

Quality and flavor changes in beef jerky caused by high hydrostatic pressure combined with moisture regulator treatments during storage

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Abstract: The impact of high hydrostatic pressure (HHP) combined with moisture regulators (MR) on the quality and flavor attributes of beef jerky during storage was investigated in this study. During storage, moisture content decreased in all the treatments, and it was significantly higher in MR + HHP samples than in HHP and control samples ($P < 0.05$). At 0 and 15 days, the water activity was approximately 0.7, and at 60 days, it decreased to 0.652 for control samples and 0.678 for MR + HHP samples. During storage, the MR + HHP samples had lower shear force and thiobarbituric acid reactive substances (TBARs) value than the control and HHP samples ($P < 0.05$). MR + HHP increased the formation of volatile compounds derived from spices while inhibiting the formation of volatile compounds derived from lipid oxidation. The sensory scores of MR + HHP samples for tenderness, color, taste, and flavor were significantly higher than that of the HHP and control samples ($P < 0.05$). This study revealed that HHP and MR treatment reduced the quality deterioration of beef jerky during storage.

Keywords: moisture regulators; high hydrostatic pressure; beef jerky; tenderness; moisture content; flavor

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1 Introduction

Beef jerky is a delicious snack that is widely popular in Asia and other parts of the world because of its high nutritional content and unique flavor [1–2]. Usually, beef jerky is made by the following major procedures: cutting, curing, and drying. During marinating, many seasonings and spices are used to enhance the flavor of beef jerky. Beef jerky has a lower water activity (a_w) and moisture content than other meats, which gives it longer shelf life. However, the low water content in jerky makes it difficult to chew and swallow [3]. Consumers generally prefer a chewy texture. However, a texture that is too hard and tough because of a low moisture content is not preferred [4]. The population of older people around the world is rapidly increasing, for whom beef jerky is a tough product to digest owing to their low chewing ability [5]. Hence, improving the tenderness of beef jerky is necessary for expanding its market size.

High hydrostatic pressure (HHP) is a non-thermal processing technology that can be used to tenderize meat and improve meat quality [6]. Since HHP does not affect the covalent bond of meat protein, it can be used to treat meat without altering the nutritional quality (vitamins, minerals, etc.) [7]. The pressure is applied to the entire piece of meat instantaneously and uniformly, which may induce myofibrillar protein denaturation and muscle tissue disintegration, tenderizing the meat [8]. Souza et al. [9] reported that HHP treatment reduced cooking and dripping losses in pork, and they speculated that the enhanced tenderization and texture was due to higher water retention in the meat. Recent studies have

found that HHP treatment promotes the development of volatile compounds in meat and meat products [10]. Yang et al. [11] reported that HHP (150–300 MPa; 15 min) promoted the formation of volatile compounds from brine and lipid oxidation. Llorido et al. [12] reported that HHP treatment enhanced the overall flavor and flavor persistence of hams.

The tenderness, juiciness, and storage stability of beef jerky are all influenced by moisture content. Increasing water content or water-holding capacity (WHC) of meat is a common strategy for improving tenderness. However, excessive moisture can result in relatively high a_w , reducing the shelf life. Therefore, determining how to increase the moisture content of beef jerky while maintaining a certain a_w is crucial for the production of high-quality jerky products. Moisture regulators (MR) are materials that can increase water content while reducing a_w , and they can be used to improve the tenderness and juiciness of jerky products [13].

Salts and polyhydroxy compounds, such as phosphates, glycerin, and trehalose, make up the majority of MR used in meat products [14–15]. Glycerin is widely used in meat products because of its water absorption and WHC [16]. Owing to the multiple hydroxyl groups in its structure, glycerin can bind to water through the hydrogen bonds, resulting in water retention [17]. Glycerin is also an effective additive for reducing a_w and extending product shelf life [18]. Sorapukdee et al. [15] reported that glycerin reduced the shear force and hardness of chicken jerky, and reduced the a_w from 0.854 to 0.630. Trehalose can improve hydration properties, enhance hydrophilicity, and reduce water migration [13]. Phosphates have been widely used in the meat industry owing to

their water retention ability [19]. Kılıç et al. [20] indicated that phosphates can reduce cooking loss, inhibit lipid oxidation, and improve texture and sensory qualities of processed meat products.

In our previous study, the influence of MR containing phosphates, glycerin, and trehalose on shear force, a_w , and moisture content of jerky were investigated. Studies have revealed that the addition of MR enhances the tenderness and moisture content of jerky. We also evaluated the influence of HHP at different pressures levels (0.1, 100, 200, and 300 MPa) combined with MR (MR + HHP) on the tenderness and quality of beef jerky [13]. The results indicated that the MR + HHP treatment at 200 MPa (MR + HHP-200) improved the tenderness and sensory quality of beef jerky. However, there are no literature reports on the change of quality and flavor of beef jerky which subjected to MR+HHP during storage. Hence, this study is aimed at investigating the effect of MR + HHP-200 on the quality and flavor attributes of beef jerky over 60 days of storage.

2 Materials and methods

2.1 Materials and chemicals

The beef was obtained from the Grand Farm Meat Corporation (Harbin, China) within 48 h of postmortem and was transported to a laboratory at 4 °C. Food-grade ingredients included NaCl, spices, phosphates, glycerin, and trehalose. Thiobarbituric acid, trichloroacetic acid, chloroform, and ortho-dichlorobenzene were analytical grade and supplied from Sigma Chemical Co. (St. Louis, MO, USA).

2.2 Preparation of beef jerky

Three different batches of beef jerky were prepared, with three different treatments of beef jerky in each batch. The left and right *Longissimus thoracis* (LT) from three carcasses (20–22 months old crossbred Simmental bulls) were used, and 6 kg of beef was obtained for each carcass. The beef was cut into 5 cm × 2 cm × 2 cm strips. The following ingredients were used to marinate the beef strips (g/kg meat): salt (15 g), mixed spices (5 g), cooking wine (5 g), white granulated sugar (10 g), ginger powder (1 g), ascorbic acid (1 g), monosodium glutamate (0.6 g), and nitrite (0.1 g). Fennel, clove, cassia bark, cumin, pepper, round cardamom, amomum fruit, and aniseed were among the spices in the mixed spice blend. The strips were subsequently marinated for 12 h at 4 °C. The marinated samples were allocated into three groups (treatments) at random. Each group had 6.0 kg of marinated beef strips. The first group received no MR and was not treated with HHP (control); the second group received HHP at 200 MPa for 20 min; the third group received the MR and was subsequently treated with HHP at 200 MPa for 20 min (MR + HHP). The temperature of pressure equipment (Renhe Electromechanical Equipment Co., Ltd, Shenyang, China) was set to 20 °C and kept this temperature during the pressure treatment. The following were used to make the MR (g/kg meat): glycerin (35 g), trehalose (15 g), and compound phosphate (3 g) (1 g each for sodium tripolyphosphate, sodium pyrophosphate, and sodium hexametaphosphate). For the MR + HHP samples, the MR was added to the beef before marination. Afterward, the marinated samples were vacuum-packed and subjected to pressure treatment. High-pressure processing was carried out as described by Han et al. [13]. Subsequently, the meat samples were dried for 1.5 h at 62–65 °C in a hot air drier (Gallendkamp Plus II, Weiss Technik, UK), and were dried

continuously at 5–57 °C until the a_w value reached a specific range (0.700 ± 0.030). The dried samples were cooled to room temperature and subsequently vacuum-packed (50 g per package). The packaged beef jerkies were stored at room temperature (20 ± 2) °C for 60 days. The beef jerky was collected for analysis on days 0, 15, 30, 45, and 60. For each group, 40 packages of beef jerky (approximately 2 kg in weight) were used for analysis, with 8 packages used at each storage time. Five packages of beef jerky from each group and storage time were used for the sensory panel evaluation, and another three were used to evaluate moisture content, a_w , shear force, lipid oxidation, color, and volatile compounds.

2.3 Moisture content and water activity determination

Moisture content was determined by Association of Official Analytical Chemists (AOAC) procedures [21]. An Aqualab Prekit water activity meter (Decagon Devices, USA) was used to determine a_w at 25 °C.

2.4 Shear force determination

Using a texture analyzer TA-XT plus (Stable Micro System, UK) and a shear blade (A/MORS), the samples were cut into 2 cm × 1 cm × 1 cm strips and sheared perpendicular to the direction of muscle fibers [13]. For each repetition, six strips were analyzed for each treatment. The test speed and the compression load cell were 100 mm/min and 50 kg, respectively.

2.5 Thiobarbituric acid reactive substance value determination

The degree of lipid oxidation was determined by the thiobarbituric acid reactive substances (TBARs) assay. TBARs value was measured according to the methods of Sun et al. [22]. In brief, 2 g of chopped meat sample was mixed in 3 mL of thiobarbituric acid (1%), and 17 mL of trichloroacetic acid (2.5%) was subsequently added. After that, the mixture was heated in boiling water for 30 min and cooled at room temperature. A supernatant (4 mL) was mixed by vortexing with isometric chloroform, followed by centrifugation at $3\,000 \times g$ for 10 min. The absorbance of the supernatant was recorded at 532 nm. The TBARs values, expressed as milligrams of malonaldehyde (MDA) per kilogram of beef jerky, were calculated as follows:

$$\text{TBARs value (mg MDA/kg)} = A_{532\text{ nm}}/m_s \times 9.48$$

Where $A_{532\text{ nm}}$ is the absorbance of the solution, m_s is the jerky weight (g), and 9.48 is a constant derived from the dilution factor and the molar extinction coefficient (152 000 L/(mol·cm) of the red thiobarbituric acid reaction product).

2.6 Color determination

The color was evaluated by the method of Zhang et al. [23]. The beef jerky samples were minced with a mincer (JR05-300, SUPOR, Zhejiang, China) and a total of 2 g of minced jerky was used to analyse the changes in color. The lightness (L^*), redness (a^*), and yellowness (b^*) values were determined by a ZE-6000 Chroma Meter (Juki Corp, Tokyo, Japan) using a 50 mm illumination area, Illuminant D65, and a 10° observer. Before the measurement, the colorimeter was calibrated with a white reference tile ($L^* = 95.26$, $a^* = -0.89$, $b^* = 1.18$). Each sample was measured in three different locations.

2.7 Volatile compound determination

The volatile compounds in beef jerky were extracted using headspace solid-phase microextraction (HS-SPME) and identified by gas chromatography-mass spectrometry (GC-MS, QP2020 NX GC/MS, Shimadzu Co., Japan) as described by Wen et al. [24]. Two grams of minced beef jerky samples were put in a 20 mL headspace bottle. The internal standard (IS) was ortho-dichlorobenzene (2 μ L) diluted in methanol. After equilibrating for 25 min at 50 °C, an SPME fiber was inserted into the sample bottle for 40 min at 50 °C. After that, the fiber was desorbed for 3 min at the injection port of the gas chromatography.

Volatile compounds were separated on a GC-MS system using an inert cap wax capillary column (0.25 mm $\times$ 60 m, 0.25 μ m). The oven temperature was held at 35 °C for 8 min, raised from 35 to 74 °C at 3 °C/min and subsequently raised from 75 to 155 °C at 3 °C/min. Subsequently, the temperature was maintained at 210 °C at a rate of 15 °C/min for 2 min. The electron ionization was 70 eV, and the mass scan range was from m/z 45 to 500. The compounds were identified by comparing mass spectra with the NIST 17 mass spectral library. The concentration of target compounds was calculated by comparing its area with the internal standard.

2.8 Sensory analysis

At the end of each storage period, the beef jerky was subjected to sensory evaluation according to the method in reference [25]. Twelve qualified panelists (6 males and 6 females) were selected from among faculty, graduate students, and staff across 3 sessions. Each panelist was trained before the sensory assessments. Each panelist was required to have mastered the operation process of sensory evaluation and the evaluation criteria for different sensory characteristics through training. The training sessions were held 4 times a week for 2 weeks, with each session lasting for 2 h [26]. The sensory assessments were conducted in a sensory testing room at mid-morning. Three tasting sessions, corresponding to the different storage times, were carried out on different days. The beef jerky was cut into cubes (approximately 1 cm³ in volume) and served on white plastic plates with randomized 3-digit numbers. A “warm-up” sample was evaluated at the beginning of the session to familiarize the panel with the scale range. The panelists were served with water and unsalted bread to clean their mouths and taste buds between each sampling. The tenderness, color, taste, and flavor of the beef jerky sample were evaluated using a seven-point line-scale: for tenderness, 1 = tough, 7 = tender; for color, 1 = dark brown, 7 = bright red; for taste, 1 = weak, 7 = strong; for flavor, 1 = mild jerky flavor, 7 = intense jerky flavor.

2.9 Statistical analysis

Three independent batches of beef jerky (replicates) were produced, and the specific experiments were performed in triplicate (triplicate observations) for each beef jerky batch. The data were evaluated using the general linear model procedure of the Statistix 8.1 (St. Paul, MN, USA) analytical software. The results were expressed in the form of mean $\pm$ standard error (SE). The data were subjected to an analysis of variance (ANOVA) with Tukey's multiple comparisons. The figures and graphs were plotted using Origin (version 2019, Northampton, MA, USA), SPSS 22.0 (Analytical Software, USA), or MetaboAnalyst 5.0 (<https://www.metaboanalyst.ca/>). The moisture content, a_w , shear force, TBARs value, and volatile compound content of the beef jerky were

analyzed using a mixed model with replicates as a random effect and different treatments (control, HHP, and MR + HHP) and storage times (0, 15, 30, 45, and 60 days) as fixed terms. For sensory analysis, different treatments, storage times, and sensory attributes were taken as fixed terms, whereas panelist number and session number were taken as random terms.

3 Results and discussion

3.1 Moisture content and water activity

The changes in the moisture content of the beef jerky during storage are presented in Figure 1(A). HHP and MR + HHP had considerably higher moisture contents at 0 d than control samples, with the MR + HHP samples having the highest moisture content ($P < 0.05$). HHP treatment may boost the degree of hydration between water and muscle proteins, causing a tighter combination between water and meat matrix, reducing water exudation during storage [27], and the presence of the MR enhanced this effect. In this experiment, the MR was composed of glycerin, trehalose, and compound phosphate. Glycerin, a hydrophilic compound, can bind stably with water and reduce water loss in the product. Trehalose has a high hydration capacity, making it easy to combine with functional groups ($-\text{NH}_2$, $-\text{OH}$, etc.) in meat protein and capture water molecules in the myofibrillar network, resulting in a tight trehalose-protein-water interaction [28]. Furthermore, phosphates may enhance electrostatic repulsion between the proteins, allowing more water entry into the myofibril structure [19]. The moisture content in all the samples decreased as the storage period increased. During storage, the moisture content of the MR + HHP samples decreased slowly and was significantly higher than that of the HHP and control samples ($P < 0.05$). Therefore, the presence of the MR effectively reduced the water loss in beef jerky during storage.

The a_w has a significant effect on food shelf life. The a_w must be kept below a certain level after drying to guarantee storage stability and prevent microbial growth in meat products [29]. The changes in a_w of beef jerky during storage at 20 °C are shown in Figure 1(B). The a_w of all the samples was between 0.695 and 0.701 at 0 days, and after 30 days of storage, the a_w of the control and HHP samples decreased. The rate of a_w decrease in control samples was faster than in the HHP and MR + HHP samples. At 60 days, a_w decreased to 0.652 for control samples and 0.678 for MR + HHP samples.

3.2 Shear force

Shear force increased in all the treatments during storage, resulting in increased hardness and decreased tenderness (Figure 2(A)). The increase in shear force could be due to moisture loss in products during storage. The control samples had a shear force of 65.43 N at 0 days, which was significantly higher than that of the HHP (54.01 N) and MR + HHP samples (40.23 N) ($P < 0.05$). The decrease in shear force values in the HHP and MR + HHP samples could be due to the increased water contents and the changes in muscle microstructure caused by the high-pressure treatment [30]. In our previous work, the H-band of a sarcomere was deformed and the Z-line was broken after treatment at 200 MPa [13]. Similar results were seen in a study of dry-cured hams [31]. During 60 days of storage, the shear force values of the MR + HHP samples increased slowly and were always lower than those of the HHP and control samples ($P < 0.05$), indicating that HHP and MR treatments improved the tenderness of beef jerky and delayed the increase in shear force during storage.

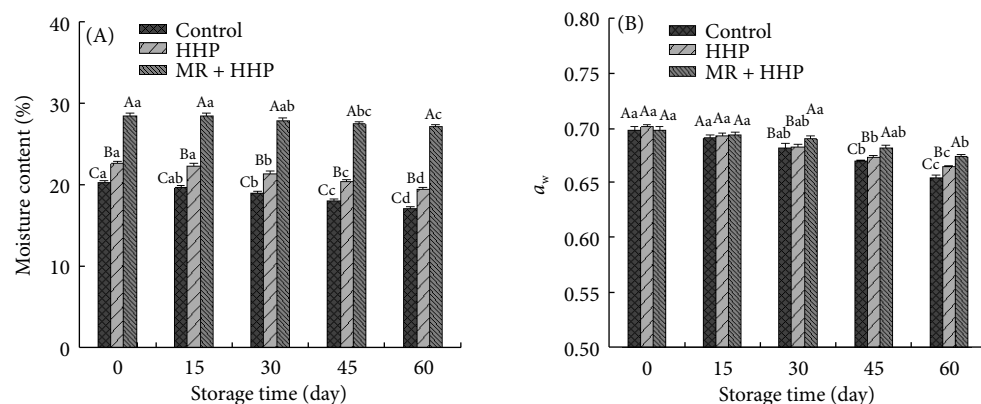


Figure 1 Influence of high hydrostatic pressure combined with moisture regulators on moisture content (A) and water activity (a_w) (B) of beef jerky during storage. The experimental data were expressed as the mean $\pm$ SE. HHP, high hydrostatic pressure; MR + HHP, moisture regulator combined with high hydrostatic pressure. Different uppercase letters (A–C) indicate significant differences among different treatments at the same storage time ($P < 0.05$); different lowercase letters (a–d) indicate significant differences among different storage times at the same treatment ($P < 0.05$).

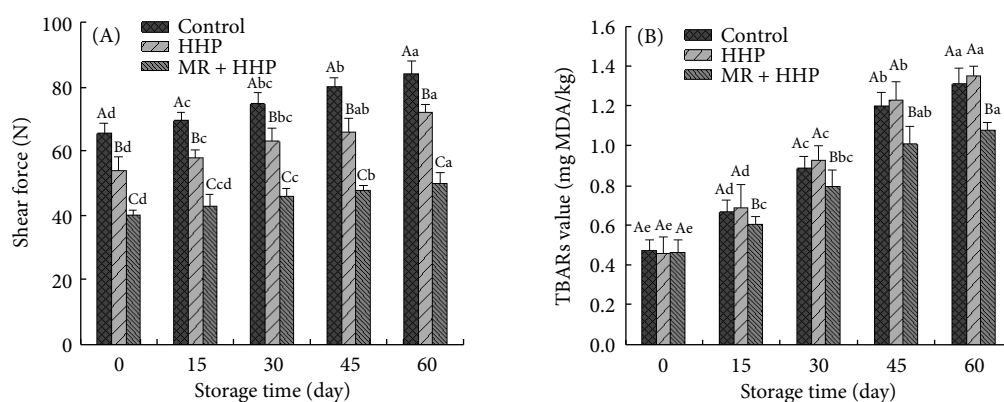


Figure 2 Influence of high hydrostatic pressure combined with moisture regulators on shear force (A) and TBARs value (B) of beef jerky during storage. The experimental data were expressed as the mean $\pm$ SE. HHP, high hydrostatic pressure; MR + HHP, moisture regulator combined with high hydrostatic pressure. Different uppercase letters (A–C) indicate significant differences among different treatments at the same storage time ($P < 0.05$); different lowercase letters (a–e) indicate significant differences among different storage times at the same treatment ($P < 0.05$).

3.3 Thiobarbituric acid reactive substances

TBARs value is one of the main indicators for evaluating the degree of lipid oxidation during storage, as well as the formation of secondary oxidation products [1]. The initial TBARs values in all samples ranged from 0.45 to 0.48 mg MDA/kg (Figure 2(B)). During storage, an increasing tendency in TBARs values was observed for all samples ($P < 0.05$), indicating that lipid oxidation increased as storage time was extended. At 0 days, there was no statistical difference in TBARs values between MR + HHP, HHP, and control samples ($P > 0.05$). The TBARs values of the MR + HHP samples were significantly lower than those of the HHP and control samples ($P < 0.05$) during storage, with no significant difference between control and HHP samples ($P > 0.05$). Chuang et al. [32] reported that meat lipid oxidation may be triggered by HHP at or above 300 MPa. Our study proved that lower HHP treatments (200 MPa for 20 min) had no adverse effects on beef jerky lipid oxidation. Furthermore, the addition of the MR reduced lipid oxidation of beef jerky during storage. The antioxidant effect of the MR could be attributed to trehalose and complex phosphates. Trehalose, as a potential biomolecular protective agent, forms a glass structure on the biofilm, which protects proteins and cell membranes from denaturation or inactivation induced by a variety of stress conditions such as oxidation, drying, low temperature, and dehydration [33]. Furthermore, the content of free iron ions related

to lipid oxidation could be reduced by phosphate, effectively inhibiting lipid oxidation [19].

3.4 Color

The results showed that the color of beef jerky was affected by storage times (Table 1). Increased storage time decreased the L^* value in all of the treatments. The decrease in L^* values could be due to a decrease of moisture content in beef jerky during storage time. Chen et al. [34] also found that there was a high positive correlation between the L^* value of the muscle surface and moisture content. The MR + HHP and HHP samples had significantly higher L^* values than the control samples ($P < 0.05$). Del Olmo et al. [35] proved that meat treated with HHP at or above 200 MPa increased the L^* value by a significant amount. The increase in L^* values caused by HHP could be due to the changes in sarcoplasmic refraction and light scattering of the meat under high pressure [36]. During storage, the L^* values of the MR + HHP samples were higher, which could be due to the high moisture content on its surface (Figure 1(A)). The more moisture on the meat surface, the more light scattering occurs, giving the meat a brighter appearance.

With prolonged storage time, the redness (a^* value) and the yellowness (b^* value) gradually decreased (Table 1). This result was consistent with that of Fernandes et al. [37], who explored the effect of the storage time on the color of lamb burgers. Their results revealed that the a^* values and b^* values of the samples decreased

Table 1 Influence of high hydrostatic pressure combined with moisture regulators on the color of beef jerky during storage.

Color attributes	Group	Storage period (day)				
		0	15	30	45	60
L^*	Control	37.34 ± 0.42 ^{Ca}	36.42 ± 0.22 ^{Cab}	35.56 ± 0.19 ^{Cb}	33.25 ± 0.28 ^{Bc}	32.87 ± 0.31 ^{Cd}
	HHP	39.72 ± 0.31 ^{Ba}	38.02 ± 0.38 ^{Bab}	37.35 ± 0.32 ^{Bb}	35.79 ± 0.18 ^{Bc}	34.55 ± 0.19 ^{Bd}
	MR + HHP	41.07 ± 0.37 ^{Aa}	40.79 ± 0.18 ^{Aa}	39.85 ± 0.12 ^{Ab}	39.03 ± 0.25 ^{Ab}	38.23 ± 0.16 ^{Ac}
a^*	Control	21.22 ± 0.46 ^{Aa}	20.15 ± 0.35 ^{Aab}	19.03 ± 0.27 ^{Abc}	18.04 ± 0.45 ^{Bc}	16.52 ± 0.42 ^{Bd}
	HHP	22.02 ± 0.34 ^{Aa}	20.12 ± 0.22 ^{Ab}	19.32 ± 0.24 ^{Ac}	17.06 ± 0.57 ^{Bcd}	15.96 ± 0.64 ^{Bd}
	MR + HHP	21.78 ± 0.27 ^{Aa}	21.20 ± 0.44 ^{Aab}	20.63 ± 0.35 ^{Abc}	20.14 ± 0.72 ^{AcD}	19.75 ± 0.33 ^{Ad}
b^*	Control	14.52 ± 0.42 ^{Aa}	13.15 ± 0.35 ^{Ab}	12.33 ± 0.27 ^{Ac}	11.28 ± 0.45 ^{Bd}	10.52 ± 0.72 ^{Be}
	HHP	14.43 ± 0.35 ^{Aa}	13.65 ± 0.27 ^{Aab}	12.78 ± 0.41 ^{Ab}	11.53 ± 0.68 ^{Bc}	10.69 ± 0.39 ^{Bd}
	MR + HHP	14.72 ± 0.67 ^{Aa}	14.29 ± 0.54 ^{Aab}	13.85 ± 0.55 ^{Ac}	13.12 ± 0.26 ^{Ab}	12.46 ± 0.28 ^{Ac}

Note: the experimental data were expressed as the mean ± SE. ^{a-d} Indicates with different lowercase letters in the same row differ significantly ($P < 0.05$). ^{A-C} Indicates with different uppercase letters in the same column for the same index differ significantly ($P < 0.05$). HHP, high hydrostatic pressure; MR + HHP, moisture regulator combined with high hydrostatic pressure.

after 120 days of storage. This could be due to metmyoglobin formation and lipid oxidation [38]. Notably, the a^* values and b^* values of the MR + HHP samples showed a slower decline trend than that of the HHP and control samples during storage ($P < 0.05$). Therefore, the combination of MR and HHP treatment can effectively reduce the change in the a^* values and b^* values of beef jerky samples.

3.5 Volatile compound analysis

The concentrations of volatile flavor compounds in the control, HHP, and MR + HHP samples at different storage times are presented in Table 2. In this study, 56 volatile compounds were identified in beef jerky samples, which were categorized according to their chemical family as follows: 10 hydrocarbons, 13 aldehydes, 12 alcohols, 6 ketones, 5 acids, 5 esters, 4 pyrazines, and 1 furans. These volatile compounds are produced by protein and lipid oxidation, microbial metabolism, amino acid metabolism, carbohydrate catabolism, and spices [39]. The MR samples contain some unique flavor compounds, such as ethylbenzene, 2-methylundecanol, and (2S,3S)-(+)-2,3-butanediol.

The contents of hexanol, linalool, nerolidol, and geranyl acetate in the HHP and MR + HHP samples were higher than those in the control samples ($P < 0.05$), owing to the spices and wine added during the processing of beef jerky. This could be because some components can easily penetrate the muscle through capillary force after the beef has been treated by HHP [40]. Compounds with pleasant odors, such as linalool, pinene, and geranyl ester, decreased as storage time increased, while compounds, such as heptanal, nonanal, octanal, hexanal, and benzaldehyde, which cause by lipid oxidation, increased. Nonanal, octanal, and benzaldehyde produced an unpleasant and pungent odor that was not conducive to the overall flavor of beef jerky [41], which may be one of the important reasons for the poor sensory flavor scores of the beef jerky stored for 60 days (Table 3).

Aldehydes are common lipid oxidation products with low odor threshold which play the most important role in the flavor development of meat products [42]. Straight chain aldehydes detected in beef jerky, such as hexanal, octanal, nonanal, and heptanal, are mainly produced by the oxidation of unsaturated fatty acids [43]. Nonanal confers carnation, citrus, and laurel odors [44], while octanal contributes to the sweet and grassy flavor in beef jerky [45]. When present at low contents, hexanal gives apple

aromas and green grass to meat, while high hexanal contents may result in a rancid aroma, which is often used as a lipid oxidation indicator [46]. As shown in Table 2, the lower hexanal levels in the MR + HHP groups indicated that excessive lipid oxidation was inhibited, which was consistent with the TBARs values. Overall, the content of most aldehyde compounds appeared to increase as storage time increased, which is mainly due to lipid oxidation during beef jerky storage.

Alcohols were mostly formed through lipid oxidation and spices, the majority of which had pleasant aromas such as fruit, wood, vegetable aroma, and vanilla [45]. A large number of alcohols present tended to increase in all samples at the end of storage (60 days), indicating that certain alcohols, such as hexanol, 1-octen-3-ol, 1-pentene-3-ol, and phenethyl alcohol, can accumulate over time. Only the content of ethanol increased initially (0–30 days) and subsequently decreased (30–60 days) during storage, which was related to the esterification of ethanol and acid toward the end of storage [39].

Ethyl esters, such as ethyl acetate, ethyl propionate, and ethyl hexanoate, were the most common esters in beef jerky. Esters are usually made by esterifying short-chain acids and alcohols, and they have a fruity, sweet, and floral aroma [47]. Esters are generally considered to be one of the most important contributors to the distinct flavor of meat products because of their low threshold [48]. The generation of esters depends on the activity of microbial esterases and the presence of alcohols and acids [48]. Ketones were shown to have long-lasting fruity and creamy aromas as a result of lipid oxidation and microbial metabolism [41]. Although higher levels of ketones were identified, they had little effect on the overall flavor of beef jerky owing to their relatively high threshold values. Furthermore, 9 hydrocarbons compounds were found in the beef jerky, with the contents of 6 hydrocarbons compounds decreased during storage. Alkene compounds, mainly derived from spices, were among them. Shahidi et al. [49] found that both saturated and unsaturated hydrocarbons play a small role in the formation of the overall flavor of food.

3.6 Partial least squares-discriminant analysis of volatile compounds

Partial least squares-discriminant analysis (PLS-DA) is a supervised analysis method widely used in the food industry [50]. The effects

Table 2 Volatile compounds content in beef jerky at 0, 30, and 60 days identified and quantified by gas chromatography/mass spectrometry. (µg/g)

Volatile compounds	0 days			30 days			60 days		
	Control	HHP	MR + HHP	Control	HHP	MR + HHP	Control	HHP	MR + HHP
Hydrocarbons									
Myrcene	3.83 ± 0.03 ^{Aa}	4.02 ± 0.02 ^{Aa}	4.04 ± 0.05 ^{Aa}	2.60 ± 0.23 ^{Ab}	2.74 ± 0.14 ^{Ab}	2.87 ± 0.35 ^{Ab}	1.27 ± 0.36 ^{Ac}	1.06 ± 0.24 ^{Ac}	1.15 ± 0.21 ^{Ac}
Tridecane	1.13 ± 0.03 ^{Bc}	1.10 ± 0.04 ^{Bc}	1.71 ± 0.07 ^{Ac}	2.19 ± 0.15 ^{Bb}	2.20 ± 0.07 ^{Bb}	3.07 ± 0.21 ^{Ab}	3.69 ± 0.06 ^{Ba}	3.69 ± 0.06 ^{Ba}	4.56 ± 0.23 ^{Aa}
β-Caryophyllene	2.67 ± 0.80 ^{Ba}	2.45 ± 0.20 ^{Ba}	3.01 ± 0.50 ^{Aa}	1.03 ± 0.30 ^{Bb}	1.04 ± 0.15 ^{Bb}	1.41 ± 0.37 ^{Ab}	0.43 ± 0.04 ^{Bc}	0.44 ± 0.10 ^{Bc}	0.81 ± 0.17 ^{Ac}
α-Pinene	0.13 ± 0.07 ^{Ac}	0.10 ± 0.03 ^{Ac}	0.11 ± 0.01 ^{Ac}	0.63 ± 0.09 ^{Ab}	0.70 ± 0.13 ^{Ab}	0.65 ± 0.08 ^{Ab}	1.33 ± 0.35 ^{Aa}	1.47 ± 0.13 ^{Aa}	1.56 ± 0.18 ^{Aa}
Limonene	11.91 ± 0.60 ^{Ba}	16.56 ± 1.28 ^{Aa}	16.49 ± 1.76 ^{Aa}	9.27 ± 0.34 ^{Bb}	14.46 ± 0.52 ^{Ab}	14.02 ± 0.29 ^{Ab}	5.45 ± 0.54 ^{Bc}	8.38 ± 0.50 ^{Ac}	8.63 ± 0.46 ^{Ac}
Terpinene	2.53 ± 0.23 ^{Aa}	2.78 ± 0.32 ^{Aa}	2.64 ± 0.35 ^{Aa}	0.97 ± 0.16 ^{Ab}	0.90 ± 0.21 ^{Ab}	0.95 ± 0.19 ^{Ab}	ND	0.10 ± 0.03 ^{Ac}	0.06 ± 0.01 ^{Ac}
3-Methyl-tridecane	2.55 ± 0.07 ^{Bc}	2.46 ± 0.09 ^{Bc}	4.06 ± 0.15 ^{Ac}	3.74 ± 0.05 ^{Bb}	3.79 ± 0.06 ^{Bb}	5.16 ± 0.23 ^{Ab}	5.93 ± 0.08 ^{Ba}	6.04 ± 0.08 ^{Ba}	7.10 ± 0.10 ^{Aa}
Cyclohexene	15.32 ± 0.70 ^{Aa}	14.93 ± 0.30 ^{Aa}	14.94 ± 0.34 ^{Aa}	11.92 ± 1.43 ^{Ab}	11.69 ± 0.56 ^{Ab}	11.70 ± 0.99 ^{Bb}	7.83 ± 0.63 ^{Ac}	7.62 ± 0.02 ^{Ac}	7.64 ± 0.05 ^{Ac}
Ethyl benzene	ND	ND	4.72 ± 0.14 ^{Aa}	ND	ND	3.30 ± 0.24 ^{Ab}	ND	ND	2.07 ± 0.28 ^{Ac}
Styrene	10.51 ± 0.70 ^{Aa}	10.31 ± 0.30 ^{Aa}	10.83 ± 0.30 ^{Aa}	8.29 ± 0.45 ^{Ab}	8.25 ± 0.38 ^{Ab}	8.46 ± 0.41 ^{Ab}	4.46 ± 0.24 ^{Ac}	4.34 ± 0.31 ^{Ac}	4.69 ± 0.23 ^{Ac}
Aldehydes									
3-Methylbutanal	13.0 ± 0.70 ^{Ba}	18.4 ± 0.24 ^{Aa}	6.89 ± 0.19 ^{Cb}	15.2 ± 0.40 ^{Ba}	20.4 ± 0.24 ^{Aa}	7.44 ± 0.19 ^{Cb}	17.7 ± 0.23 ^{Aa}	18.3 ± 0.22 ^{Aa}	10.1 ± 0.19 ^{Ba}
Hexanal	5.43 ± 0.05 ^{Ac}	5.78 ± 0.05 ^{Ac}	5.44 ± 0.05 ^{Ac}	10.5 ± 0.34 ^{Ab}	10.7 ± 0.62 ^{Ab}	6.40 ± 0.28 ^{Bb}	15.7 ± 0.34 ^{Aa}	15.6 ± 0.52 ^{Aa}	9.02 ± 0.29 ^{Ba}
Nonanal	3.78 ± 0.13 ^{Bc}	6.02 ± 0.04 ^{Ac}	1.43 ± 0.03 ^{Cc}	7.79 ± 0.54 ^{Ab}	8.08 ± 0.62 ^{Ab}	5.02 ± 0.20 ^{Bb}	9.29 ± 0.45 ^{Aa}	10.65 ± 0.38 ^{Aa}	8.46 ± 0.41 ^{Ba}
Cinnamaldehyde	4.45 ± 0.04 ^{Aa}	4.44 ± 0.01 ^{Aa}	4.23 ± 0.33 ^{Aa}	3.65 ± 0.1 ^{Ab}	3.82 ± 0.21 ^{Ab}	3.74 ± 0.23 ^{Ab}	1.45 ± 0.23 ^{Bc}	1.64 ± 0.11 ^{Bc}	1.47 ± 0.13 ^{Ac}
Octanal	7.72 ± 0.05 ^{Ac}	7.63 ± 0.03 ^{Ac}	7.60 ± 0.09 ^{Ac}	11.70 ± 0.13 ^{Ab}	11.69 ± 0.36 ^{Ab}	9.20 ± 0.09 ^{Bb}	12.77 ± 0.25 ^{Aa}	12.74 ± 0.03 ^{Aa}	11.40 ± 0.09 ^{Ba}
Heptanal	2.22 ± 0.11 ^{Ac}	2.01 ± 0.16 ^{Ac}	2.07 ± 0.19 ^{Ac}	3.53 ± 0.34 ^{Ab}	3.72 ± 0.62 ^{Ab}	2.55 ± 0.28 ^{Bb}	5.34 ± 0.56 ^{Aa}	5.70 ± 0.72 ^{Aa}	3.17 ± 0.39 ^{Ba}
2-Octanal	4.78 ± 0.02 ^{Ac}	4.83 ± 0.11 ^{Ac}	4.76 ± 0.08 ^{Ac}	5.34 ± 0.29 ^{Ab}	5.45 ± 0.22 ^{Ab}	5.38 ± 0.31 ^{Aa}	6.21 ± 0.08 ^{Aa}	6.45 ± 0.12 ^{Aa}	5.48 ± 0.05 ^{Ba}
Benzaldehyde	1.57 ± 0.52 ^{Ac}	1.77 ± 0.34 ^{Ac}	1.70 ± 0.28 ^{Ac}	4.89 ± 0.40 ^{Ab}	5.03 ± 0.80 ^{Ab}	3.00 ± 1.22 ^{Bb}	10.34 ± 0.15 ^{Aa}	10.14 ± 0.24 ^{Aa}	6.32 ± 0.19 ^{Ba}
Phenylacetaldehyde	4.45 ± 0.12 ^{Ac}	3.93 ± 0.08 ^{Bc}	2.20 ± 0.03 ^{Cc}	11.85 ± 0.23 ^{Ab}	11.79 ± 0.43 ^{Ab}	9.89 ± 0.11 ^{Bb}	13.75 ± 0.22 ^{Aa}	13.76 ± 0.19 ^{Aa}	12.60 ± 0.08 ^{Ba}
2-Nonenal	4.40 ± 0.04 ^{Aa}	3.22 ± 0.04 ^{Ba}	3.45 ± 0.06 ^{Ba}	5.54 ± 0.41 ^{Aa}	5.87 ± 0.59 ^{Aa}	4.49 ± 0.34 ^{Ba}	5.02 ± 0.06 ^{Aa}	5.24 ± 0.04 ^{Aa}	4.40 ± 0.04 ^{Ba}
Lauraldehyde	0.33 ± 0.07 ^{Ac}	0.40 ± 0.03 ^{Ac}	0.41 ± 0.01 ^{Ac}	1.13 ± 0.14 ^{Ab}	1.04 ± 0.09 ^{Ab}	1.02 ± 0.23 ^{Ab}	2.44 ± 0.44 ^{Aa}	2.32 ± 0.62 ^{Aa}	2.05 ± 0.28 ^{Ba}
2-Hexenal	2.30 ± 0.04 ^{Bc}	4.43 ± 0.03 ^{Ac}	2.09 ± 0.12 ^{Bc}	7.76 ± 0.12 ^{Bb}	8.89 ± 0.09 ^{Ab}	5.56 ± 0.12 ^{Cb}	12.88 ± 0.13 ^{Ba}	13.79 ± 0.06 ^{Aa}	10.09 ± 0.03 ^{Ca}
Cuminaldehyde	1.44 ± 0.09 ^{Aa}	1.54 ± 0.06 ^{Aa}	1.43 ± 0.09 ^{Aa}	1.45 ± 0.13 ^{Aa}	1.30 ± 0.26 ^{Aa}	1.37 ± 0.18 ^{Aa}	0.55 ± 0.07 ^{Ab}	0.60 ± 0.14 ^{Ab}	0.57 ± 0.08 ^{Ab}
Alcohols									
Pentanol	2.30 ± 0.34 ^{Ab}	2.34 ± 0.44 ^{Ab}	2.67 ± 0.22 ^{Ab}	2.43 ± 0.39 ^{Ab}	2.32 ± 0.51 ^{Ab}	2.45 ± 0.58 ^{Ab}	3.53 ± 0.32 ^{Aa}	3.54 ± 0.40 ^{Aa}	3.77 ± 0.30 ^{Aa}
Cineole	1.45 ± 0.19 ^{Aa}	1.64 ± 0.16 ^{Aa}	1.73 ± 0.13 ^{Aa}	0.65 ± 0.09 ^{Ab}	0.60 ± 0.06 ^{Ab}	0.57 ± 0.05 ^{Ab}	0.15 ± 0.09 ^{Ac}	0.20 ± 0.06 ^{Ac}	0.17 ± 0.04 ^{Ac}
Hexanol	1.27 ± 0.09 ^{Bc}	2.06 ± 0.04 ^{Ac}	2.15 ± 0.11 ^{Ac}	4.34 ± 0.15 ^{Bb}	5.79 ± 0.24 ^{Ab}	5.96 ± 0.19 ^{Ab}	8.34 ± 0.15 ^{Ba}	10.14 ± 0.24 ^{Aa}	10.32 ± 0.19 ^{Aa}
1-Octen-3-ol	1.07 ± 0.01 ^{Ac}	1.10 ± 0.46 ^{Ac}	1.04 ± 0.18 ^{Ac}	15.85 ± 1.23 ^{Ab}	15.79 ± 0.83 ^{Ab}	9.89 ± 1.11 ^{Bb}	33.57 ± 3.12 ^{Aa}	35.76 ± 2.19 ^{Aa}	16.60 ± 0.08 ^{Ba}
Nerolidol	7.21 ± 0.74 ^{Aa}	7.33 ± 0.80 ^{Aa}	7.00 ± 1.22 ^{Aa}	5.02 ± 0.36 ^{Ab}	5.24 ± 0.44 ^{Ab}	5.10 ± 0.52 ^{Ab}	4.30 ± 0.26 ^{Ac}	4.43 ± 0.33 ^{Ac}	4.19 ± 0.42 ^{Ac}
Linalool	3.53 ± 0.03 ^{Ba}	7.04 ± 0.12 ^{Aa}	7.16 ± 0.17 ^{Aa}	3.06 ± 0.23 ^{Bb}	6.63 ± 0.19 ^{Ab}	6.86 ± 0.25 ^{Ab}	2.13 ± 0.15 ^{Bc}	5.57 ± 0.34 ^{Ac}	5.36 ± 0.38 ^{Ac}
1-Pentene-3-ol	8.34 ± 0.70 ^{Ac}	8.78 ± 1.23 ^{Ac}	9.44 ± 0.80 ^{Ac}	12.45 ± 1.43 ^{Ab}	12.76 ± 1.51 ^{Ab}	13.39 ± 2.06 ^{Ab}	20.45 ± 1.22 ^{Aa}	20.58 ± 1.89 ^{Aa}	21.60 ± 2.08 ^{Aa}
Phenethyl alcohol	3.43 ± 0.37 ^{Ac}	3.09 ± 0.33 ^{Ac}	3.24 ± 0.45 ^{Ac}	5.39 ± 0.50 ^{Ab}	5.10 ± 0.52 ^{Ab}	5.17 ± 0.34 ^{Ab}	7.03 ± 0.38 ^{Aa}	7.82 ± 0.41 ^{Aa}	7.74 ± 0.35 ^{Aa}
Ethanol	2.93 ± 0.12 ^{Ab}	3.04 ± 0.10 ^{Ab}	3.17 ± 0.10 ^{Ab}	5.28 ± 0.17 ^{Aa}	5.16 ± 0.21 ^{Aa}	5.35 ± 0.16 ^{Aa}	1.37 ± 0.17 ^{Ac}	1.41 ± 0.13 ^{Ac}	1.29 ± 0.14 ^{Ac}
1-Heptanol	4.56 ± 0.09 ^{Ba}	4.54 ± 0.12 ^{Ba}	4.89 ± 0.21 ^{Aa}	4.25 ± 0.33 ^{Ba}	4.37 ± 0.22 ^{Ba}	4.86 ± 0.37 ^{Aa}	3.42 ± 0.43 ^{Ab}	3.47 ± 0.32 ^{Ab}	3.86 ± 0.41 ^{Ab}
2-Methyl-undecanol	ND	ND	0.64 ± 0.03 ^{Ac}	ND	ND	0.95 ± 0.11 ^{Ab}	ND	ND	1.66 ± 0.42 ^{Aa}
(2S,3S)-(+)-2,3-Butanediol	ND	ND	2.13 ± 0.10 ^{Ac}	ND	ND	3.05 ± 0.10 ^{Ab}	ND	ND	5.56 ± 0.10 ^{Aa}
Acids									
Nonanoic acid	1.24 ± 0.01 ^{Ab}	1.23 ± 0.12 ^{Ab}	1.37 ± 0.21 ^{Ab}	2.68 ± 0.12 ^{Aa}	3.00 ± 0.16 ^{Aa}	3.07 ± 0.18 ^{Aa}	1.13 ± 0.17 ^{Ab}	1.25 ± 0.19 ^{Ab}	1.11 ± 0.11 ^{Ab}
Octanoic acid	0.64 ± 0.11 ^{Ac}	0.53 ± 0.12 ^{Ac}	0.61 ± 0.14 ^{Ac}	0.95 ± 0.12 ^{Ab}	0.83 ± 0.11 ^{Ab}	0.92 ± 0.18 ^{Ab}	1.59 ± 0.02 ^{Aa}	1.43 ± 0.10 ^{Aa}	1.53 ± 0.12 ^{Aa}
Hexanoic acid	2.44 ± 0.12 ^{Ab}	2.45 ± 0.01 ^{Ab}	2.34 ± 0.03 ^{Ab}	2.89 ± 0.02 ^{Aa}	3.03 ± 0.10 ^{Aa}	2.93 ± 0.12 ^{Aa}	1.92 ± 0.10 ^{Ac}	1.85 ± 0.19 ^{Ac}	2.00 ± 0.07 ^{Ac}
3-Methylbutyric acid	1.25 ± 0.11 ^{Ac}	1.36 ± 0.14 ^{Ac}	1.10 ± 0.21 ^{Ac}	1.88 ± 0.23 ^{Ab}	1.87 ± 0.15 ^{Ab}	1.73 ± 0.13 ^{Ab}	2.39 ± 0.10 ^{Aa}	2.40 ± 0.14 ^{Aa}	2.35 ± 0.15 ^{Aa}
2-Methylbutyric acid	1.26 ± 0.30 ^{Ac}	1.23 ± 0.10 ^{Ac}	1.04 ± 0.40 ^{Ac}	1.68 ± 0.19 ^{Ab}	1.70 ± 0.12 ^{Ab}	1.77 ± 0.14 ^{Ab}	2.89 ± 0.20 ^{Aa}	2.93 ± 0.35 ^{Aa}	3.13 ± 0.23 ^{Aa}

Table 2 (Continued)

Volatile compounds	0 days			30 days			60 days		
	Control	HHP	MR + HHP	Control	HHP	MR + HHP	Control	HHP	MR + HHP
Ketones									
2,5-Octanedione	4.57 ± 0.41 ^{Ac}	4.43 ± 0.30 ^{Ac}	3.25 ± 0.53 ^{Bc}	7.56 ± 0.73 ^{Ab}	7.64 ± 0.52 ^{Ab}	5.53 ± 0.48 ^{Bb}	15.86 ± 1.23 ^{Aa}	16.23 ± 1.19 ^{Aa}	12.46 ± 1.25 ^{Ba}
Acetophenone	4.89 ± 0.20 ^{Ac}	5.03 ± 0.10 ^{Ac}	4.83 ± 0.12 ^{Ac}	13.89 ± 0.65 ^{Aa}	13.83 ± 0.70 ^{Aa}	14.23 ± 0.72 ^{Aa}	6.65 ± 0.56 ^{Ab}	6.93 ± 0.49 ^{Ab}	6.57 ± 0.53 ^{Ab}
2-Heptanone	4.13 ± 0.33 ^{Bc}	4.78 ± 0.14 ^{Ac}	3.67 ± 0.69 ^{Cc}	7.25 ± 0.50 ^{Ab}	7.19 ± 0.52 ^{Ab}	5.17 ± 0.34 ^{Ab}	11.03 ± 0.38 ^{Ba}	13.82 ± 0.41 ^{Aa}	10.74 ± 0.35 ^{Ca}
3-Hydroxy-2-butanone	7.67 ± 0.43 ^{Ac}	7.44 ± 0.67 ^{Ac}	7.45 ± 0.17 ^{Ac}	11.35 ± 1.69 ^{Ab}	11.36 ± 1.56 ^{Ab}	11.10 ± 1.21 ^{Ab}	17.63 ± 1.15 ^{Aa}	17.71 ± 1.32 ^{Aa}	17.75 ± 1.63 ^{Aa}
2,3-Octanedione	4.92 ± 0.31 ^{Ac}	5.14 ± 0.34 ^{Ac}	4.89 ± 0.14 ^{Ac}	9.59 ± 0.02 ^{Ab}	9.73 ± 0.10 ^{Ab}	6.63 ± 0.12 ^{Bb}	18.63 ± 0.80 ^{Ab}	18.79 ± 1.22 ^{Aa}	14.52 ± 0.36 ^{Ba}
Hydroxyacetone	4.61 ± 0.35 ^{Ac}	4.45 ± 0.10 ^{Ac}	4.44 ± 0.13 ^{Ac}	6.65 ± 0.46 ^{Ab}	6.93 ± 0.43 ^{Ab}	7.07 ± 0.28 ^{Ab}	7.67 ± 0.63 ^{Aa}	7.64 ± 0.35 ^{Aa}	7.79 ± 0.53 ^{Aa}
Esters									
Ethyl acetate	4.21 ± 0.01 ^{Bb}	4.11 ± 0.04 ^{Bb}	5.34 ± 0.45 ^{Ab}	9.43 ± 0.71 ^{Ba}	9.57 ± 0.44 ^{Ba}	10.74 ± 0.69 ^{Aa}	9.02 ± 0.44 ^{Ba}	9.89 ± 0.69 ^{Aa}	10.07 ± 0.51 ^{Aa}
Ethyl propionate	5.45 ± 0.23 ^{Ac}	5.64 ± 0.34 ^{Ac}	5.23 ± 0.33 ^{Ac}	8.59 ± 0.44 ^{Aa}	8.78 ± 0.62 ^{Aa}	8.82 ± 0.20 ^{Aa}	7.21 ± 0.32 ^{Ab}	7.45 ± 0.42 ^{Ab}	7.46 ± 0.39 ^{Ab}
Ethyl hexanoate	8.03 ± 0.04 ^{Cc}	11.6 ± 0.09 ^{Ac}	9.64 ± 0.35 ^{Bc}	10.3 ± 0.24 ^{Cb}	11.45 ± 0.26 ^{Ab}	10.94 ± 0.31 ^{Bb}	13.06 ± 0.13 ^{Ba}	13.65 ± 0.34 ^{Aa}	13.86 ± 0.23 ^{Aa}
Octanoic acid methyl ester	8.31 ± 0.37 ^{Aa}	8.03 ± 0.34 ^{Aa}	8.15 ± 0.26 ^{Aa}	6.04 ± 0.23 ^{Ab}	5.86 ± 0.45 ^{Ab}	5.83 ± 0.36 ^{Ab}	5.92 ± 0.23 ^{Ab}	5.73 ± 0.35 ^{Ab}	5.63 ± 0.67 ^{Ab}
Geranyl ester	4.04 ± 0.23 ^{Ba}	5.89 ± 0.45 ^{Aa}	5.45 ± 0.54 ^{Aa}	3.05 ± 0.19 ^{Bb}	3.49 ± 0.05 ^{Ab}	3.55 ± 0.05 ^{Ab}	1.07 ± 0.23 ^{Bc}	1.78 ± 0.25 ^{Ac}	1.85 ± 0.05 ^{Ac}
Pyrazines									
4-Methyl pyrazine	1.45 ± 0.02 ^{Ac}	1.33 ± 0.03 ^{Ac}	1.54 ± 0.01 ^{Ac}	2.35 ± 0.34 ^{Ab}	2.48 ± 0.32 ^{Ab}	2.60 ± 0.50 ^{Ab}	3.25 ± 0.39 ^{Aa}	3.15 ± 0.05 ^{Aa}	3.35 ± 0.05 ^{Aa}
3-Methyl pyrazine	ND	0.13 ± 0.03 ^{Ac}	0.14 ± 0.08 ^{Ac}	0.53 ± 0.04 ^{Ab}	0.55 ± 0.06 ^{Ab}	0.49 ± 0.03 ^{Ab}	1.11 ± 0.10 ^{Aa}	1.03 ± 0.15 ^{Aa}	1.15 ± 0.16 ^{Aa}
2-Methyl pyrazine	2.53 ± 0.40 ^{Ac}	2.47 ± 0.70 ^{Ac}	2.57 ± 0.30 ^{Ac}	3.34 ± 0.15 ^{Ab}	3.38 ± 0.24 ^{Ab}	3.40 ± 0.290 ^{Ab}	4.77 ± 0.23 ^{Aa}	4.89 ± 0.45 ^{Aa}	4.75 ± 0.54 ^{Aa}
2,3-Dimethyl-pyrazine	0.38 ± 0.01 ^{Ac}	0.40 ± 0.09 ^{Ac}	0.34 ± 0.09 ^{Ac}	1.27 ± 0.15 ^{Ab}	1.48 ± 0.17 ^{Ab}	1.35 ± 0.25 ^{Ab}	1.87 ± 0.42 ^{Aa}	1.93 ± 0.30 ^{Aa}	1.90 ± 0.28 ^{Aa}
Furans									
2-Pentyl-furan	0.35 ± 0.07 ^{Ab}	0.36 ± 0.07 ^{Ab}	0.34 ± 0.23 ^{Ab}	0.73 ± 0.27 ^{Aa}	0.66 ± 0.15 ^{Aa}	0.64 ± 0.26 ^{Aa}	0.75 ± 0.15 ^{Aa}	0.76 ± 0.27 ^{Aa}	0.72 ± 0.21 ^{Aa}

Note: the experimental data were expressed as the mean ± SE. ^{a-d} Indicates with different lowercase letters in the same row differ significantly ($P < 0.05$); ^{A-C} Indicates with different uppercase letters in the same column for the same index differ significantly ($P < 0.05$). HHP, high hydrostatic pressure; MR + HHP, moisture regulator combined with high hydrostatic pressure; ND, not detected.

Table 3 Influence of high hydrostatic pressure combined with moisture regulator on the sensory characteristics of beef jerky during storage.

Sensory characteristics	Group	Storage period (day)				
		0	15	30	45	60
Tenderness	Control	5.12 ± 1.04 ^{Ca}	4.58 ± 1.18 ^{Cab}	4.26 ± 0.94 ^{Cb}	3.41 ± 0.71 ^{Cc}	3.17 ± 0.93 ^{Cd}
	HHP	5.59 ± 0.58 ^{Ba}	4.91 ± 1.16 ^{Bab}	4.79 ± 0.63 ^{Bab}	3.92 ± 0.78 ^{Bb}	3.32 ± 0.64 ^{Bc}
	MR + HHP	6.02 ± 0.66 ^{Aa}	5.83 ± 0.53 ^{Aa}	5.11 ± 0.34 ^{Aab}	4.28 ± 0.36 ^{Ab}	4.02 ± 0.26 ^{Ac}
Color	Control	5.63 ± 1.45 ^{Aa}	5.56 ± 1.24 ^{Aa}	4.72 ± 0.83 ^{Bb}	4.39 ± 0.78 ^{Bc}	3.89 ± 1.09 ^{Bd}
	HHP	5.42 ± 1.56 ^{Aa}	5.35 ± 0.91 ^{Aa}	4.61 ± 1.12 ^{Bb}	4.18 ± 0.85 ^{Bbc}	3.76 ± 1.19 ^{Bc}
	MR + HHP	5.39 ± 1.09 ^{Aa}	5.34 ± 0.88 ^{Aa}	5.16 ± 0.69 ^{Aab}	5.02 ± 1.40 ^{Abc}	4.72 ± 0.79 ^{Ac}
Taste	Control	5.72 ± 0.52 ^{Aa}	5.76 ± 0.93 ^{Aa}	5.30 ± 0.42 ^{Bab}	4.85 ± 0.62 ^{Bb}	3.96 ± 0.59 ^{Bc}
	HHP	5.88 ± 0.89 ^{Aa}	5.72 ± 0.73 ^{Aa}	5.28 ± 0.82 ^{Bab}	4.78 ± 0.82 ^{Bb}	3.82 ± 0.65 ^{Bc}
	MR + HHP	5.98 ± 0.75 ^{Aa}	5.66 ± 0.68 ^{Aa}	5.44 ± 0.71 ^{Aab}	5.02 ± 0.50 ^{Abc}	4.22 ± 0.88 ^{Ac}
Flavor	Control	5.54 ± 1.42 ^{Aa}	5.41 ± 0.23 ^{Aa}	4.63 ± 1.52 ^{Bb}	3.68 ± 1.24 ^{Bc}	3.08 ± 1.51 ^{Bd}
	HHP	5.56 ± 1.74 ^{Aa}	5.44 ± 1.42 ^{Aa}	4.56 ± 0.72 ^{Bb}	3.46 ± 0.52 ^{Bc}	3.06 ± 0.45 ^{Bd}
	MR + HHP	5.37 ± 0.95 ^{Aa}	5.26 ± 1.09 ^{Aa}	4.92 ± 0.79 ^{Aab}	4.62 ± 0.89 ^{Abc}	4.12 ± 1.79 ^{Ac}

Note: the experimental data were expressed as the mean ± SE. ^{a-d} Indicates with different lowercase letters in the same row differ significantly ($P < 0.05$); ^{A-C} Indicates with different uppercase letters in the same column for the same index differ significantly ($P < 0.05$). HHP, high hydrostatic pressure; MR + HHP, moisture regulator combined with high hydrostatic pressure.

of different treatments on volatile compounds of beef jerky can be obtained using a supervised PLS-DA model. As shown in Figure 3(A), two principal components explained 90.2% of the total variance. The control samples were clustered at the top of the score

plot, while the HHP and MR + HHP samples were clustered at the bottom of the score plot. To further identify the key compounds that affect beef jerky flavor, the variable importance projection (VIP) score was used, with the VIP value > 1 being defined as the key

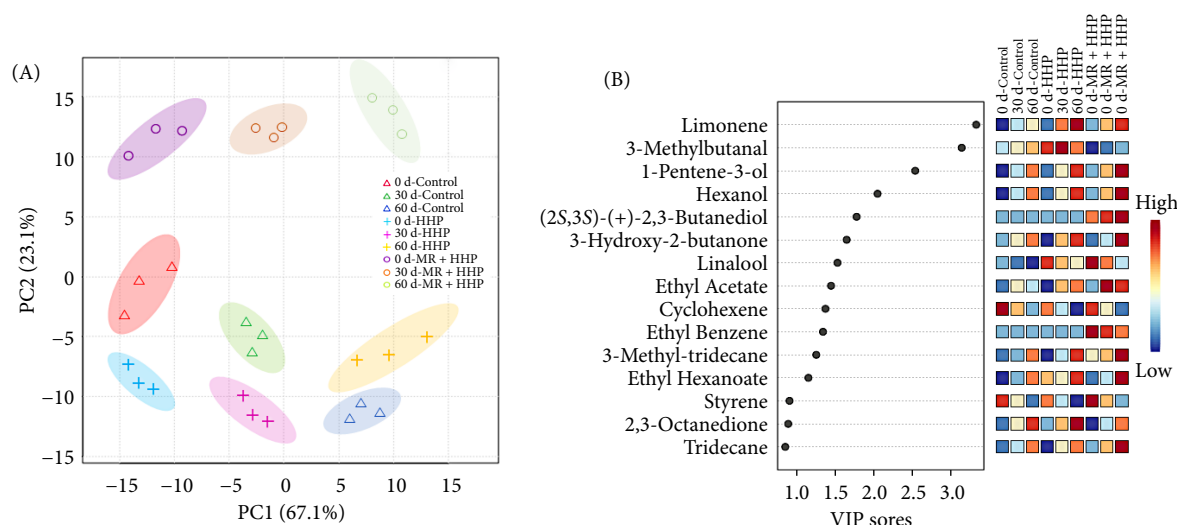


Figure 3 PLS-DA score plot of all volatile compounds (A) and variable importance projection (VIP) scores of top 15 volatile compounds (B) of beef jerky with different treatments at 0, 30, and 60 days. HHP, high hydrostatic pressure; MR + HHP, moisture regulator combined with high hydrostatic pressure.

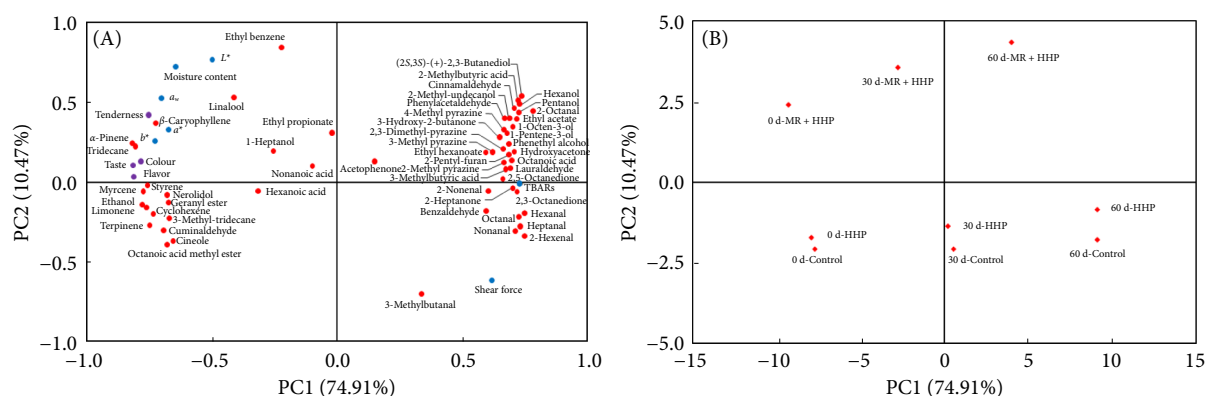


Figure 4 (A) PCA loading plot of physicochemical properties (blue circles), volatile compounds (red circles), and sensory characteristics (purple circles) of beef jerky. (B) PCA score plot of beef jerky with different treatments at 0, 30, and 60 days. HHP, high hydrostatic pressure; MR + HHP, moisture regulator combined with high hydrostatic pressure.

volatile compounds of beef jerky [51]. Twelve key differential volatile compounds (limonene, 3-methylbutanal, 1-pentene-3-ol, hexanol, (2S,3S)-(+)-2,3-butanediol, 3-hydroxy-2-butanone, linalool, ethyl acetate, cyclohexene, ethylbenzene, 3-methyl-tridecane, and ethyl hexanoate) had VIP score > 1 (Figure 3(B)). Therefore, these volatile compounds could be used as putative markers to distinguish different types of beef jerky. The contents of (2S,3S)-(+)-2,3-butanediol, 3-methyl-tridecane, and ethylbenzene were higher in the MR + HHP samples than in the control and HHP samples ($P < 0.05$), indicating that the MR + HHP samples have a higher odor threshold and contributes less to the overall flavor of beef jerky. The HHP and MR + HHP samples had higher contents of limonene, linalool, and ethyl acetate, with a low odor threshold than the control samples ($P < 0.05$), contributing floral and fruity odors to the beef jerky [52]. Limonene and linalool were mainly derived from the spices used in the beef jerky preparation [11].

3.7 Sensory analysis

The results of the sensory attributes of beef jerky were summarized in Table 3. From 0 to 15 days of storage, there were no significant differences in sensory attributes regardless of treatments ($P > 0.05$). With the increase of the storage times (30, 45, and 60 days), the sensory scores of all samples decreased significantly ($P < 0.05$), and

the MR + HHP samples had significantly higher sensory scores than the HHP and control samples ($P < 0.05$). Throughout the storage duration, MR + HHP samples had higher tenderness scores than the HHP and control samples ($P < 0.05$), which was consistent with the SF results (Figure 2(A)), indicating that the presence of the MR effectively enhanced the tenderness of beef jerky. It was discovered that the MR had no significant effect on the color, taste, and flavor of beef jerky at 0 days of storage ($P > 0.05$). In summary, the MR + HHP treatment delayed the sensory quality of beef jerky from deteriorating.

3.8 Principal component analysis (PCA)

The moisture content, a_w , TBARs value, shear force, L^* , a^* , b^* , sensory characteristics, and volatile compounds of beef jerky with different treatments and storage times were investigated using PCA (Figure 4(A)). The variance contribution rates of the first and second principal components (PCs) were 74.91% and 10.47%, respectively. PC1 was positively related to TBARs and most volatile lipid oxidation compounds, such as hexanal, nonanal, octanal, heptanal, phenylacetaldehyde, 2,5-octanedione, 2-heptanone, 3-hydroxy-2-butanone, 2,3-octanedione, and hydroxyacetone. Furthermore, PC1 was negatively related with the a^* value, b^* value, and volatile compounds such as myrcene, β -caryophyllene,

α -pinene, nerolidol, linalool, geranyl ester, and sensory parameters. The results of the three treatments with PC1 and PC2 as loading factors at different storage times are shown in Figure 4(B). The beef jerky stored for 60 days had the highest PC1 value, indicating that this parameter was related to lipid oxidation. In contrast, the beef jerky stored for 60 days was negatively correlated with the moisture content, and the beef jerky stored for 30 days was at an intermediate level. It is worth noting that the MR + HHP samples were closer to moisture content, whereas the control samples were closer to the SF for different storage times, confirming the importance of MRs in improving the tenderness of beef jerky. These were consistent with the results of sensory analysis (Table 3).

4 Conclusion

MR + HHP effectively increased the moisture content when the a_w of the beef jerky was maintained at approximately 0.7. During storage, the SF and TBARs values of the MR + HHP samples were significantly lower than those of the HHP and control samples, indicating that the MR + HHP treatment improved the tenderness and reduced the lipid oxidation of beef jerky. According to the sensory evaluation, the MR + HHP samples had higher tenderness, color, taste, and flavor scores than the control and HHP samples during storage. Thus, HHP combined with MR could be a viable solution for improving the quality of beef jerky and reducing the quality deterioration during storage.

Conflict of interest

The authors have no conflict of interest to declare.

Acknowledgments

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