Effects of ultrasound pretreatment on the quality, nutrients and volatile compounds of dry-cured yak meat

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ABSTRACT

The objective of the present study was to assess the effects of ultrasound pretreatment on the quality of dry-cured yak meat. The ultrasonic power with 0, 200, 300 and 400 W (ultrasonic frequency of 20 kHz) were used to assist processing of dry-cured yak meat. The meat quality, nutrient substances, sensory quality, electronic nose, electronic tongue and volatile compounds of dry-cured yak meat were determined. The results indicated that the moisture content and hardness value of ultrasonic treatment group was significantly lower compared to the control group ($P < 0.05$). Ultrasound treatment increased the value of $b^*$, and decreased the value of $L^*$, $a^*$, $pH$, chewiness, melting temperature and enthalpy. Springiness value significantly increased from control group to 300 W of ultrasonic power group. Shear force significantly decreased with the increase of ultrasonic power ($P < 0.05$). Ultrasonic treatment had no effect on the TVB-N content, but it could increase the TBARS content. Ultrasound treatment significantly increased the essential FAA (EFAA) and total FAA ($P < 0.05$). In addition, the saturated fatty acid (SFA) content significantly increased with the increase of ultrasonic power ($P < 0.05$). Ultrasound treatment negatively affected the meat’s color, smell, and taste but increased its tenderness and the overall acceptability. It also significantly increased alcohols and aldehydes contents ($P < 0.05$), which were consistent with the measurement of electronic nose and electronic tongue. The results demonstrated that the appropriate ultrasonic power assisted in the processing improves quality of dry-cured yak meat, particularly for the power of 300 W.

1. Introduction

The dry-cured yak meat is a unique cured meat product originating in Yunnan Province, China. It is a fermented meat product, processed mainly from yak hind legs with low-temperature dry-curing, ripening, and drying. The moisture gradually loses and the meat hardens. Fermented meat products are a result of a series of biochemical and physical changes in raw meat, which occur via microbial fermentation or enzyme activity. These meat products thus develop a special flavor, color, and texture as well as demonstrate a prolonged shelf life [1]. Dry-cured yak meat is mainly used for dry-curing with high salt content. Excessive airing and dry-curing can lead to excessive darkening, water loss, and hardening of dry-cured yak meat, seriously affecting its quality and sensory profile. Moreover, defects such as large size, bareness, and mildew may severely restrict the production and sales of these meat products. Therefore, modern technology–based processing may aid in improving dry-cured yak meat quality.

The consumer demand for safe, nutritious, and high-quality meat products with health benefits has led to the development of dry-cured meat products. Ultrasound is a novel, environmentally friendly technology, widely used in food processing and analysis [2]. It can improve the effect of food fermentation and reduce processing costs significantly. Therefore, this approach has great potential in high-quality fermented food production [3–6]. For food processing, ultrasonic frequencies of 16–100 kHz (with power intensity within 10–1000 W/cm²) are used commonly because these frequencies affect the chemical and physical properties of food. When ultrasound travels through a liquid medium, tiny bubbles oscillating with pressure fluctuation leads to implosion. Moreover, the implosion zone produced by shock waves, micro jets, and acoustic currents may cause acceleration of mass transfer and decomposition of biological materials, which ultimately causes modifications in the characteristics, microstructures, and molecular reactions within...
the treated food [7,8]. Ultrasound also affects the structure of the meat product through its own cavitation, mechanical, and thermal effects. Many studies have indicated that ultrasound accelerates processing without impairing food products’ quality. In foods, ultrasound can improve enzyme activity and metabolism as well as promote Maillard reaction, oxidation, esterification, and protein hydrolysis, leading to the maturation of and improvement in the texture, color, flavor and taste of fermented foods [9]. Ultrasound can improve the tenderness of meat products and effectively remove bound water to shorten the drying time [10]. Ojha et al. found that as ultrasound frequency increased, the taurine content in beef jerky increased and its texture improved [11]. Ultrasound treatment could significantly increase the relative contents of volatile flavor compounds, especially aldehydes, ketones, and alcohols, and then improve the flavor of spiced beef (Zou et al., 2018) [12]. Xu et al. also found that the ultrasound could change the flavor profile of meat products by enhancing the interaction process between volatile compounds and muscle proteins [13]. Amanor-Atiemo et al. found that ultrasonic treatment led to increased total free amino acid levels in apples [14]. Studies have also shown that ultrasound frequency and processing time affect the proportions of polysaturated fatty acids (PUFAs) and saturated fatty acids (SFAs) in beef jerky [15]. In addition, the cavitation effect of ultrasound, which facilitates the processing of meat products, cracks the water molecules to produce hydroxyl radicals and produces hydrogen peroxide (which has strong oxidizing properties), leading to protein and lipid oxidation in meat. Lipid and protein oxidation is the main reason for improved flavor substance levels in meat products [16]. However, the role of ultrasound-assisted dry-cured yak meat processing and the effect on its quality remain unclear. Therefore, considering the technological trend to use nonconventional processing techniques in the meat industry, this study investigated the effects of ultrasound pretreatment on meat quality, nutrients, and volatile compounds of dry-cured yak meat, ultimately providing theoretical and scientific basis for ultrasound-assisted industrial production of dry-cured yak meat products.

2. Material and methods

2.1. Materials

Fresh yak (Semitendinosus) meat, used in this study, was obtained from a local meat processing factory in Xining, China. The seasonings used for dry-cured yak meat preparation, including salt, white granulated sugar, sodium nitrate, sodium red alginate, and vitamin C (Vc), were purchased from a local supermarket (Lanzhou, China). Anhydrous sodium sulfate, trichloroacetic acid (TCA), petroleum ether, ethanol (95%), copper sulfate, potassium sulfate, potassium iodide, trichloroacetic acid, sodium thiosulfate, hydrochloric acid, chloroform, concentrated sulfuric acid, disodium diamine tetraacetate, anhydrous sodium carbonate, chiral barbituric acid, magnesium oxide, glacial acetic acid, and octenyl succinic anhydride were purchased from Merck (Darmstadt, Germany). All the seasonings were food grade.

2.2. Dry-cured yak meat preparation and treatment

The obtained yak meat was stored at 4 °C, trimmed, and then cut into slices of similar size with a meat slicer (10.00 × 3.00 × 2.00 cm², L × W × H). The pieces of yak meat were cured with 4.0% salt, 0.04% sodium nitrate, 1% white granulated sugar, 0.05% sodium red alginate, and 0.001% Vc (based on the raw meat weight). The meat was stirred frequently to mix all ingredients with meat thoroughly. All the samples were divided into four groups: one control and three treatment groups. Each treatment group was subjected to ultrasound pretreatments at ultrasonic power of 200, 300, or 400 W using a 20-kHz ultrasonic processor (VCX 750; SONICS, USA) for 30 min. The control group was not treated with ultrasound. Treatment group samples were treated on ultrasonic at 25 °C. Next, ice was added to the ultrasonic bath to keep the temperature constant. The meat was then sealed and stored in a clay urn, dry-cured, and ripened for 15 days in constant climate chambers (BD-RSZ, Nanjing, China) at 25 °C with 70% relative humidity. Then, all dry-cured yak meat slices were dried in a hot air dryer (101-1H; Beijing Kewei Yongxing, China) at 55 °C for 24 h. We followed strict hygiene procedures during the test process to avoid microbial contamination and conducted three independent experimental trials.

2.3. Chemical and physical analysis

2.3.1. Moisture and water activity

The moisture content of the dry-cured yak meat was determined using a 101-1H digital display hot air dryer (Beijing, China) at 105 °C with a constant weight. The water activity was measured using an HD-3A intelligent moisture meter (Maiky Technology, Beijing, China).

2.3.2. pH

The pH of the dry-cured yak meat was determined by using methods of the Association of Official Analytical Chemists (2007) [17]. In total, 5 g of sample were homogenized with 50 mL of distilled water for 60 s with a portable pH meter (Testo 205 portable waterproof pH; Testo instruments international Trading Ltd, Shanghai, China).

2.3.3. Meat color

The color parameters (L*, a*, and b*) of the dry-cured yak meat were determined using a Minolta chromameter (CR-300; Minolta Camera, Japan) at three different positions on the surface of the cross-section after the sample was exposed to air for 30 min at 4 °C. The chroma meter was calibrated with a white ceramic plate after the light source flashed three times [18].

2.3.4. Texture profiles

The texture of the dry-cured yak meat was analyzed according to the method by Ma et al. [19], with several modifications. The texture was determined on a TA.XT Plus texture analyzer (Stable Micro Systems, UK). The samples were cut into 1 × 1 × 1-cm³ pieces. The measurement conditions were as follows: velocity (pretest, test, and posttest), 2.0 mm/s; interval for the second pressing, 5 s; induction power, 10 g; and probe type, P5. The textures of the dry-cured yak meat were characterized by its hardness, springiness, and chewiness.

2.3.5. Shear force

The shear force of the dry-cured yak meat was determined according to the method of Guo et al. [18] by using a TA.XT Plus texture analyzer (Stable Micro Systems, UK). The measurement parameters were as follows: probe speed, 2 mm/s; test speed, 2 mm/s; post speed, 1 mm/s; compression distance, 60%; height calibration, 10 mm; trigger force, 10 g; load cell, 50 kg; sample area, 1 cm²; and sample length, 1 cm.

2.3.6. Thiobarbituric acid reactive substance (TBARS)

TBARS was determined using a modification of the procedure described by Mukumbo et al. [20]. The absorbance was measured at 530 nm using an ultraviolet 756p spectrophotometer (Shimadzu, Japan), and TBARS was expressed as malondialdehyde (MDA) content (mg/kg). TBARS was calculated as follows:

\[
\text{MDA (mg/kg)} = \frac{c \times V \times 1000}{m \times 1000}
\]

where c is MDA concentration obtained from the standard curve, V is the sample solution constant volume, and m is the sample quality.

2.3.7. Total volatile basic nitrogen (TVB-N)

TVB-N was determined using the method of Dhaouadi et al. [21]. In total, 10 g of dry-cured yak meat was homogenized with 90 mL of perchloric acid for 2 min; then, 5.0 mL of the solution was pipetted and
filtered it into a retort reaction chamber. A conical flask containing 10 mL of boric acid and 5–6 drops of mixed indicator liquid was placed at the lower end of the semi-micro-nitrogen distillation condensing tube. The absorbing solution was titrated with a standard solution of hydrochloric acid (0.01 mol/L) until it turned bluish purple. TVB-N was calculated as follows:

\[ \text{TVB-N} = \frac{N \times (mg/100g)}{V1 - V2} \times 0.01 \times 2800 \]

where V1 and V2 are the titration volumes of HCl in the sample and blank, respectively.

2.3.8. Differential scanning calorimetry (DSC)

The melting point of ultrasound-treated samples were determined on a differential scanning calorimeter (TA Corp., New Castle, DE, USA) by using the method of He et al. [22]. In total, 3–5 mg of meat were placed in a sealed aluminum pan and heated from 25 °C to 100 °C at a rate of 5 °C/min to dissolve the meat and determine the melting points (°C) and enthalpies (J/g).

2.4. Sensory evaluation

The sensory evaluation of the dry-cured yak meat was performed as described by Zhang et al. [23], with several modifications. In total, 12 people (5 male and 7 female individuals) with prior sensory evaluation experience evaluated the dry-cured yak meat. The experiment was conducted at the Animal Products Processing Laboratory of the Gansu Agricultural University (Gansu, China). The dry-cured yak meat was then cut into pieces of approximately 1 cm³ before serving. Sensory scores were rated using a 7-point linear scale for the color (1 = dark and dull, 7 = red and shiny), smell (1 = mild, 7 = intense), texture (1 = tough, 7 = tender), and overall acceptability (1 = low, 7 = high) of the dry-cured yak meat. The evaluation process was performed in well-lit conditions. The consumers waited 1 min before testing the next sample to reduce sensory fatigue and used lemon water (lemon extract:water = 1:100) to clean their mouth before tasting each sample.

2.5. Volatile compounds

The volatile compounds in the dry-cured yak meat were measured and analyzed through headspace solid-phase microextraction (HS-SPME) and gas chromatography-mass spectrometry (GC-MS; Agilent, USA) on an HP-5MS column (30 m × 0.25 mm; film thickness, 0.25 μm). In brief, 5.0 g of dry-cured yak meat sample, 2 g of NaCl, and 5 μL of 0.1% (v/v) cyclohexanone–methanol was placed in a sealed vial at 25 °C and extracted through HS-SPME, followed by GC-MS analysis. The temperature of the injection port was 270 °C, which was held for 15 min. Helium was used as the carrier gas, and the split injection flow rate was 1.0 mL/min, with a split ratio of 20:1. The initial oven temperature was 50 °C, which was held for 1.0 min; it was increased to 60 °C at 10 °C/min and held for 3 min. Next, the temperature was increased to 140 °C at 4 °C/min and held for 8 min and finally to 230 °C at 15 °C/min and held for 5 min. The mass spectrum was acquired in 70 eV of electron ionization with 230 °C ion source temperature, 150 °C Quadrupole temperature, and 230 °C transmission line temperature. The scanning range was 30–550 m/z. The volatile compounds were analyzed using NIST 05 mass spectrometry library (National Institute of Standards and Technology, Gaithersburg, MD, USA). The compounds with matching degree of 800 (maximum = 1000) were reported, and the relative percentage of each component was calculated using the chromatographic peak area normalization method.

2.6. Fatty acids

Fatty acids were extracted from the dry-cured yak meat and methylated as described by Gao et al. [24] and analyzed through gas chromatography (SRI Model 8610C, USA). The nitrogen flow rate was set to 1.2 mL/min, and the air flow rate was set to 450 mL/min. The column was operated isothermally at 140–240 °C at 5 °C/min and kept at 240 °C for 15 min. The injection and detector temperatures were 260 °C and 250 °C, respectively. Hydrogen (40 mL/min) was used as the carrier gas. Fatty acids were qualitatively identified by comparing the retention times of 37 fatty acids (Supelco 37 FAME Mix 47885-U, USA) and quantified through a comparison of the peak areas of the sample and the internal standard (i.e., C11:0). The results were reported as grams of fatty acid per 100 g of dry-cured yak meat. The nutritional properties of dry-cured yak meat were evaluated by calculating the PUFA/SFA and n-6/n-3 fatty acid ratios.

2.7. Free amino acids (FAAs)

The amino acid content of the dry-cured yak meat was determined using a modification of the procedure described by Zou et al. [12] on an Automatic Amino Acid Analyzer L-8900 (Hitachi, Tokyo). In total, 1.0 g of minced dry-cured yak meat was thoroughly mixed with 10 mL of 5-sulfosalicylic acid (30 g/L) in a centrifuge tube. This was followed by incubation in dark for 1 h and then centrifugation at 10,000 rpm and 4 °C for 15 min in a high-speed freezing centrifuge (1–14 K, Sigma, Germany). After 2 mL of the supernatant was mixed with n-hexane, the solution was filtered through a 0.22-μm membrane. The resulting filtrate was used for analysis on the aforementioned automatic analyzer. Each group analyzed three times, with each measurement performed in triplicate.

2.8. Electronic tongue

Minced dry-cured yak meat (10 g) was mixed with 100 mL of distilled water (40 °C), homogenized, and finally mixed for 1 min to extract taste substances. The mixed solution was centrifuged for 10 min at 3000 × g, and the supernatant was used for analysis using the method of Du et al. [25]. The taste-sensing system was a Smartongue (Ruiwen Instruments, China), and it was used to analyzed sourness, sweetness, bitterness, astringency, saltiness, umami, richness (fresh aftertaste), aftertaste B (astringent aftertaste), and aftertaste A (bitter aftertaste). The values are expressed as the average value of triplicate measurements.

2.9. Electronic nose

The odorant characteristics of the dry-cured yak meat were analyzed on the electronic nose system PEN-3 (Schwerin, Germany) using the procedure described by Du et al. [25], with slight modifications. The electronic nose system consists of 10 chemical sensors: W1C (sensitive to aromatic constituents, benzene), W5C (highly sensitive to nitrogen oxides), W3C (sensitive to ammonia), W6S (sensitive to hydrides), W2S (sensitive to hydrogen), W1S (sensitive to olefin, short-chain aromatic compounds), W1S (sensitive to methyl), W1W (sensitive to sulfides, pyrazine), W2S (sensitive to alcohols, aldehydes, and ketones), W2W (sensitive to organic sulfides), and W3S (sensitive to long-chain alkanes). In total, 5.0 g of minced dry-cured yak meat was placed in 20-mL headspace sample vials (CNW Technologies, Germany). These sample vials were then heated in a water bath at 45 °C for 30 min. The electronic nose system parameters were set with a 200 mL/min chamber flow rate, 200 mL/min injection flow rate, and 120 s measurement period.

2.10. Statistical analysis

All the measurements were performed in triplicate, and the data are expressed as means ± standard deviations. Statistical analyses of the results were performed using one-way analysis of variance and a Duncan multiple range test at a 5% significance level on SPSS (version 22; IBM,
Armonk, NY, USA). All dry-cured yak meat data were evaluated using principal component analysis (PCA) on Origin (version 9.0), its appropriateness was confirmed by Bartlett’s sphericity test.

3. Results and discussion

3.1. Effects of different ultrasonic powers on dry-cured yak meat quality

Moisture content is a key index in determining dry-cured yak meat quality characteristics: the ideal moisture content should be 35%-50% [26,27]. Water activity is related to storage stability. The United States Department of Agriculture/Food Safety and Inspection Service recommends that a water activity (aw) level of ≤ 0.85 can effectively inhibit harmful bacterial growth [28]. Fig. 1A demonstrates that compared with the control group, the 300 W ultrasonic power led to significantly decreased moisture content ($P < 0.05$). Moreover, the difference between the moisture content after 300 W and 400 W ultrasound treatment was nonsignificant. Kang et al. found that the moisture content of beef increased with an increase in ultrasonic power [29]. However, these

Fig. 1. The quality of dry-cured yak meat. (A) The moisture content and water activity. (B) Meat color (L*, a*, b*) and pH. (C) Hardness and springiness. (D) Shear force and chewiness. (E) TVB-N and TBARS. (F) Melting point and enthalpy of dry-cured yak meat in different group. Control, 200 W, 300 W and 400 W were four treatment groups. Different lowercase letters (a-d) represent significant differences at $P < 0.05$. 


ultrasound generates air turbulence at the air-product interface, which aids the removal of the moisture from the surface [30]. Fig. 1A indicates that low water activity after 400 W ultrasonic treatment, a result was similar to those of Lees et al. [31].

The color of dry-cured yak meat is one of the most important physical indicators as it affects consumers acceptance and selectivity. Fig. 1B demonstrates the meat color and pH of dry-cured yak meat between the control and treatment groups. The L* value in the control group was nearly 40.55, but it was significantly lower in the treatment groups. The a* value in the control group was 15.35, and it significantly decreased with 300 W ultrasonic treatment (P < 0.05), but it became nonsignificant from 300 W to 400 W ultrasonic treatment. The b* value increased with increases in ultrasonic power. Sikes et al. indicated that ultrasound had no effect on meat color because the heat generated was insufficient to denature proteins and pigments [32]. Alves et al. also found no changes in beef meat color with increases in ultrasonic power [33]. This result is slightly different from those of the current results.

pH directly affects protein stability and structure property. It can influence meat color, cooking loss, and the shear force of the meat. In the control group, pH was 5.62, which decreased as the ultrasonic power increase. There were no significant differences between pH values after 200 W, 300 W, and 400 W ultrasonic treatments (Fig. 1B). Studies have found that protein oxidation influenced the texture, color, aroma, flavor, and biological function of meat [37]. In this condition is more prone to be oxidized [39]. Guo et al. found that protein oxidation influenced the texture, color, cooking loss, and the shear force of the meat. In the control group (Fig. 1B). Studies have demonstrated that pH decreases as ultrasonic power increases [34].

Texture is a crucial element for evaluating meat quality. It directly affects consumer acceptance and awareness. The texture profiles of dry-cured yak meat (Fig. 1C and D) demonstrated that the effects of different ultrasonic power treatments on hardness, springiness, chewiness, and shear force values. Hardness value in 200 W, 300 W and 400 W ultrasonic treatment groups was significantly lower than that in the control group (P < 0.05). In the control group, the springiness value was 0.76, and it significantly increased from the control group to the 300 W ultrasonic treatment group (P < 0.05). Chewiness value significantly decreased from the control group to the 300-W ultrasonic treatment group (P < 0.05). It then became nonsignificant from 300 W to 400 W ultrasonic power. Shear force significantly decreased with increases in ultrasonic power (P < 0.05). The different ultrasonic powers aided in tenderizing the meat, which mainly involved denaturing cytoskeletal proteins, responsible for maintaining the structure of meat muscle. Li et al. found that high-intensity ultrasound, which causes serious damage to the muscle cell membranes and basic structures of muscle fibers, has been traditionally used to tenderize meat [35]. A suitable ultrasonic power might change muscle fiber structure and reduce shear force [36].

The TVB-N and TBARS contents in the different groups are shown in Fig. 1E. There was no significant difference in the TVB-N contents between the treatment and control groups. TBARS is an important indicator of the degree of protein oxidative deterioration. Rysman et al. found that protein oxidation influenced the texture, color, aroma, flavor, water holding capacity, and biological function of meat [37]. In this study, we found that the ultrasound treatment of the dry-cured yak meat can delay protein oxidative deterioration by determining the TBV-N content. TBARS is an important indicator of lipid oxidation in meat products [38]. The TBARS contents after ultrasound treatments were significantly higher compared with the control group, but there were no significant differences between 200 W and 300 W of ultrasonic treatment groups. Some studies have found that the ultrasound cavitation zone demonstrates high temperature and high pressure, where the lipid in this condition is more prone to be oxidized [39]. Gao et al. found that TBARS contents increased with increases in ultrasonic power during ultrasound-assisted thawing of frozen white yak meat [34]. The reaction involves TBARS reacting with malondialdehyde (MDA), obtained via oxidative decomposition of unsaturated fatty acids. In general, lipids affect the generation of aromatic properties flavor compounds, leading to the development of a unique flavor [40]. These results show that ultrasound-assisted processing promotes lipid oxidation and that it may improve the flavor of dry-cured yak meat.

Ultrasound-assisted processing demonstrated a significant effect on the melting temperature and enthalpy of the dry-cured yak meat (Fig. 1F). All dry-cured yak meat showed single, broad endothermic peaks. The melting temperature in the treatment groups were significantly lower than in the control group (P < 0.05). Moreover, the enthalpies of the dry-cured yak meat significantly decreased from 200 W to 300 W ultrasonic treatment (P < 0.05), possibly because thermal stability differences are correlated with structure changes of dry-cured yak meat during the ultrasound-assisted processing. He et al. (2021) reported that melting temperature and enthalpy decreases with an increase in the ultrasonic power because the molecular structure of oxhide gelatin is modified by ultrasound [22].

Table 1

| FAA content (g/100 g) | Control | 200 W | 300 W | 400 W |
|-----------------------|---------|-------|-------|-------|
| Aspartic acid         | 1.391 ± 0.073b | 1.420 ± 0.046a | 1.938 ± 0.016a |
| Threonine             | 2.497 ± 0.012b | 2.104 ± 0.006b | 2.529 ± 0.004b |
| Serine                | 0.793 ± 0.061b | 0.851 ± 0.014b | 1.915 ± 0.017b |
| Glutamic acid         | 3.635 ± 0.282b | 2.554 ± 0.016b | 2.383 ± 0.040b |
| Glycine               | 0.912 ± 0.025b | 0.817 ± 0.017b | 0.754 ± 0.054b |
| Alanine               | 2.197 ± 0.177b | 1.748 ± 0.008b | 1.541 ± 0.012b |
| Cysteine              | 0.250 ± 0.003b | 0.100 ± 0.006b | 0.083 ± 0.006b |
| Valine                | 1.075 ± 0.083b | 1.353 ± 0.012b | 1.957 ± 0.041b |
| Methionine            | 0.334 ± 0.066b | 0.443 ± 0.045b | 1.507 ± 0.039b |
| Isoleucine            | 0.607 ± 0.096b | 1.107 ± 0.008b | 1.507 ± 0.045b |
| Leucine               | 1.061 ± 0.035b | 1.967 ± 0.042b | 2.012 ± 0.031b |
| Tyrosine              | 0.972 ± 0.054b | 2.673 ± 0.015b | 3.165 ± 0.044b |
| Phenylalanine         | 0.959 ± 0.054b | 1.434 ± 0.004b | 1.544 ± 0.044b |
| Lysolecine            | 0.884 ± 0.001b | 1.546 ± 0.011b | 1.530 ± 0.038b |
| Histidine             | 1.068 ± 0.151b | 0.788 ± 0.003b | 0.622 ± 0.028b |
| Arginine              | 0.931 ± 0.015b | 2.622 ± 0.009b | 3.261 ± 0.016b |
| Proline               | 0.865 ± 0.023b | 0.669 ± 0.009b | 0.696 ± 0.016b |
| EFAA                  | 7.436 ± 0.023b | 8.945 ± 0.059b | 9.565 ± 0.016b |
| NEFAA                 | 13.011 ± 0.023b | 14.240 ± 0.009b | 15.355 ± 0.016b |
| Total FAA             | 20.447 ± 0.056b | 23.185 ± 0.053b | 24.920 ± 0.144b |
| EFAA/NEAA             | 0.571 ± 0.051b | 0.628 ± 0.003b | 0.623 ± 0.001b |

* Represents essential amino acids.

Within a row, values with different superscript letters within the same line indicate significant differences (P < 0.05) between the content of amino acids in different treatment groups. Values are shown as the mean values ± S.D.
contents. It also significantly increased the content of arginine, the umami-related amino acids (P < 0.05). non-EFAA (NEFAA) contents also increased from 200 W to 400 W of ultrasonic treatment significantly (P < 0.05). However, the contents of glutamic acid, glycine, and alanine, which are umami-related amino acids, decreased. Protein degradation is an important part of metabolic reaction and it affects the metabolic process. Several metabolic reactions underlie the whole process of dry-cured meat products, and protein degradation, which generates FAAAs, is the major reason for taste formation [42]. Essential amino acids cannot be synthesized in the human body, or the speed of their synthesis cannot meet demand of the human body. Ultrasound treatment reduced threonine contents, which is similar to the results of Zou et al. [12], whereas the increase in isoleucine and phenylalanine contents, similar to the results of Guo et al. [34]. However, no significant difference was noted in the effect of ultrasound treatment on methionine contents. Previous studies have shown that the cavitation produced by ultrasound in a liquid can induce the water molecules to crack to free radicals which could improve the level of protein degradation during the brining process of beef [43]. The generated FAA by protein degradation might more than the loss in the process. This might be the cause of the increase in FAA levels of some essential amino acids caused by different ultrasonic power treatment in this study.

### 3.3. Effects of different ultrasonic powers on fatty acid content

Fatty acid profiles after treatment of the dry-cured yak meat with different ultrasonic powers are presented in Table 2. The SFA content increased significantly with the increase in ultrasonic power (P < 0.05). In particular, ultrasound treatment could increase C18:0 contents significantly (P < 0.05), whereas those of monounsaturated fatty acid (MUFA) and polyunsaturated fatty acid (PUFA) decreased. This was because the high degree of unsaturation, the unsaturated fatty acid could remove protons and generate free radicals, thereby accelerating lipid oxidation and reducing the PUFA: MUFA ratio [24,44]. Wang et al. (2017) reported similar results [45]. Kang et al. (2016) also found that ultrasound treatment greatly promotes lipid oxidation [46]. Lipid oxidation of commercial sea cucumbers can reduce unsaturated fatty acid contents during the drying process [47]. This demonstrates that the cavitation effect of ultrasound can oxidize unsaturated fatty acids, and the extent of unsaturated fatty acids oxidation increases with an increase in ultrasonic power, resulting in a decrease of unsaturated fatty acids in meat products. In the control group, the PUPA/SFA and n-6/n-3 ratios were 0.52 and 4.44 in this study, respectively, which then significantly decreased as ultrasonic power increased. According to Oztürk-Kerimoglu et al. [48], the PUPA/SFA ratio in a healthy human diet should be > 0.4, and the maximum n-6/n-3 ratio should be 4. This shows that dry-cured yak meat was treatment with 300 W of ultrasonic power is more suitable for healthy human diet.

### 3.4. Effects of different ultrasonic powers on dry-cured yak meat sensory characteristics

The sensory properties of control and treatment groups, including its color, smell, taste, juiciness, tenderness, and overall acceptability, are presented in Fig. 2. The color scores of dry-cured yak meat significantly decreased as the ultrasonic power increased (P < 0.05). Moreover, 400 W of ultrasonic power led to the lowest color score (P < 0.05). These results were consistent with the results of meat quality analysis. Stadnik and Dolatowski found that ultrasound could accelerate overall change in color, limiting oxymyoglobin formation and slowing down metmyoglobin formation in the study of influence of sonication on beef color [49]. The smell score significantly decreased with the increase in ultrasonic power (P < 0.05). The taste score also decreased with the increase in ultrasonic power, and the treatment group of 300 W and 400 W of ultrasonic treatment was significantly lower than that in the control group (P < 0.05). Faustman et al. (2010) demonstrated that high-intensity ultrasound promotes protein and lipid oxidation and that off-flavor and off-odor from lipid oxidation can negatively impact sensory characteristics [50]. The tenderness of dry-cured yak meat significantly increased with the increase of ultrasonic power (P < 0.05). This result was supported by Peña-González et al. [51]. This was possibly because the ultrasonic treatment destroyed the myofibrillar protein structures [52]. Nevertheless, the overall acceptability of 300-W ultrasonic treatment group was significantly higher than that of 200 and 400 W ultrasonic treatment and control groups. Ultrasound-assisted processing thus

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**Table 2**

| Fatty acid (g/100 g) | Control | 200 W | 300 W | 400 W |
|----------------------|---------|-------|-------|-------|
| C11:0                | 0.83 ± 0.02 | 0.75 ± 0.03 | 0.85 ± 0.02 | 0.89 ± 0.05 |
| C14:0                | 5.06 ± 0.02 | 4.28 ± 0.12 | 3.68 ± 0.08 | 2.72 ± 0.37 |
| C15:0                | 0.93 ± 0.03 | 0.65 ± 0.02 | 0.66 ± 0.01 | 0.66 ± 0.01 |
| C16:0                | 19.31 ± 0.67 | 21.62 ± 0.35 | 22.53 ± 0.37 | 25.30 ± 0.07 |
| C16:1                | 1.34 ± 0.01 | 2.59 ± 0.08 | 2.80 ± 0.01 | 3.14 ± 0.04 |
| C17:0                | 0.81 ± 0.03 | 0.83 ± 0.02 | 1.11 ± 0.05 | 3.90 ± 0.09 |
| C18:0                | 9.01 ± 0.50 | 10.38 ± 0.30 | 12.68 ± 0.29 | 15.70 ± 0.90 |
| C18:1                | 34.81 ± 0.03 | 31.96 ± 0.30 | 30.74 ± 0.29 | 27.61 ± 0.08 |
| C18:2                | 6.88 ± 0.16 | 6.01 ± 0.16 | 5.77 ± 0.16 | 4.33 ± 0.55 |
| C18:3                | 4.75 ± 0.11 | 4.90 ± 0.11 | 4.44 ± 0.10 | 3.33 ± 0.08 |
| C20:0                | 0.25 ± 0.02 | 0.11 ± 0.05 | 0.19 ± 0.02 | 0.02 ± 0.02 |
| C20:3                | 1.90 ± 0.04 | 1.83 ± 0.11 | 1.39 ± 0.06 | 0.78 ± 0.05 |
| C20:4                | 5.37 ± 0.28 | 5.35 ± 0.09 | 4.29 ± 0.23 | 2.25 ± 0.02 |
| SFA                  | 36.18 ± 0.18 | 38.60 ± 0.15 | 41.78 ± 0.20 | 49.78 ± 0.38 |
| MUFA                 | 36.15 ± 0.04 | 34.54 ± 0.04 | 33.54 ± 0.04 | 30.75 ± 0.04 |
| PUFA                 | 18.89 ± 0.04 | 18.08 ± 0.04 | 15.89 ± 0.20 | 10.68 ± 0.70 |
| n-3                  | 3.48 ± 0.13 | 3.35 ± 0.13 | 3.17 ± 0.03 | 2.69 ± 0.13 |
| n-6                  | 15.42 ± 0.15 | 14.73 ± 0.12 | 12.72 ± 0.12 | 7.99 ± 0.57 |
| PUPA/SFA             | 0.52 ± 0.02 | 0.47 ± 0.01 | 0.38 ± 0.01 | 0.21 ± 0.02 |
| n-6/n-3              | 4.44 ± 0.01 | 4.40 ± 0.13 | 4.01 ± 0.01 | 2.97 ± 0.07 |

SFA, MUFA, PUFA and n represent saturated fatty acid, mono unsaturated fatty acid, poly unsaturated fatty acid and omega, respectively.

- a-d Within a row, values with different superscript letters differ (P < 0.05).
- Values Data are shown as the mean values ± S.D.

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Fig. 2. Spider web chart of sensory properties data for dry-cured yak meat with different ultrasonic power treatments. Each value represents the average taste intensity of three measurements. Control, 200 W, 300 W and 400 W were four treatment groups.
improved the tenderness and quality of the dry-cured yak meat but negatively affected the color and smell scores. Overall, 300 W ultrasonic power was more suitable for ultrasound-assisted processing of dry-cured yak meat.

3.5. Effects of different ultrasonic powers on dry-cured yak meat volatile compounds

About 53 volatile compounds were identified in the dry-cured yak meat treated with different ultrasonic powers. According to their chemical structures, these volatile compounds included 8 types (acids, alcohols, aldehydes, hydrocarbons, esters, furan, ketones, and others; Fig. 3). Alcohols, aldehydes, and hydrocarbons were the three most abundant volatile flavor substances in the dry-cured yak meat, but ultrasound treatment had no influence on acid, ester, and furan contents. The alcohol contents were significantly higher in the treatment groups than in the control group ($P < 0.05$). However, there was no significant difference among the 200 W, 300 W, and 400 W ultrasonic treatment groups. Watanabe et al. found that alcohols contribute less to the aroma of meat samples for higher odor thresholds [53]. The aldehydes form from the reaction of the amino acids and peptides with xylose during heating. Aldehyde contents in the dry-cured yak meat significantly increased with increases in ultrasonic power ($P < 0.05$). This might be because as ultrasonic power increased, lipid oxidation and fatty acid degradation were increased, resulting in an increase in aldehyde contents [53]. Aldehydes afford larger contributions to the aroma of meat samples for lower odor thresholds [54]. Hydrocarbon contents was significantly lower in 400-W ultrasonic treatment group than those in the other groups ($P < 0.05$). Thus, some hydrocarbons in the 400-W ultrasonic treatment group might have transformed into other substances. Ketones are produced during amino acid degradation and unsaturated fatty acid oxidation [55]. Ketone contents increased as the ultrasonic power increased, similar to the results of Zou et al. [12]. According to the results for volatile compounds, the treatment of dry-cured yak meat with appropriate ultrasonic power can effectively improve its flavor.

3.6. Electronic tongue and electronic nose analysis results

Electronic tongue converts electrical signals to taste signals to distinguish the taste of food, whereby it can exclude the subjectivity of sensory evaluation due to its small sensory threshold [56]. Fig. 4A presents the response values of sourness, bitterness, astrignency, aftertaste-B, aftertaste-A, umami, richness, saltiness, and sweetness, and PCA of the taste response to dry-cured yak meat treated with different ultrasonic powers. Sourness, aftertaste-B, aftertaste-A, and sweetness did not change significantly with the increase in the ultrasonic power ($P > 0.05$). The signal value of sourness agreed with the results for volatile compounds. The bitterness, astrigency, umami, and richness in the treatment groups were significantly higher than those in the control group ($P < 0.05$). The increase of bitterness might be due to the increase in fural production caused by increased ultrasonic power, which provides meats with a bitter almond flavor [57]. The increased signal value of umami and richness might be attributable to muscle hydrolysate [58]. However, the saltiness decreased with the increase in ultrasonic power. Here, the saltiness was possibly contributed by unreacted short peptides [59]. The PCA plot of the electronic tongue results showed that the contributions of PC1 and PC2 were 70.0% and 21.1%, respectively, and the cumulative contribution was 91.1%. Therefore, PC1 and PC2 could reflect the taste characteristics of the sample.

Electronic nose is an electronic system that imitates the structure of the human nose’s structure and selectively recognizes different molecules, which can distinguish subtle changes in volatile compounds [60]. Fig. 4B illustrates the response values of the electronic nose for dry-cured yak meat with treated with different ultrasonic powers. As ultrasonic power increased, the most significant changes were noted in WSS (highly sensitive to nitrogen oxides), W3C (sensitive to aroma, ammonia), W5C (sensitive to olefin, short-chain aromatic compounds), and W2S (sensitive to alcohols, aldehydes, and ketones). The PCA plot of the electronic nose results showed that PC1 and PC2 contributed 64.1% and 26.8% of the total variance, respectively. This indicated that these principal components could reflect all the characteristics of dry-cured yak meat treated with different ultrasonic powers.

The electronic nose and electronic tongue analysis results demonstrated that the appropriate ultrasonic power could assist in the processing dry-cured yak meat by improving its taste and smell.

3.7. PCA results

PCA can reduce the dimensionality of complex data and further reflect the overall information of the sample [61]. Here, PCA was performed to better characterize dry-cured yak meat quality during ultrasound-assisted processing. Two principal components were extracted, which explained 86.10% of the total variance in the dataset (Table 3). The first principal component (PC1) and second principal component (PC2) contributed 77.50% and 8.60% of the variability,
respectively. The four treatment groups in this study were clearly separated by PC1; some SFAs (C11:0, C16:0, C17:0, C18:0, and C20:0), most textural profiles (shear force, hardness, and chewiness), most nonessential amino acids (proline, glutamic acid, cysteine, glycine, histidine, and alanine), and meat quality stability characteristics (pH, moisture, and water activity) were located in the PC1 negative quadrant. In contrast, the most unsaturated fatty acids and essential amino acids were located in the PC1 positive quadrant (Fig. 5). Therefore, the results indicated that the PCA could well characterize the quality of dry-cured yak meat during the ultrasound-assisted processing.

Table 3
Extraction of the main component factors of different dry-cured yak meat qualities.

| Main Ingredient | Eigenvalues | Contribution rate/% | Cumulative contribution rate/% |
|-----------------|-------------|----------------------|-------------------------------|
| PC1             | 32.54       | 77.50                | 77.50                         |
| PC2             | 3.63        | 8.60                 | 86.10                         |

Fig. 4. The radar chart and principal component analysis of electronic tongue data for dry-cured yak meat with different ultrasonic power (A). The radar chart and principal component analysis of electronic nose data for dry-cured yak meat with different ultrasonic power (B).

Fig. 5. Factor loading diagram of two principal components of dry-cured ya meat. Control, 200 W, 300 W and 400 W were four treatment groups.
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4. Conclusion
In conclusion, the current results indicated that 20-kHz ultrasound-assisted processing of different powers could significantly improve dry-cured yak meat quality due to the cavitation effects. However, it negatively affected the color of the meat. Accelerated lipid oxidation caused unsaturated fatty acid contents to decrease and SFA contents to increase; it also increased volatile compounds types and contents. In particular, the contents of alcohols and aldehydes significantly increased with increase in the ultrasonic power. In addition, ultrasound treatment could significantly increase the essential FAA (EFAA) and total FAA contents. The electronic nose and electronic tongue results showed that ultrasound-assisted processing significantly increased the taste and flavor, including bitterness, umami, richness, WS2 (sensitive to alcohols, aldehydes, and ketones), and WSS (highly sensitive to nitrogen oxides), of the dry-cured yak meat. Therefore, the results indicated that ultrasound-assisted processing can be a potential technology to effectively improve dry-cured yak meat quality.

CRediT authorship contribution statement
Gaoliang Bao: Investigation, Data curation, Methodology, Formal analysis, Writing – original draft. Jun Niu: Investigation, Methodology, Software. Shaobin Li: Investigation, Software, Formal analysis. Li Zhang: Conceptualization, Supervision, Validation, Writing – review & editing, Project administration. Yuzhu Luo: Conceptualization, Supervision, Writing – review & editing, Validation, Project administration.

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

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