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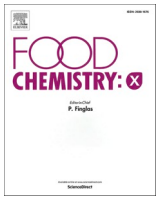

Characterization and discrimination of the taste and aroma of Tibetan Qingke baijiu using electronic tongue, electronic nose and gas chromatography–mass spectrometry

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ABSTRACT

Consumers rely on flavor characteristics to distinguish different types of Qingke Baijiu (QKBJ). Clarifying QKBJ's traits enhances its recognition and long-term growth. Thus, this study analyzed eight QKBJ samples from different regions of Tibet (Lhasa, Sannan, Shigatse, and Qamdo) using GC–MS, electronic nose and electronic tongue. The radar charts of the electronic tongue and electronic nose revealed highly similar profiles for all eight samples. Fifteen common compounds were found in all samples, with the main alcohol compounds being 3-Methyl-1-butanol, 1-hexanol, isobutanol, 1-butanol, 1-nonanol, and phenylethyl alcohol, imparting fruity, floral, and herbal aromas. However, the Sannan samples had higher total alcohol content than total ester content, emphasizing bitterness. Lhasa1 exhibited the most prominent sweetness, Lhasa2 the most noticeable sourness, and Qamdo the most pronounced umami. Lhasa3 and Lhasa4 had total acid content second only to total ester content. Tyd had the highest alkanes, while Lhasa had most aldehydes among samples.

1. Introduction

Qingke baijiu (QKBJ), one of China's traditional liquors, enjoys immense popularity in the western regions of China, particularly in high-altitude areas like Tibet and Qinghai. One of the key factors contributing to this popularity is the prominence of Qingke, one of the world's oldest crops and a dominant staple in Tibet. This grain boasts a rich nutritional profile, encompassing essential elements such as protein, amino acids, β-glucan, flavonoids, a wide array of vitamins, trace minerals, and dietary fiber (Guo, Horvath, Chen, Chen, & Zhang, 2020). A substantial body of research underscores the manifold health benefits of Qingke, including its role as an antioxidant and its potential in managing conditions like diabetes and hypertension (Yin et al., 2023). However, as a beverage of preference, the unique taste and flavor of Baijiu are the key attractions for consumers (Merlino et al., 2022). In a comparative analysis between QKBJ and 16 other types of Chinese Baijiu, it is revealed that QKBJ possesses elevate levels of key aroma compounds such as linalool, β-damascenone, and β-ionone, which impart floral and honey-like fragrances (An, Qian, & Chen, 2019). Some researchers classify QKBJ as a type of the light aroma type Chinese liquor, which should be colorless, clear and transparent, with no suspension and no precipitation, pure in fragrance, with the elegant and harmonious aroma of ethyl acetate (Gao, Fan, & Xu, 2014).

Indeed, QKBJ from different regions exhibits distinct stylistic features. In Qinghai, critical flavor compounds in QKBJ were identified as phenylethyl acetate, ethyl hexanoate, 2-methyl-1-butanol, ethyl acetate, γ-nonalactone, and 2,3-dimethyl-5-ethyl pyrazine (Wang et al., 2023). In Sichuan, the primary correlated aroma compounds included acetylglycine ethyl ester, ethyl hydrogen succinate, ethyl palmitate, ethyl phenylacetate, 2,3-butanediol, pentanoic acid, and hexanoic acid. Notably, acetylglycine ethyl ester was identified as a characteristic flavor compound unique to Sichuan QKBJ (Zhang et al., 2019). Conversely, Tibetan QKBJ was found to be characterized by key flavor compounds such as phenylacetaldehyde, β-phenylethanol, ethyl phenylacetate,

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sotolon, furaneol, methional, methionol, γ-nonalactone, ethyl 2-methylbutanoate, β-damascenone, ethyl 3-methylbutanoate, ethyl acetate, ethyl butanoate, and acetic acid (Fan, Tang, Xu, & Chen, 2020). Further analysis revealed that the flavor profiles of Tibetan QKBJ from the Lhasa and Nyingchi regions differed from those originating in Qamdo (Zhang et al., 2019).

Due to the significant variations in temperature, wind speed, air pressure, and oxygen content across different regions within the vast altitude range of approximately 3500–5000 m in Tibet, there is a rich diversity of Qingke varieties, numbering up to thousands. Consequently, Qingke from different origins (Habschied et al., 2019) and colors (Ge et al., 2021) often exhibit significant differences in nutritional and active components. These variations contribute to differences in the quality of QKBJ produced. Additionally, variations in esterification power, fermentation power, and enzymatic properties of Tibetan yeast strains show significant differences across regions (Chen, Wang, Liu, & Feng, 2023). Multiple factors such as brewing climate, raw materials, and Jiuqu contribute to the diverse styles of QKBJ across different regions (Qiao, Wang, Wang, Zhang, & Zheng, 2023).

The flavor characteristics of QKBJ influence consumer acceptance and quality evaluation. Therefore, a comprehensive analysis of the distinct features of QKBJ from different regions in Tibet is urgently needed. As a result, this study employed cutting-edge techniques, including electronic nose (*E*-nose), and electronic tongue (E-tongue), and GC–MS, to delve into the nuanced variations in taste and aroma exhibited by QKBJ available across diverse regions of Tibet. This will enhance the recognizability of QKBJ, tailor recommendations to consumer preferences, and pave the way for the long-term development of QKBJ.

2. Materials and methods

2.1. Materials

The main cultivation areas of Qingke in the Tibet are distributed in cities such as Shigatse, Qamdo, Lhasa, and Sannan. A comprehensive set of eight QKBJ samples, sourced from different urban centers within Tibet, China, was procured from local enterprises. As depicted in Fig. 1, these eight samples were crafted utilizing Qingke as their primary raw material and exhibited an alcohol content surpassing 50% ethanol (*v*/v). The nomenclature of each sample was derived from different areas. Thus, the samples were identified by the following designations: Tyd, Lhasa1, Lhasa2, Lhasa3, Lhasa4, Shigatse, Sannan, and Qamdo.

2.2. Methods

2.2.1. Determination of taste by E-tongue

E-tongue analysis was conducted using a TS-5000Z E-tongue system (Insent Inc., Atsugi-Shi, Japan). To facilitate the cleaning and referencing processes, a standard solution was prepared by dissolving 30 mM potassium chloride and 0.3 mM tartaric acid in distilled water. Additionally, two distinct washing solutions were formulated—one for negatively charged sensors involving dilution of absolute ethanol to 30% ethanol with distilled water, and another for positively charged sensors involving the addition of 100 mM hydrochloric acid or a mixture of 100 mM potassium chloride and 10 mM potassium hydroxide. All chemicals employed adhered to analytical-grade standards. For the analysis, all QKBJ samples were diluted to attain a 10% ethanol (*v*/v). The methodology for assessing taste in QKBJ was aligned with the approach outlined by Zhang, Zhang, Meng, Li, and Ren (2015). Throughout the process, each sample underwent repeated measurements, with the entire procedure being replicated up to five times. As recommended by the supplier for the purpose of sensor conditioning, the initial two runs were disregarded (Woertz, Tissen, Kleinebudde, & Breitkreutz, 2011). The obtained raw data, expressed in millivolts (mV), was subsequently converted into taste values, which constituted the outcomes of the tests. The data collected via the *E*-tongue system underwent meticulous review, and the mean values extracted from the last three measurement cycles were harnessed for subsequent statistical analysis.

2.2.2. Odor analysis by E-nose

E-nose analysis was executed utilizing a PEN3.5 E-nose system (Insent Inc., Kyoto, Japan). Accurately measured 10 mL of the sample, sealed it in a 40 mL bottle, and placed it in a water bath at 50 °C for 30 min before testing. Initiated, calibrated, and diagnosed the electronic nose equipment first. The sample preparation time was 5 s; sensor cleaning time was 240 s; sensor zeroing time was 10 s; the injection rate was 300 mL/min; analysis sampling time was 90 s. After completing this test, the system reset and standardized before the next headspace sampling. The characteristics of the electronic nose sensors were shown in Table 1.

2.2.3. Extraction of volatile compounds

Employing Wu et al.'s methodology (2023) with minor adaptations, the QKBJ samples underwent dilution to achieve a 10% ethanol (v/v) using redistilled water. Subsequently, 8 mL of the diluted Baijiu and 2.5 g of NaCl were combined within a 20 mL headspace vial, followed by subjecting the mixture to a 5-min thermal shock at 50 °C. This was

Fig. 1. Eight kinds of QKBJ samples.

Table 1
Electronic nose sensor array characteristics.

Array serial number	Sensor name	Characteristics
R1	W1C	High sensitivity to aromatic compounds
R2	W5S	High sensitivity to nitrogen oxides compounds
R3	W3C	High sensitivity to ammonia and aromatic compounds
R4	W6S	High sensitivity to hydrogen compounds
R5	W5C	High sensitivity to alkanes and aromatics compounds
R6	W1S	High sensitivity to methane
R7	W1W	High sensitivity to sulfur compounds
R8	W2S	High sensitivity to alcohols compounds
R9	W2W	High sensitivity to aromatics and organic sulfur compounds
R10	W3S	High sensitivity to long-chain alkanes compounds

succeeded by volatile compound extraction utilizing an automatic sampler (Supelco, Bellefonte, PA, United States) in tandem with a SPME fiber (DVB/CAR/PDC, divinylbenzene/carboxen/polydimethylsiloxane, 2 cm, 50/30 μm, Supelco Inc., Bellefonte, PA, United States) at a temperature of 50 °C for a duration of 45 min. Upon the completion of the extraction process, the SPME fiber was introduced into the injection port of the GC–MS system, wherein desorption of the volatile compounds was executed at a temperature of 250 °C for a period of 5 min. This phase marked the transition from extraction to analytical assessment of the volatile compounds present in the QKBJ samples.

2.2.4. Determination of volatile components

Volatile compounds underwent analysis through GC–MS, facilitated by a Perkin Elmer instrument (Perkin Elmer, Inc., New York, United States). This analysis was conducted employing an Elite-Wax column (30 m length, 0.25 mm i.d., 0.25 μm film thickness; Perkin Elmer, Inc.). Helium was employed as the carrier gas, maintained at a consistent flow rate of 1 mL/min. The temperature profile of the GC was programmed as follows: initiated at 40 °C and held steady for 2 min, increased to 100 °C at a rate of 2 °C/min, further raised to 140 °C at 5 °C/min, and eventually elevated to 230 °C at 10 °C/min, where it was sustained for 6 min. Both the ion source and the quadrupole were set at a temperature of 250 °C. The mass selective detector utilized an electron ionization energy of 70 eV, covering a mass range spanning from m/z 35 to 400. This configuration ensured the accurate identification and quantification of volatile compounds present in the QKBJ samples.

Aroma components displaying a matching degree surpassing 800 were systematically identified. This identification process was achieved through a comprehensive analysis involving the comparison of the mass spectra of volatile compounds with the entries within the Nist11 library. Furthermore, the alignment of Kovats retention index (RI) values with those previously documented in the literature (Fan et al., 2020; Qian, An, Chen, & Qian, 2019; Zhang et al., 2019) played an integral role in the robust identification process. For a more quantitative understanding, the relative content of each individual volatile substance was computed using the peak area normalization method.

2.3. Statistical analysis

The conducted experiments were executed in a minimum of three replicates to ensure robustness and reliability of the data. Subsequently, data representation was accomplished utilizing Microsoft Excel 2010 software (Office 2010; Microsoft Corporation, United States), presented as mean values accompanied by their corresponding standard deviations (SD). Data analysis and visualization were performed employing SPSS 26 (SPSS Inc., Chicago, USA) as well as Origin 2021 software. Significant level were judged in the analyses was determined at $p < 0.05$.

3. Results and discussion

3.1. Taste difference of QKBJ

The *E*-tongue, utilizing artificial lipid membrane technology, provides a digital assessment of the aftertaste, encompassing fundamental taste parameters, including acidity, bitterness, astringency, sweetness, saltiness, and umami (Jiang, Zhang, & Adhikari, 2018). Furthermore, a key reference point was the tasteless node, representing the absence of taste, and which was established utilizing the reference solution containing potassium chloride and tartaric acid. This solution, although slightly acidic and salty, provided a basis for comparison. Taste values lower than this tasteless reference indicated a lack of taste within the sample (An et al., 2022). As depicted in Fig. 2A, all analyzed samples exhibited notable disparities in the attributes of sourness, bitterness, astringency, umami, saltiness, and sweetness ($p < 0.05$). Intriguingly, astringency, aftertaste-B, aftertaste-A, and saltiness levels for all eight QKBJ variants fell below the tasteless threshold, signifying an absence of these taste attributes. Notably, the bitterness value for Lhasa3 and Sannan surpassed the tasteless point, indicating an enhanced bitterness quotient. This distinct bitterness could potentially explain the differentiation of Sannan from the other samples (Fig. 2C). Bitter peptides and higher alcohols, recognized microbial metabolites, are considered major contributors to the bitterness encountered in Baijiu (Luo, Kong, Xue, Wang, & Xia, 2020). In addition, Lhasa1 is notably sweet, Lhasa2 exhibits pronounced acidity, and Qamdo stands out for freshness (Fig. 2A). This could be linked to varying levels of polysaccharides, organic acids, polyphenols, and ethanol in the liquor, influencing sweetness, acidity, and bitterness (Canon, Caille, Sarni-Manchado, & Cheynier, 2022). Moderate amounts of volatile acids can diminish bitterness, reduce off-flavors, and enhance sweetness, acting as flavor modifiers (Wei, Zou, Shen, & Yang, 2020).

3.2. Odor difference of QKBJ

The electronic nose, equipped with specialized sensors and a pattern recognition system, can rapidly offer comprehensive insights into the sample's flavor profile and concealed characteristics (Tiggemann et al., 2017). The response intensities of sensors are closely related to the content of corresponding compounds in samples (Yang et al., 2016). Illustrated in Fig. 3A, sensors W5S, W1S, W1W, W2S, and W2W demonstrated heightened reaction intensities. This observation strongly suggests that the QKBJ samples contain elevated levels of nitrogen oxides, methane, sulfur compounds, alcohols, aldehydes, ketones, aromatics, and organic sulfur compounds. In contrast, soy sauce-aroma baijiu differs in its sensor responses. Except for W3S and W6S, the remaining eight sensors exhibit distinct response values. Notably, sensors W5S and W1W show elevated response values when compared to other sensors (Wu et al., 2023). Further analysis reveals deviations in response intensities: W1S and W3S in Tyd, W1W, W2W, and W2S in Lhasa4, and W5S in Qamdo, all exhibit higher intensities compared to other samples. This indicates that these three samples have distinct flavor profiles. Meanwhile, by combining the information from Fig. 3A and Fig. 3B, it is evident that the overall flavor profiles of all QKBJ samples share similarities. This may be attributed to the samples having similar volatile substances with different concentrations (Cui, Wang, Yang, Wu, & Wang, 2015).

Principal component analysis (PCA) serves as a statistical methodology aimed at extracting insights from variables and elucidating variations present in samples (Dong et al., 2019). The PCA score chart, illustrated in Fig. 3D, captures the response intensity data. Notably, the two primary components of variance accounted for a substantial 88.2% of the total variance, indicative of E-nose's effectiveness in effectively distinguishing diverse QKBJ samples. Visual inspection of the PCA score chart reveals distinct groupings: Tyd, Sannan, and Lhasa4 samples are notably isolated from the others and are distributed across different

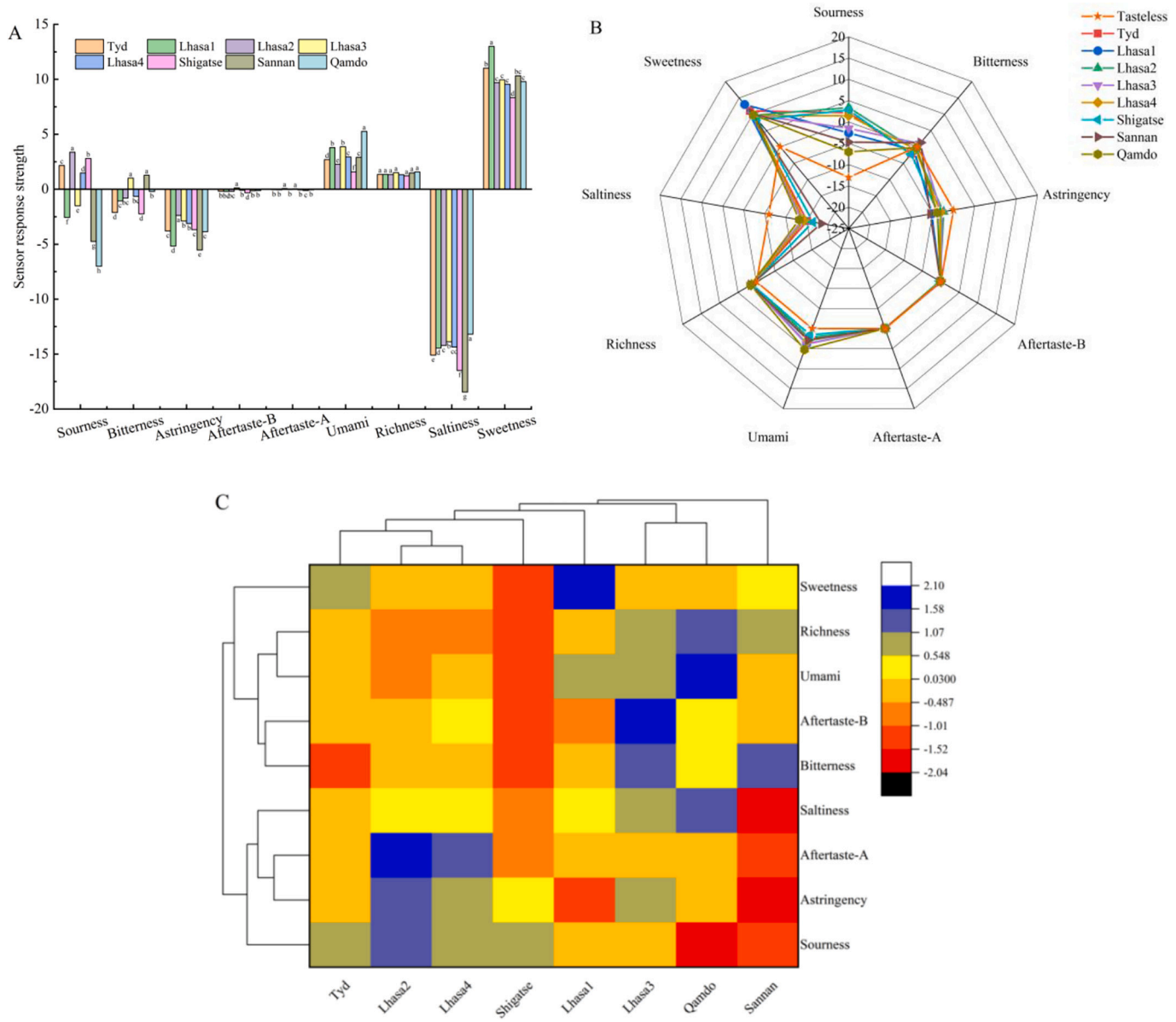

Fig. 2. Bar chart (A) radar plots (B) and cluster heat map (C) of *E*-tongue sensor response of different QKBJ. Different letters indicate statistical significance at $p < 0.05$.

quadrants. Conversely, Lhasa1, Lhasa2, Lhasa3, Shigatse, and Qamdo samples exhibit close proximity to each other. Fig. 3C corroborates these findings, with the samples categorized into three distinct clusters. Subdividing the classification into four categories further isolates Lhasa4 from the remaining samples. The combined analysis presented by Fig. 3C and Fig. 3D consistently highlights the distinct aroma profiles of Tyd and Sannan, characterizing them as distinctly separated from the other samples. In the context of the Sannan sample, sensors W1S, W1W, W2S, and W2W exhibited significantly lower response values compared to other samples. On the contrary, W1C, W3C, and W5C sensors showcased heightened responses. A distinct feature of Tyd's flavor profile emerged wherein the W1S response value was notably elevated, whereas the W5S response value remained comparatively lower in comparison to the other samples.

3.3. Differences in volatile components of QKBJ

A comprehensive total of 142 compounds were successfully identified within the samples through GC–MS analysis. This collection encompassed various compound categories: 66 esters, 16 alcohols, 9 acids, 18 aldehydes, 9 ketones, 6 alkanes, 4 phenols, and 14 other compounds, as depicted in Fig. 4. Notably, Fig. 5A showcases the quantity of volatile flavor substances within each sample, with Tyd, Lhasa1, Lhasa2, Lhasa3, Lhasa4, Shigatse, Sannan, and Qamdo hosting 65, 76, 62, 51, 66, 46, 48, and 68 unique compounds respectively. This distinction underscores the pronounced diversity in their characteristic profiles. Fig. 5B and Fig. 5C reveal more nuanced insights into the distinctive aspects of the volatile flavor compounds. Each sample featured a unique set of compounds contributing to their distinct characteristics. Taken together, the volatile components exhibit a significant reliance on the microbial community and processes, while also showing associations with environmental factors like storage conditions, aligning with prior research findings (Jia et al., 2024; Luo et al., 2023).

3.3.1. Esters

Esters, integral to flavor development, can be formed through alcohololylation or via the action of alcohol-acyltransferase catalyzed by acetyl-CoA and higher alcohols as fermentation substrates (Fan & Qian,

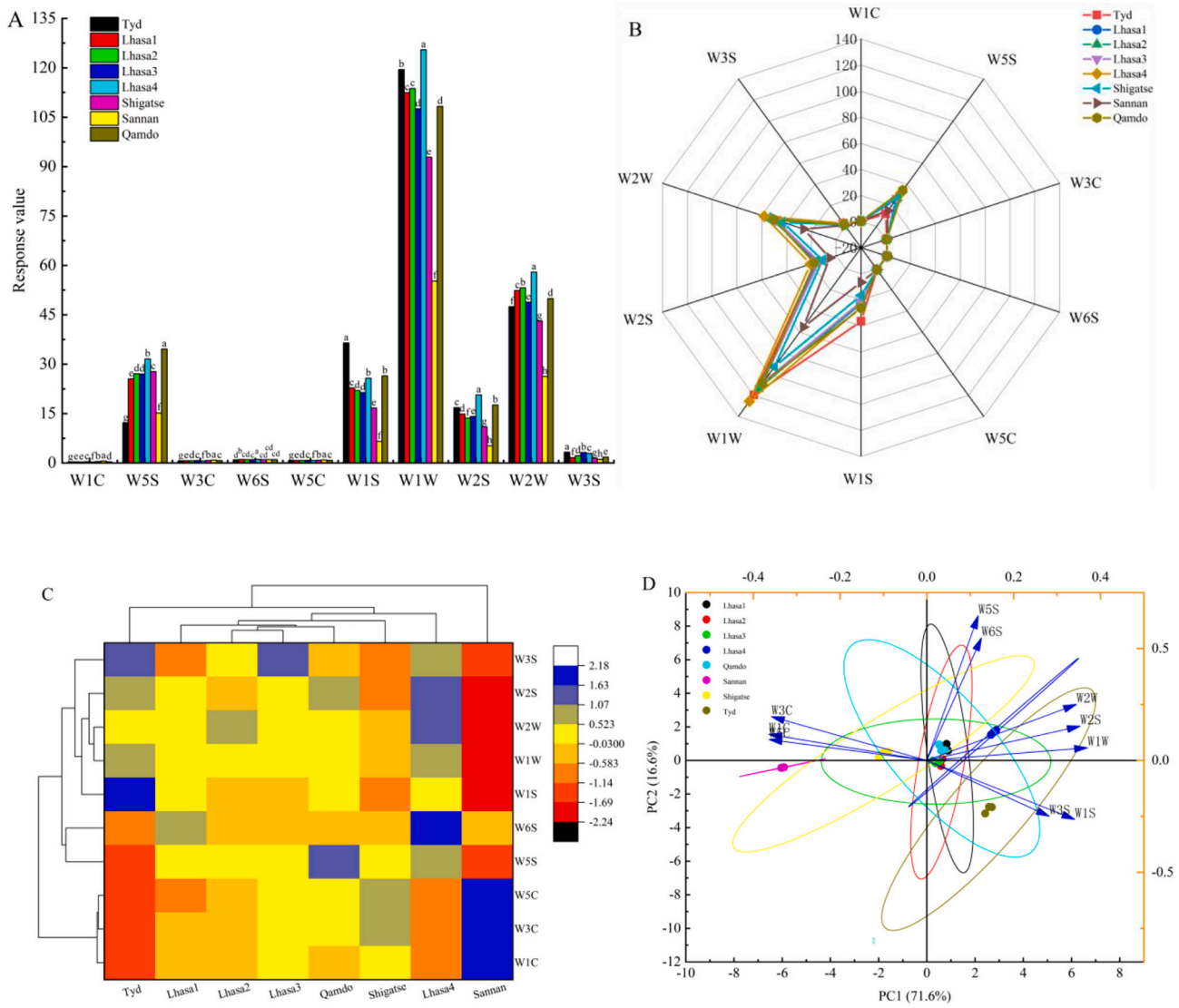

Fig. 3. Bar chart(A), radar plots (B), cluster heat map (C) and principal component analysis (PCA) loadings plot (D) of *E*-nose sensor response of different QKBJ. W1C, W5S, W3C, W6S, W5C, W1S, W1W, W2S, W2W, and W3S are the number of the E-nose sensor. Different letters indicate statistical significance at $p < 0.05$.

2005). A comprehensive total of 66 esters were identified within the 8 QKBJ samples, with individual counts of 40, 41, 32, 24, 44, 25, 21, and 26 in Tyd, Lhasa1, Lhasa2, Lhasa3, Lhasa4, Shigatse, Sannan, and Qamdo samples respectively. Nine core esters, including ethyl acetate, ethyl hexanoate, ethyl heptanoate, ethyl lactate, ethyl octanoate, ethyl decanoate, ethyl benzoate, ethyl phenylacetate, and ethyl hexadecanoate, serve as prominent contributors to the aroma profile of QKBJ. These compounds are associated with aromas ranging from pineapple and fruity notes to sweetness, with ethyl phenylacetate imparting hints of rose and honey fragrances. Prior studies have concurred on the significance of these nine compounds as key aroma components within QKBJ (Fan et al., 2020; Qian et al., 2019; Wang et al., 2023). Furthermore, a set of 29 esters were common across more than four highland barley wine samples, collectively embodying the shared characteristics of QKBJ. Distinctive flavor profiles emerged due to unique esters identified in specific samples: ethyl non-3-enoate, 2-nonenoic acid ethyl ester, ethyl 9-decenoate, ethyl undecanoate (exclusive to Tyd), isobutyl butyrate, butyl butanoate, 3-phenylpropyl acetate (found only in Lhasa1), ethyl 2-hexenoate, heptyl formate, butyl caprylate, hexyl octanoate (distinct to Lhasa4), methyl benzoate, apricolin, ethyl 9-oxononanoate, ethyl cinnamate (exclusive to Sannan), and isoamyl decanoate, 1-propen-2-ol, acetate (found solely in Qamdo). Fig. 5D highlights the diversity in ester content, ranging from 26.48% to 95.30%. Brewing yeast possesses outstanding fermentation capabilities, while non-brewing yeast can enhance the diversity of aroma and flavor profiles (Liu et al., 2019). Variations in dominant yeast strains among different koji may contribute to differences in total ester content in QKBJ (Ma, Geng, Jia, Zhang, & Xue, 2021).

3.3.2. *Alcohols*

Alcohols are predominantly generated by yeast during fermentation through pathways such as ketoacid synthesis and amino acid degradation (Jiang, Lu, & Liu, 2020). Of particular note, the total alcohol content in Sannan samples exceeds the total ester content, whereas the opposite is observed in other samples. The variation in starters used for fermentation primarily accounts for differences in alcohol and ester levels (Yang, Xia, Wang, & Yu, 2017). While a moderate amount of advanced alcohols contributes to the overall liquor aroma, higher alcohols notably contribute to the bitter profile. This is consistent with the observation that the Sannan samples exhibited a more prominent bitter taste compared to the other samples (Fig. 2A). Within the eight QKBJ samples, a total of 16 alcohols were identified. The highest count of 11 alcohols was detected in Lhasa1 samples, while the fewest, only 5, were detected in Lhasa4 samples. Despite the variations in alcohol content

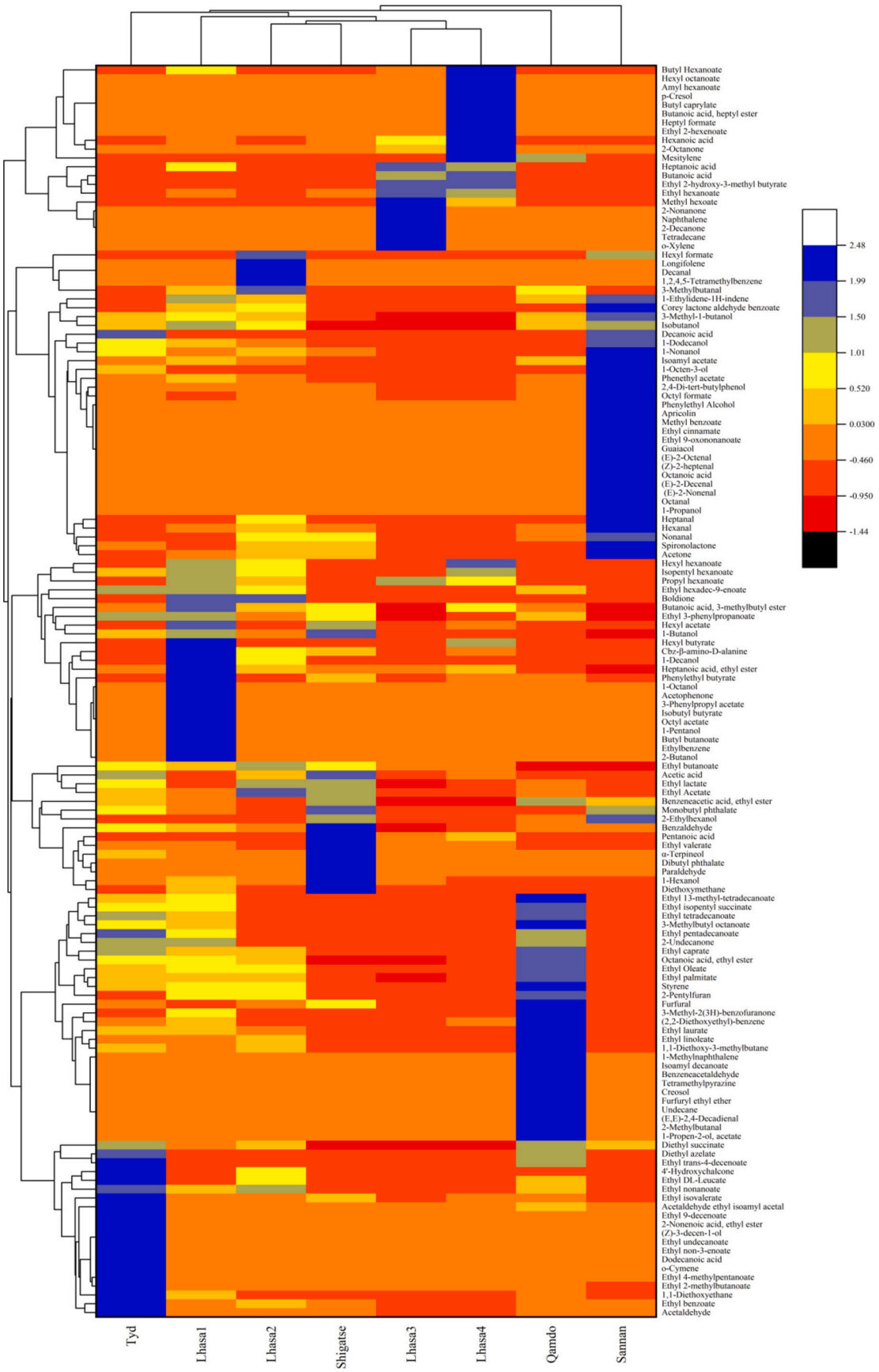

Fig. 4. Heatmap and dendrogram of the volatile compounds profiles present in QKBJ samples. The heatmap plot indicates the relative abundances of volatile compounds(variables clustered on the vertical axis). For hierarchical clustering of the heatmap, the concentrations for the detected volatiles were standardized using in (concentration + 1), then the color scale bar represents the normalized concentration value.

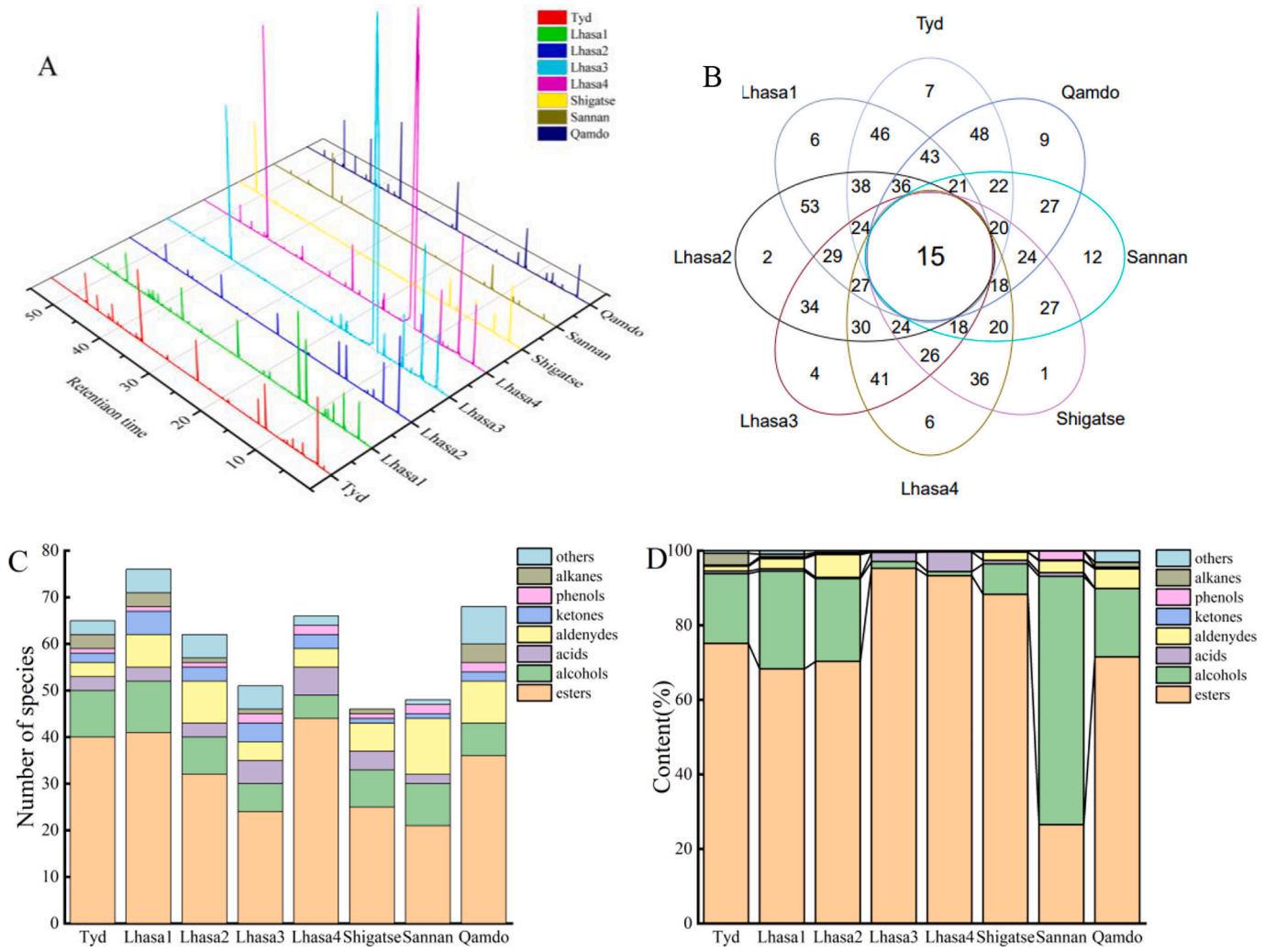

Fig. 5. The ion flow diagram (A), Venn diagram(B), the species (C) and the content (D) statistical diagrams of the volatile components of QKBJ.

across the eight QKBJ samples, six primary alcohols, namely 3-methyl-1-butanol, isobutanol-hexanol, 1-butanol, 1-nonanol, and phenylethyl alcohol, collectively constituted >91% of the total alcohol content. These alcohols contribute to nail polish mellow, floral, and cucumber aromas (Fan et al., 2020). However, 3-methyl-1-butanol was exclusively detected in Tyd and Sannan samples, marking a distinct characteristic within these specific QKBJ variants.

3.3.3. Acids

Acids play a vital role in the Baijiu fermentation process, primarily produced by yeasts and lactic acid bacteria. They contribute to aromas associated with fruitiness, cheese, and fatty notes (Xiao et al., 2014). Appropriate acid levels can buffer and harmonize the taste of liquor, while excessive concentrations may result in unpleasant odors (Wei et al., 2020). However, no acidic substances were detected in the samples from Qamdo, potentially resulting in a lack of richness in the liquor (Wei et al., 2020). Within the eight QKBJ samples, nine distinct acids were detected: acetic acid, butanoic acid, pentanoic acid, hexanoic acid, heptanoic acid, octanoic acid, cbz-β-amino-d-alanine, decanoic acid, and dodecanoic acid. Notably, Lhasa3 and Lhasa4 samples showcased a shared presence of acetic acid, butanoic acid, pentanoic acid, hexanoic acid, and heptanoic acid, exhibiting high similarity in acid composition and content. In contrast, the other six QKBJ samples demonstrated substantial variations in acid types and concentrations. Remarkably, decanoic acid in Tyd and Sannan imparted a paint-like aroma, while Sannan's octanoic acid introduced fruity and floral notes. It's noteworthy that acetic acid, while potentially irritating at high concentrations, can react with ethanol to produce esters, thereby enhancing the overall flavor of spirits (Cai et al., 2019).

3.3.4. Aldehydes and ketones

Aldehydes and ketones are crucial flavor compounds that contribute to the harmonization and taste effects in Baijiu. They arise through oxidation or dehydrogenation of alcohols (Zhang et al., 2021) or are synthesized from the metabolism of unsaturated fatty acids via lipoxygenase activity during fermentation (Ouyang et al., 2017). Among the eight QKBJ variants, eighteen distinct aldehydes and nine different ketones were identified, with only acetaldehyde, benzaldehyde, and furfural being common among them. Acetaldehyde, in particular, exerts a carrying effect on fragrances and substantially lowers the threshold for volatile substances, thereby enhancing the aromatic experience of the liquor. Benzaldehyde imparts fruity and berry-like notes. In Tyd samples, acetaldehyde and benzaldehyde registered the highest amounts. Furfural, originating from the thermal decomposition of polypentose in grain husks, contributes an almond-like aroma and sweetness, significantly contributing to the robust caramel flavor found in QKBJ (Fan, Fan, & Xu, 2015). Excessive furfural, however, can lead to burnt flavors, and its content was notably higher in Qamdo samples compared to others. The distribution of other aldehyde and ketone compounds across QKBJ samples displayed considerable variation. Among them, Sannan exhibited the highest number of aldehydes, and Lhasa2 featured the highest content. It's noteworthy that previous research by Wang et al.

(2023) identified (E,E)-2,4-Decadienal as a key aroma compound in QKBJ, and interestingly, this compound was also detected in Qamdo samples.

3.3.5. Other flavor compounds

The spectrum of flavor compounds within the eight QKBJ samples also encompassed phenols, alkanes, pyrazines, furans, terpenes, and other compounds, all of which played specific roles in shaping the overall QKBJ flavor profile. For instance, 2,4-di-tert-butylphenol was identified as potent odorants in QKBJ (Song et al., 2020). For instance, the presence of tetramethylpyrazine in the Qamdo sample contributed a roasted incense aroma. Pyrazines, on the other hand, primarily arise from the Maillard reaction between sugars and nitrogen-containing amino compounds. Higher fermentation temperatures, typical of strong-aroma types of Baijiu, can promote the Maillard reaction and consequently generate more pyrazines (Jin, Zhu, & Xu, 2017). Certainly, the flavor of QKBJ is closely linked to the microorganisms involved in fermentation (Guo et al., 2020; Guo, Horvath, et al., 2020). To gain a better understanding of the differences in flavor among various QKBJ, further investigation should delve into the interplay between fermentation agents and the fermentation process.

4. Conclusions

In this study, eight representative varieties of QKBJ from various Tibetan locales were collected. Through the application of analytical techniques such as GC–MS, *E*-nose, and E-tongue, several key characteristics of QKBJ were identified, which paves the way for enhancing the flavor of QKBJ and promoting industry development. Firstly, the predominant taste profile of QKBJ primarily exhibits characteristics of sweetness, acidity, and freshness. Secondly, compounds such as sulfur compounds, alcohols, aldehydes, ketones, aromatic compounds, and organic sulfur compounds exhibited notably higher sensor responses. Thirdly, there were a total of 15 common compounds found in QKBJ, with the key alcohols being 3-Methyl-1-butanol, 1-hexanol, isobutanol, 1-butanol, 1-nonanol, and phenylethyl alcohol, imparting fruity, floral, and herbal aromas. Furthermore, it was important to note that QKBJ also demonstrates variations in both taste and flavor. Firstly, the bitterness was more pronounced in samples from Lhasa3 and Sannan. Secondly, the sensor responses of the Sannan sample's W1S, W1W, W2S, and W2W sensors were significantly lower than those of other samples, while the responses of W1C, W3C, and W5C sensors were notably higher. An distinguishing characteristic of Tyd lay in the higher response value of W1S and the comparatively lower response value of W5S. Lastly, each variety of QKBJ displayed distinctive ion flow diagrams, with varying proportions of esters, alcohols, acids, aldehydes, and ketones.

Ethics statements

The authors indicate that this research did not include any human subjects and animal experiments.

CRediT authorship contribution statement

Xiaoqing Yin: Conceptualization, Data curation, Writing – original draft. **Man Zhang:** Supervision. **Shanshan Wang:** Formal analysis, Validation. **Zhirong Wang:** Writing – review & editing. **Huaying Wen:** Data curation, Writing – review & editing. **Zhiwei Sun:** Supervision. **Yuhong Zhang:** Supervision, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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