity significantly impacted the Daqu-microorganism culture (Zheng et al. 2014; Ma et al. 2022a) and the final Baijiu flavour. Synthesising the different SFB-producing areas, Luzhou has a stable climate and provides environmental support for the Baijiu fermentation. Other environmental conditions, in addition to the climatic environment, were further investigated below.

ECOLOGICAL ENVIRONMENT ANALYSIS IN LUZHOU REGION

Topography effect. The Luzhou area is located in the southeastern part of Sichuan, on the outskirts of the Sichuan Basin in the north and the gently sloping Yunnan-Guizhou Plateau in the south, and thus has both

basin and hilly topography. During the study, it was also found that a paleo uplift trend began to evolve in southeastern Sichuan from the Indo-Chinese period onwards (Wang et al. 2021), providing an excellent dynamic basis for the subsurface and surface resources (Potter 2018) of the later Luzhou region. The Luzhou region has developed topographic features of high south and low north, as well as various landform types and agrotypes, because of the continuous change and coupling of land masses.

Topography is one of the most important conditions for the advancement of civilisation. Comparing the distribution of 300 distilleries in Luzhou, we discovered that flat plains and mountainous valleys are the gathering places for Baijiu factories (Figure 5). This illustrates a topographic dependence, which may be related to human activities and crop-growing habits at this developmental stage. At the same time, topography influences local soil conditions (Wu et al. 2017a; Zhu et al. 2019), plant species (Khuroo et al. 2021), and mi-

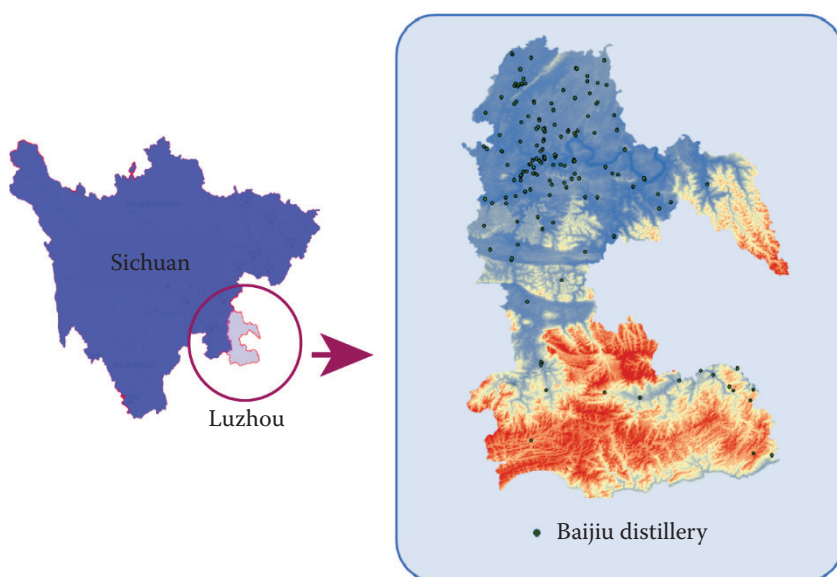


Figure 5. Distribution of 300 Baijiu distilleries in Luzhou

crobial diversity (Hariharan and Buckley 2022). In general, the topography of Luzhou, which includes plains and mountains, has affected the local climate and human conditions. Long-term crustal movements, on the other hand, have laid the foundations for soil resources and microbial diversity.

Surface runoff. Rivers are the source of recharge for an area and are essential for the development of local civilisation and economic industry. The overall water system was extracted according to Digital Elevation Model (DEM) analysis (Geospatial Data Cloud 2023). In Luzhou, we observed that a dense regional river network (Figure 6). The Luzhou region has several rivers and is located in the upper reaches of the Yangtze River. The Tuo River, the Yongning River, and the Chishui Riv-

er are the three major rivers. They are also located in the upper Yangtze River Fish Sanctuary (Yu and Xian 2009; Kindong et al. 2020), which has abundant water resources. The rivers that run through the region are vital to the production of Luzhou-Baijiu, as they help to maintain the quality of the water used for brewing.

More than 90% of the distilleries in Luzhou are located along rivers, particularly near the upper reaches of the Yangtze (Figure 5). On the one hand, sufficient water resources are available for SFB brewing. Water transport, on the other hand, has historically been more convenient for economic trade in the complex terrain of southern Sichuan.

Water is essential in the brewing and production of Luzhou-SFB. Flow velocity plays a key role in the microbial

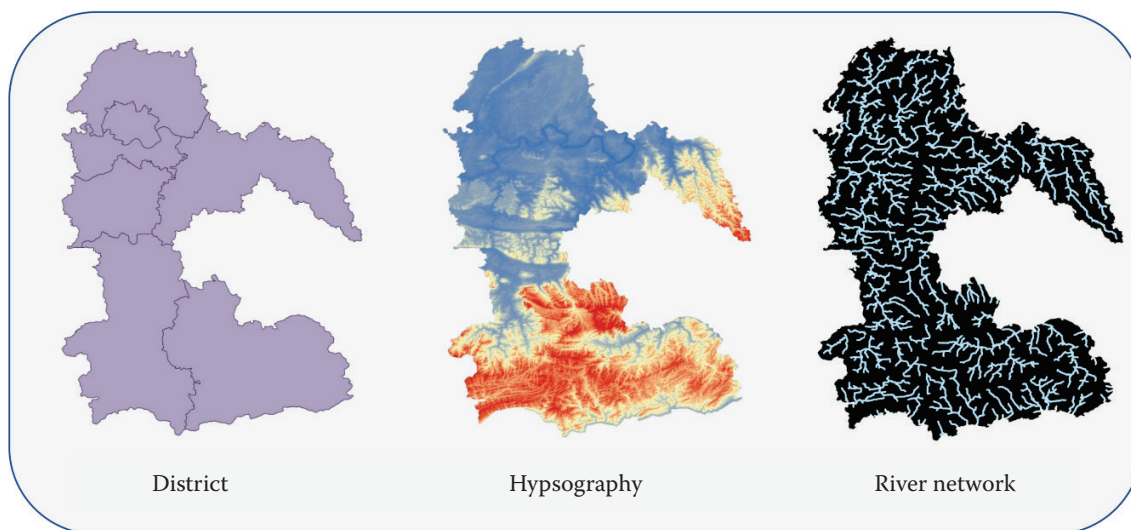


Figure 6. The administrative division, hypsography, and distribution of the river network in the Luzhou region

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community and the dissipation of pollutants in the river, according to an analysis of the impact of different sections on river biology (Mu et al. 2021; Song et al. 2022a; Song et al. 2022b). The upper reaches of the Yangtze River flow from Tibet into Sichuan, and Luzhou is at the head of the upper reaches. The Luzhou River section provides stable microbial growth conditions and a fermentation environment. Coupled with the local rainy climatic characteristics of Luzhou, the runoff increases significantly. At the same time, the river meanders and has many piled plains due to the complexity of the terrain, providing pure yellow sand for a fermentative pit mud (Hu et al. 2016; Yi et al. 2021), which aided in the completion of the core fermentation process. Overall, the unique hydrological conditions provide a sufficient ecological foundation as well as trade and transportation channels for the development of Luzhou-SFB.

Soil. In a sense, the soil of Luzhou has nurtured the local Baijiu. It is necessary to contact a large amount of soil for the raw materials and the fermentation process, which is critical for plant growth and ecosystem circulation (Zhou and Wang 2015). Previous research discovered that topography (Cho et al. 2018) and parent material factors (Hu et al. 2021) had a significant impact on the soil to obtain a large amount of organic matter, which determined the amount and structure of biomass in the soil (Wang et al. 2013; Zhou and Wang 2015; Tripathi et al. 2018). Luzhou is located in southern Sichuan and has various soil types, with purple-red and yellow loams predominating, according to palaeogeographical and evolutionary analysis. The soil type chosen for growing sorghum locally in Luzhou is red or purple-red loam, which originates from the Jurassic purple parent rock and has a high organic matter content and high fertility levels conducive to soil microbial growth with high enzyme activity (Zhang et al. 2013). The organic matter and humus in the soil play an important role in crop growth and provide quality raw materials for fermentation.

More importantly, the soil is rich in native microorganisms (Dumbrell et al. 2010; Li et al. 2015; Xu et al. 2022a), which have a significant impact on the microbiological control of the entire fermentative process. In a study of Daqu, the soil-derived *Bacillus licheniformis* was inoculated into the Daqu, and its specific metabolic activity was used to alter the flavour profile of Baijiu (Wang et al. 2017), suggesting that soil microorganisms could influence the fermentation environment. In the meantime, numerous fungi, archaea, and actinomycetes in the soil affect the metabolism and volatile compounds produced by mi-

croorganisms in the fermentative pit (Hu et al. 2016). Thus, the soil provides energy for the cultivation and fermentation, as well as a natural microbial base for the brewing of SFB.

Microecology brewing environment analysis.

The production process of SFB includes raw ingredient handling, Daqu addition, grain steaming, fermentation, moving into a pit, and re-fermentation. As the renowned Baijiu production region in China, the Luzhou region is known for its SFB which has a rich and fragrant aroma, a smooth and pure body, and a harmonious and mellow taste. Based on engineering practice, it is known that it is not possible to replicate the flavour of Luzhou-SFB in other regions solely through the transfer of production techniques. Therefore, the unique ecological environment factors in the Luzhou region are the key to forming its characteristic flavour. These factors impact raw material cultivation, Daqu production and storage, and the fermentation period, ultimately resulting in the distinctive Luzhou-SFB. The microecological environment affecting SFB quality comprises four main components: raw ingredients, Daqu, Zaopei, and fermentation pit. These critical microenvironmental factors will be discussed further below (Figure 7).

Raw ingredients. SFB is commonly produced through multi-grain fermentation of rice, wheat, corn, sorghum, and glutinous rice, with different ratios used to brew different flavours of Baijiu. Nevertheless, a unique single-grain fermentation technique in Luzhou uses local glutinous red sorghum for fermentation (Morais Cardoso et al. 2015). In terms of sorghum cultivation, Luzhou-SFB has a natural advantage. The high temperature and high humidity climate in southern Sichuan are suitable for sorghum growth (Singh et al. 2018), and glutinous red sorghum is grown in large plain areas, providing sufficient raw materials to produce Luzhou-SFB. Geographically, using native plants is more conducive to raw ingredients supply and environmental adaptation than in other regions (Shelef et al. 2017; Wu et al. 2017b).

Glutinous red sorghum has a higher proportion of branched-chain starch than other sorghum varieties (Xu et al. 2021). Saccharification begins with starch. Moreover, it is an essential energy source during the fermentation of Baijiu and is broken down into simple sugars that are more easily absorbed by microorganisms via saccharification (Srichuwong et al. 2017). *Clostridium* is a vital microorganism in SFB (Tong et al. 2022), serving as the biological foundation to produce ethyl caproate. It has been found that the

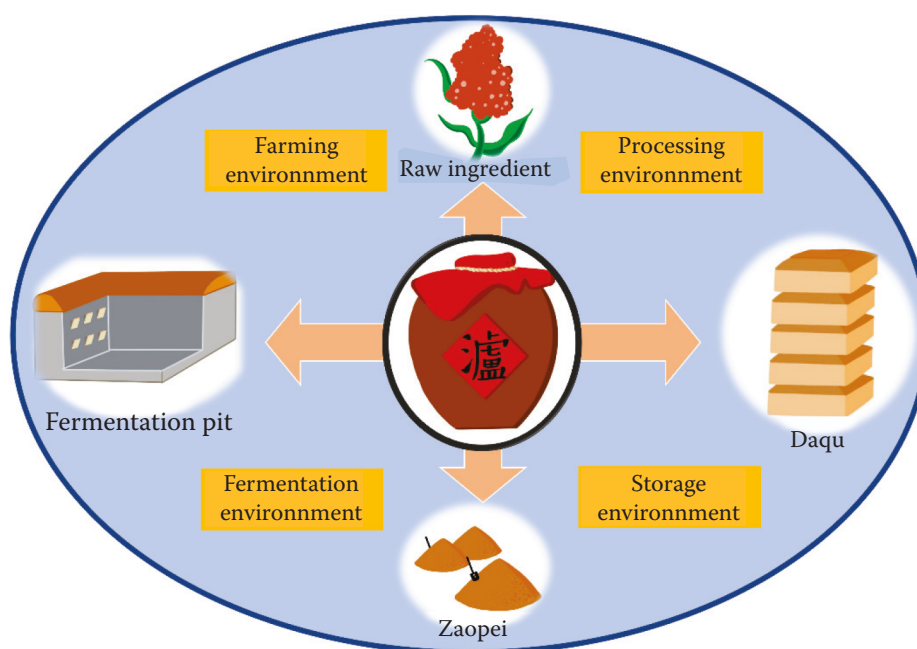


Figure 7. Micro-ecology brewing environmental factors for Luzhou-SFB, including the different environments at different stages, which impact the dynamics of the microbial community in brewing

SFB – strong-flavour Baijiu

growth of *Clostridium* is related to the surroundings, particularly the starch content provided by the sorghum (Fang et al. 2022), which explains the benefits of sorghum fermentation. Furthermore, branched-chain starch gelatinises more easily than straight-chain starch (Li et al. 2021), resulting in a glutinous red sorghum with a high yield of alcohol for Luzhou-SFB. In addition to the starch characteristics, the protein, fat, and phenolic compounds of glutinous sorghum all contribute to the pure flavour of Luzhou-SFB (Yan et al. 2011). Protein is one of the substrates for microbial growth, and it serves as the growth engine for both the fermentation process (Liu et al. 2019) and microbial growth. There was a correlation between sorghum tannin content and microbial community quality, particularly with ethyl acetate (Abdelrahman and Osman 2011; Han et al. 2017). Similarly, the total phenolic substances in sorghum can improve the flavour and human health of SFB (Sorour et al. 2017; Sun et al. 2020).

These findings show that the fermentative environment in Luzhou, where single grains are used to produce SFB, especially glutinous red sorghum as the primary raw material, is closely related to the yield and exceptional flavour of Luzhou-SFB.

Daqu. The fermentation of Baijiu is inextricably linked to the Daqu, which serves as the starter for Baijiu fermentation. Daqu is mainly composed of low,

medium, and high-temperature Daqu. To produce Luzhou-SFB, medium-temperature Daqu fermentation is generally used. The entire production process involves grinding, pressing, and stacking fermentation to control the quality, and various microorganisms are enriched from the open environment as the biological basis for Baijiu fermentation. The Daqu, a unique fermentation and saccharification agent to Luzhou-SFB, is mainly made from barley, wheat, peas, and other grains (Yang et al. 2021). The fermentative environment of the Daqu is divided into internal and external environments during the production and fermentation stages. During the study, it was discovered that the hydrolytic enzyme activities of the various types of Daqu differed, with the medium-temperature Daqu having the highest amylase activity and diversity (Liu et al. 2017a; Xia et al. 2022), as well as excellent enzymatic and microbial metabolic activity.

The external environment has the greatest impact on Daqu production and storage. Because it is an open state during the manufacturing process, it is susceptible to environmental influences and exhibits environmental sensitivity (Zheng et al. 2014; Shi et al. 2022). Members of thermophilic *Thermoactinomyces* metabolically produced in medium-temperature Daqu are primarily present in soil samples (Shanqimuge et al. 2015). Previous research found a significant positive correla-

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tion between environmental factors such as ambient humidity, moisture, and CO₂ and microbial communities during fermentation (Zhu et al. 2022). Moreover, different areas showed diversity in microbial composition, volatile matter metabolism, and potential functions (Ma et al. 2022b). The microbial profiles of the different temperatures Daqu revealed similarities between the microorganisms of the medium temperature Daqu. It formed a stable dynamic change under different environmental conditions (Zhou et al. 2022), and the fact that the fungi in Daqu were mainly derived from the tools and ground of the Daqu production environment demonstrated the response and expression of Daqu to environmental conditions (Du et al. 2019; Li et al. 2022). This microbiological profile derived from the environment is ultimately expressed in the final quality of the SFB via the Daqu. The internal microbial community, in addition to the external environmental conditions, is an important environmental factor. The coercive effect of the environment on Daqu fermentation is receiving increasing attention. It was discovered during the research that the fermentation processes in Daqu exist in dynamic microbial community changes (Li et al. 2016; Deng et al. 2020). The microorganisms were found to be constantly changing during fermentation in a medium-temperature Daqu from Luzhou (Yang et al. 2021), with an initial enrichment of *Lactobacillus*, increasing acidity and inhibiting fungal growth. Due to endogenous bioheat, thermotolerant genera predominate in later stages (Zou et al. 2018b). Consequently, the internal microbial response is an important expression of the role of the Daqu fermentation process. The dominant microorganism composition of Luzhou-Daqu is shown in Table 2.

In general, the Daqu is subject to environmental perturbations at various stages, and the metabolic influence of microorganisms is critical to the flavour of Luzhou-SFB.

Zaopei. Zaopei is the principal component of fermentation in the solid fermentation of Baijiu. The 'Old Five Cauldron' process, which originated in Luzhou, involves adding used old grains to crushed raw materials for re-steaming and cooling. This process is influenced by its surroundings and the action of the original fermented microorganisms (Liu et al. 2021).

The fermentation process of grain is in an open or semi-open environment and is highly susceptible to environmental interference. Temperature seasonal variation is an important consideration affecting the SFB microbiomes (Sun et al. 2016), and temperature changes cause significant differences in the microbial community. The source tracker technique was used to analyse the treatment process, which confirmed the influence of the environment on the microorganisms of Zaopei (Pang et al. 2020; Zhao et al. 2022a). Microorganisms transported from the workplace, the ground, the air, and most of the Daqu are growing in the Zaopei. In comparing different periods of Zaopei, it was found that the use of old Zaopei influenced the new fermentation process and was affected more by the dominant fermenting microorganisms (Xu et al. 2022b). Furthermore, this interaction has significant implications for organic acid synthesis in fermentation (Qian et al. 2021a). The dominant microorganism composition of Luzhou-Zaopei is shown in Table 3.

Zaopei is involved in the process of converting raw materials into liquid Baijiu. It is critical to comprehend the double-round fermentation process of Luzhou-SFB by examining changes in external environmental conditions and the evolution of the internal fermentation microbial environment.

Fermentation pit. An anaerobic environment is required for the fermentation of Luzhou-SFB. The pit is the most prominent location for fermentation, and the mud surrounding it is known as pit mud. The entire pit is a cuboid embedded in the ground, and yellow

Table 2. Microorganisms isolated from Luzhou-Daqu

Bacteria	Fungi	Reference
<i>Staphylococcus</i> , <i>Saccharopolyspora</i> , <i>Pseudonocardiaceae</i> , <i>Corynebacterium</i> , <i>Lactobacillus</i>	–	Mao et al. 2022a
<i>Cyanobacteria</i> , <i>Proteobacteria</i> , <i>Lactobacillus</i> , <i>Weissella</i> , <i>Staphylococcus</i>	–	Mao et al. 2022b
<i>Thermoactinomyces</i> , <i>Saccharopolyspora</i> , <i>Streptomyces</i> , <i>Kosakonia</i> , <i>Limnobacter</i> , <i>Weissella</i> , <i>Prauserella</i> , <i>Bacillus</i> , <i>Lactobacillus</i> , <i>Pediococcus</i> , <i>Rubellimicrobium</i> , <i>Pantoea</i> , <i>Enterococcus</i>	<i>Thermoascus</i> , <i>Diutina</i> , <i>Clavispora</i> , <i>Dipodascus</i>	Ma et al. 2022a
<i>Weissella</i> , <i>Lactobacillus</i> , <i>Pediococcus</i>	<i>Lichtheimia</i> , <i>Pichia</i>	Yang et al. 2021b

Table 3. Microorganisms isolated from Zaopei

Bacteria	Fungi	Reference
<i>Weissella</i> , <i>Saccharopolyspora</i> , <i>Lactobacillus</i> , <i>Aquabacterium</i> , <i>Halomonas</i> , <i>Pseudomonas</i> , <i>Kroppenstedtia</i>	<i>Thermoascus</i> , <i>Aspergillus</i> , <i>Thermomyces</i>	Yang et al. 2021b
<i>Hydrogenispora</i> , <i>Sedimentibacter</i> , <i>Proteiniphilum</i> , <i>Acetobacter</i> , <i>Lactobacillus</i> , <i>Bacillus</i> , <i>Weissella</i>	<i>Thermoascus</i> , <i>Aspergillus</i> , <i>Thermomyces</i>	Qian et al. 2021a
<i>Lactobacillus</i> , <i>Aquabacterium</i> , <i>Weissella</i> , <i>Thermoactinomyces</i> , <i>Azospirillum</i> , <i>Novosphingobium</i> , <i>Caulobacter</i> , <i>Flavobacterium</i> , <i>Pseudomonas</i> , <i>Pelomonas</i> , <i>Bacillus</i> , <i>Pantoea</i> , <i>Acinetobacter</i> , <i>Sedimentibacter</i>	<i>Aspergillus</i> , <i>Thermoascus</i> , <i>Rasamsonia</i> , <i>Malassezia</i> , <i>Penicillium</i> , <i>Russula</i> , <i>Pichia</i> , <i>Thermomyces</i> , <i>Mycosphaerella</i> , <i>Apiotrichum</i> , <i>Fusarium</i> , <i>Kazachstania</i> , <i>Hizomuco</i>	Jiao et al. 2022

mud from the local stream was chosen to build it, establishing the initial microbial environment in the pit. Besides, bamboo chips are inserted obliquely inside the cellar pond, which facilitates the adhesion of the pit mud, and on the other hand, increases the contact area between the cellar mud and the fermented grain. The cellar, as the leading fermentation site, provides suitable space, temperature, and oxygen conditions, as well as a symbiotic environment for internal microbial growth and succession.

Pit mud is pivotal in fermentation because it enriches many microorganisms in long-term fermentation (Fu et al. 2021). As a result, the diversity of microorganisms is one of the most notable characteristics of pit mud. The diversity and stability of the microbial community improve and ensure the flavour of Luzhou-SFB (Chai et al. 2021). Firmicutes, Proteobacteria, Bacteroidetes, and Actinobacteria dominated the microorganisms of pit

mud, according to the polymerase chain reaction/denaturing gradient gel electrophoresis (PCR-DGGE) method (Ding et al. 2013; Liang et al. 2014; Ding et al. 2015). Aside from microbial diversity, unique strains were isolated from the pit mud of Luzhou. *Lentilactobacillus* (Zhao et al. 2022b), *Clostridium* (Xu et al. 2019), and *Novisyntrophococcus* (Xu et al. 2019) were discovered in an aged pit used for more than 30 years in Luzhou, and the function of the strains remain unknown. The metabolism of ethyl caproate, the primary aroma component of Luzhou-SFB, was found to be mainly derived from *Clostridium bacillus* (Zou et al. 2018a), which exists in the pit mud. The presence of these dominant microorganisms ultimately alters the flavour of Luzhou-SFB. The dominant microorganism composition of Luzhou-pit mud is shown in Table 4.

In the study of the pit of Luzhou-SFB, the two main dimensions of analysis are spatial and temporal. Under

Table 4. Microorganisms isolated from pit mud

Bacteria	Fungi	Reference
<i>Methanobrevibacter</i> , <i>Caproiciproducens</i> , <i>Petrimonas</i> , <i>Lactobacillus</i> , <i>Sedimentibacter</i> , <i>Proteiniphilum</i> , <i>Syntrophomonas</i> , <i>Aminobacterium</i> , <i>Christensenellaceae</i> R-7, <i>Caldicoprobacter</i> , <i>Olsenella</i>	–	Liu et al. 2017c
–	<i>Penicillium</i> , <i>Wallemia</i> , <i>Galactomyces</i> , <i>Pestalotiopsis</i> , <i>Bjerkandera</i> , <i>Trichosporon</i> , <i>Aspergillus</i> , <i>Cladosporium</i> , <i>Candida</i> , <i>Nigrospora</i> , <i>Clavispora</i> , <i>Chaetomium</i>	Liu et al. 2017b
<i>Clostridium</i>	–	Liu et al. 2014
<i>Lactobacillus</i> , <i>Caloramator</i> , <i>Clostridium</i> , <i>Sedimentibacter</i> , <i>Butyrivibrio</i> , <i>Ruminococcus</i>	–	Zheng et al. 2015

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different conditions, the internal spatial environment of the cellar has different effects on fermentation and microbial growth. From a material standpoint, the research can be divided into studies on time-of-use pits and ageing pit. The pit in Luzhou has been in use for over 300 years, and both internal conditions and microbial communities of pit mud have changed over time (Zhang et al. 2017). Mud moisture, total acidity, and pH gradually increased with maturity, which are necessary conditions for microbial growth, demonstrating the inevitable trend of microbial changes between new and aged pit mud. Moreover, the microbial community trends were compared, revealing that while the total number of prokaryotes increased, the microbial diversity index decreased, reflecting the effect of the time shift on dominant functional strains (Wang et al. 2020b). Secondly, different positions in the pit were studied from the space perspective to investigate the impact of the multi-dimensional space environment on microorganisms. The microbial communities differed at different pit positions (Zhou et al. 2021) and covering depths (Tao et al. 2014), indicating a vertical depth discrepancy and forming a stable gradient structure. The Luzhou pit has been preserved and used to produce the unique flavour of Luzhou-SFB due to the accumulation of microbial environment and internal conditions accumulated through continuous domestication, as well as the unique ecological condition.

Pit mud is crucial for the fermentation process of Luzhou-SFB, and the unique brewing environment and rich microbial community resulted in a widely popular fermentation beverage. Therefore, understanding the internal environmental conditions aids in regulating the quality artificially.

FLAVOUR CHARACTERISTICS OF LUZHOU-SFB

The solid-state fermentation of SFB is typically spontaneous and driven by microorganisms from Daqu, pit mud, raw materials, and the environment (such as air, ground, and tools) (Wu et al. 2021). Due to the open operational environment, environmental microbial communities may colonise the fermenting grains through diffusion and settling, thereby influencing the succession of microbial communities during fermentation and the flavour characteristics (Pang et al. 2018; Wang et al. 2018b). Based on the environmental microbial communities, especially those in the air and on the ground, the Luzhou-SFB exhibits its characteristic flavour. Relevant studies have confirmed the significant

contribution of the fermentation microenvironment in the Luzhou region to the flavour of Luzhou-SFB. It has been reported that the dominant bacteria in fermented grains, such as *Clostridium*, were the main contributors to representative flavour compounds in Luzhou-SFB, such as ethyl caproate, ethyl butyrate, and ethyl acetate (Zou et al. 2018a). Sun et al. (2016) found that lactic acid bacteria were the main microbial group in Luzhou-SFB. Lactic acid bacteria could produce organic acids such as lactic acid and acetic acid by utilising fermentable sugars, which were also important substances that affect the flavour of Luzhou-SFB. Additionally, there were significant differences in the flavour of SFB brewed from different raw materials. SFB fermented with Luzhou glutinous sorghum demonstrated superior sensory characteristics compared to glutinous hybrid Jinnuoliang and non-glutinous Dongzajiao (Liu et al. 2023).

Furthermore, researchers conducted quantitative analysis on the trace components in Luzhou Laojiao Daqu jiu and found that the concentration and proportion of volatile flavour compounds had a significant impact on the flavour quality of Baijiu (Huang et al. 1996). Specifically, within a certain concentration range, higher concentrations of acids and esters resulted in better-quality of Baijiu. In a study by Wang et al. (2022), a combination of liquid-liquid extraction and solid-phase extraction coupled with comprehensive two-dimensional gas chromatography/time-of-flight mass spectrometry (GC×GC/TOF-MS) was used to analyse the volatile compounds in 18 samples of Luzhou Laojiao. A total of 320 compounds were detected, among which 24 compounds exhibited biological activity. The highest concentrations were found in ethyl hexanoate, ethyl lactate, and ethyl acetate, while butyl pentanoate, ethyl sorbate, and phenethyl butyrate were identified as distinctive markers. At the same time, research on the flavour compounds in the base Baijiu of Luzhou-SFB indicated that ethyl hexanoate, ethyl butyrate, caproic acid, ethyl acetate, and acetic acid were the five main volatile components. Ethyl valerate, pentanoic acid, 1-butanol, 1-hexanol, 3-methyl-1-butanol, ethyl caprylate, isovaleric acid, ethyl 3-phenylpropanoate, γ -decalactone, and dimethyl trisulfide were also important aromatic compounds, with esters being the main source of fruity aroma in Luzhou-SFB (Dong et al. 2019). Compared to the SFB from the Jianghuai region, Luzhou-SFB had higher levels of main esters and main acids, which may be an important factor contributing to its characteristic flavour formation (Wang et al. 2022).

CONCLUSION

The production of Baijiu is the outcome of environmental factors, influencing the ultimate flavour profiles. The co-occurring influence of the environment changes the core microbial community during the brewing process. The various geographical and location conditions, which provide native microbial communities and fermentation conditions, are crucial for the production areas. Current research, however, is primarily focused on core microorganisms and flavour metabolism. There is no systematic summary of the relationship between the ecological environment and Baijiu production, which limits high-quality development to a great extent.

SFB has a long history in China's Baijiu culture, with the most famous being produced in the Luzhou region. Based on the characteristics of environmental influence on SFB, this review took a comparative approach to macro and micro environments to illustrate the distinctive features of the Luzhou region. The warm, humid, and breezy climate, as well as the abundant soil and water resources, are the macro-environmental factors for the development of Luzhou-SFB. In addition, the intramural micro-environmental factors, in conjunction with the flavour profile, were used to summarise the local traditional brewing process, particularly the long-term accumulation of microbial community environment. The development of Luzhou-SFB is inextricably linked to the preponderance of the environment, which plays a pioneering role in providing sufficient raw materials and environmental support in the forefront of production on the one hand, and an appropriate environment for the stable growth of microbial communities in the later stages on the other.

The review of the environment should be used not only for comparison, but also for production adjustments, compounding multiple advantageous fermentation conditions, improving macro-environmental deficiencies, and controlling micro-environmental conditions. Hopefully, summarising environmental factors will provide environmental control and optimise the SFB development. The ultimate goal is to collaborate with the production environment to provide a locally adapted brewing environment for the development of Baijiu.

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