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Research Article

Effects of Hydrocolloid Injection on the Eating Quality of Pork Analyzed Based on Low-Field Nuclear Magnetic Resonance (LF-NMR)

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This study investigated the effects of hydrocolloid injection on the eating quality of porcine meat based on low-field nuclear magnetic resonance (LF-NMR). The eating quality and water distribution of hydrocolloid-injected pork were compared with control, and the principle component analysis (PCA) was applied for the identification of hydrocolloid-injected pork. Total color difference (ΔE^*), cooking loss, and moisture content of hydrocolloid-injected pork were significantly increased compared with the control ($p < 0.05$). LF-NMR indicated that significant differences in the relaxation time and peak area proportion of immobilized water (T_{21}, P_{21}) and free water (T_{22}, P_{22}) were detected among hydrocolloid-injected samples and the control ($p < 0.05$). The first two principal components (PCs) of PCA accounted for 54.07% and 33.56% of the observed variation, respectively. Based on the two PCs, the hydrocolloid-injected pork could be differentiated from the control. Therefore, LF-NMR combined with PCA offers an effective method for the analysis and detection of hydrocolloid-injected pork.

1. Introduction

Ready-to-eat meat is widely consumed in China and Western countries in recent years. Some studies have shown that adding some edible hydrocolloids in ready-to-eat meat can produce some beneficial physiological functions such as decreasing blood fat and improving immunity [1] for people. Food hydrocolloids have been widely used in sausages and minced meat for improving their eating quality. In the process of ready-to-eat meat, hydrocolloids such as carrageenan and xanthan gum are usually used to improve the physicochemical properties (WHC and tenderness) and sensory parameters (cook yield) of it. Ma et al. [2] found that locust bean gum could improve WHC, cohesiveness, and hardness of meat muscle. Mohan and Singh et al. [3] reported that adding 0.25% kappa-carrageenan during the curing process of beef steak can increase the cook yield to 78.1% compared with the control group. Jridi et al. [4] reported that adding 1.5% gelatin in the raw sausage increased the water-holding capacity. However, above researches only studied the effect of a kind of hydrocolloid on the eating quality of meat products and whether the hydrocolloid types have different effects on the sensory and physicochemical properties of meat products; few researches have been carried out in this aspect, especially for ready-to-eat meat.

It is suggested that the addition of adequate quantity of hydrocolloids (such as carrageenan and xanthan gum) has favorable effects on ready-to-eat meat quality. But, manufacturers may be more concerned about the profits of ready-to-eat meat. Therefore, the condition of ready-to-eat meat adulteration or injecting hydrocolloid solutions to ready-to-

eat meat but not truthfully labeled may exist. Meanwhile, the color and appearance of the ready-to-eat meat were similar to those of the control. Therefore, it is hard for consumers to make good judgements by visual inspection or odor inspection. So, how to identify whether hydrocolloids has been injected to ready-to-eat meat with rapid and nondestructive way has become a hot research topic. Low-field nuclear magnetic (LF-NMR) as a new detection method can not only quickly and noninvasively detect the adulterated foods, which transverse relaxation time were relatively different with quality products, but also show the water distribution and the flow of water molecules through hydrogen proton resonance. LF-NMR has gained broad interests, which is used to assess food quality, probe food functionality, and detect food adulteration. Li et al. [5] demonstrated that low-field nuclear magnetic resonance combined with magnetic resonance imaging can rapidly and noninvasively detect and map adulterated prawns injected with different hydrocolloids. Santos et al. [6] reported that whey, urea, hydrogen peroxide, synthetic urine, and synthetic milk were added to the milk samples at concentrations of 5, 15, 25, 35, and 50% v/v. The result showed that LF-NMR could effectively discriminate milk adulteration. Therefore, LF-NMR has a potential to quickly and nondestructively identify hydrocolloid-injected meat.

The objective of this research was divided into two parts: first, studying the effects of different hydrocolloids on the eating quality of pork pieces; and second, exploring whether LF-NMR combined chemical analysis can quickly and nondestructively distinguish hydrocolloid-added ready-to-eat meat.

2. Materials and Methods

2.1. Preparation of Hydrocolloid Solutions

2.1.1. Preparation of Hydrocolloid Solutions at the Same Concentration. All hydrocolloids were purchased from Beijing Solarbio Technology Co., Ltd. Hydrocolloid solutions at the same concentration (0.3% w/v) were prepared by dissolving 0.3 g solid powders into 100 mL deionized water by heating method. Subsequently, the apparent viscosity (dividing shear stress by the shear rate at a certain velocity gradient) of hydrocolloid solutions were measured immediately after cooling to room temperature, and the data of apparent viscosity were obtained by Discovery DHR-1 TA rheometer (TA instrument, USA).

2.1.2. Preparation of Hydrocolloid Solutions at the Same Apparent Viscosity. The concentrations of different hydrocolloids for the injection were selected based on the apparent viscosity. All hydrocolloid solutions need to be reaching a certain required apparent viscosity so that hydrocolloid-injected meat pieces cannot be distinguished from normal samples by visual inspection and tactile examination. So the concentration of each hydrocolloid solution was measured by ensuring that the apparent viscosity of each hydrocolloid solution was close to the average value and fell within the standard deviation of the reference. Xanthan gum (0.45%, w/v), carrageenan (0.20%, w/v), agar (0.13%, w/v), and gelatin (1.4%, w/v) solutions were prepared separately by weighing 0.45 g xanthan gum, 0.20 g carrageenan, 0.13 g agar, and 1.4 g gelatin, and then dissolved in 100 mL deionized water by the heating method. Statistical results showed that the apparent viscosity values of different hydrocolloid solutions under the abovementioned conditions had a similar apparent viscosity ($p < 0.05$) (details in Table 1).

2.1.3. Measurement of Apparent Viscosity Values. Hydrocolloid solutions were thoroughly stirred before measurement, and approximately 3 ml of each solution was coated evenly on the test platform. Rheological parameters were set as follows: the temperature of test platform, 25°C; parallel plate diameter, 50 mm; and the range of shear rate, $0.1–100\ s^{-1}$.

2.2. Preparation of Pork Samples. Pork samples (*longissimus dorsi* muscles) were purchased from a local market. Fat and connective tissues that could be seen by naked eye on the surface of pork samples were removed; then, the *longissimus* muscles were cut into small pieces (length = 6.0 cm, width = 3.0 cm, and height = 4.0 cm) along the muscle direction. Subsequently, all pieces were divided into control group, water-injected group, and hydrocolloid-injected group. The control group was prepared without any treatment, while the water-injected and hydrocolloid-injected groups were separately injected with deionized water and hydrocolloid solutions which had the same apparent viscosity (the concentrations of xanthan gum, carrageenan, agar, and gelatin were 0.45%, 0.20%, 0.13%, and 1.40%, respectively). Moreover, for each sample of water-injected and hydrocolloid-injected pork, three sites were selected for injecting deionized water or hydrocolloid solutions. The distance between each site was 2.0 cm, and the depth of each site was 2.0 cm. The purpose of that was to acquire the uniform distribution of deionized water or hydrocolloid solutions in samples. Injected samples were allowed to drain and be reinjected to the targeted weight (the percentage was 105 ± 1 of the original weight) [3]. Following a 10-min rest period, injected samples were reweighed to ensure deionized water or hydrocolloid solutions were assimilated to achieve minimum 105% of the original weight [3]. Finally, all samples that contained evenly distributed water or hydrocolloid solutions were acquired.

2.3. Color Analysis. The color of pork samples was measured by CR-400 chromatic meter (Konica Minolta, Japan) before and after injection. The total color difference (ΔE^*) was calculated as follows [7]: $\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$. In the formula, $\Delta L^* = L_1^* - L_0^*$, $\Delta a^* = a_1^* - a_0^*$, and $\Delta b^* = b_1^* - b_0^*$. ΔL^*, Δa^* and Δb^* revealed the changes of L^*, a^*, and b^*, respectively. L_0^* (lightness/darkness), a_0^* (redness/greenness), and b_0^* (yellowness/blueness) indicated the color of porcine meat before injection, while L_1^*, a_1^*, and b_1^* represented the color after injection. The differences in ΔE^* were

Table 1: Concentration and corresponding apparent viscosity of each hydrocolloid solution before injected to meat pieces.

Hydrocolloid	Concentration (% w/v)	Apparent viscosity (Pa·s)
Water	—	0.23 ± 0.08^{e}
Aga	0.13	1.03 ± 0.15^{c}
	0.30	8.04 ± 075^{a}
Xan	0.30	0.68 ± 0.03^{d}
	0.45	1.12 ± 0.08^{c}
Car	0.20	1.08 ± 0.20^{c}
	0.30	2.96 ± 0.69^{b}
Gel	0.30	0.31 ± 003^{e}
	1.40	1.09 ± 0.19^{c}

Note. Values are the average of three independent experiments. Different superscripts indicate significant differences ($p < 0.05$).

divided into six levels according to the color difference class: 0–0.5 (trace), 0.5–1.5 (slight), 1.5–3.0 (noticeable), 3.0–6.0 (appreciable), 6.0–12.0 (much), and 12.0 (very much). The color of each sample was measured 5 times, and the average was used as the effective value.

2.4. Cooking Loss Measurement. The surface moisture of pork samples was absorbed by a filter paper; then, the weight of samples before cooking was recorded as m_1. Subsequently, the pork samples were placed in plastic bags and immersed in a water bath at 72°C for 60 min to reach an internal temperature of 70°C. After that, the samples were removed immediately and cooled to room temperature for weighing, and the weight was recorded as m_2. The cooking loss was calculated as follows:

$$\text{cooking loss } (\%) = \frac{(m_1 - m_2)}{m_1} \times 100. \quad (1)$$

2.5. Texture Determination. A sampler with 2.523 cm in diameter was used to acquire samples (diameter = 2.523 cm, height = 1.5 cm) along the vertical direction of the muscle fibers. The direction of myofibrils of samples paralleled to the probe surface when the texture of samples was measured by TA-XT2i texture analyzer (Stable Micro System, UK). The specific parameters were set as follows: pretest rate: 2.00 mm/s, mid-rate: 1.00 mm/s, posttest rate: 1.00 mm/s, compression ratio: 50%, 2 times between presses: 5.0 s, load capacity: 5.0 g, trigger type: auto, probe type: P50, and data collection rate: 200 pps.

2.6. Moisture Content Measurement. The moisture content of samples was measured by oven drying according to the method of AOAC [8]. Samples (approximately 5 g) were put into weighing bottles which were dried to a constant weight in advance. Then, the weighing bottles with samples were dried at 102°C in an electric thermostatic drying oven until the weight did not change.

2.7. Determination of Transverse Relaxation Time (T_2). T_2 of hydrocolloid-injected pork was determined using PQ001 low-field nuclear magnetic resonance analyzer (Shanghai Niumag Electronic Technology Co., Ltd.). The frequency and magnetic field of spectrometer were 0.5 T and 22 MHz, respectively. The magnet temperature was set at 32°C. Samples (length: 3 cm, width: 1 cm, and thickness: 1 cm) were obtained from each group after water injection or hydrocolloid injection. The testing samples were placed in nuclear magnetic tubes with the diameter of 15 mm, and then were heated in a 32°C water bath for 10 min. Subsequently, NMR tubes equipped with plugs were put into the magnet cavity of LF-NMR for acquiring T_2 relaxation characteristics which were measured by the Carr–Purcell–Meiboom–Gill (CPMG) sequence. Each sample was repeatedly measured 3 times and the average was used as the effective value. The repetition times between two successive scans was 3.5 s, and the value of τ (time between 90° and 180° pulse) was 150 μs. Data from 3000 echoes were acquired from 16 scan repetitions.

2.8. Statistical Analysis. All measurements were carried out in triplicate, and the average was taken as the effective value. The CPMG decay curves were processed by the NMR relaxation time inversion and fitting system (Niumag Co., Ltd., Shanghai, China) to obtain relaxation times, peak areas, and proportions of peak areas. Statistical analysis was performed by the ANOVA test using SPSS software (SPSS Statistics 19.0, IBM, Chicago, Illinois, USA), and Duncan's multiple range test was used to analyze the difference among control, and water-injected and hydrocolloid-injected groups ($p < 0.05$). Paired sample t-test was applied to analyze pork color before and after injection ($p < 0.05$). All data were expressed as the means ± SD values. PCA was carried out using SPSS 19.0. Diagrams were plotted using Origin 8.6 software.

3. Results and Analysis

3.1. Apparent Viscosity of Different Hydrocolloids

3.1.1. Apparent Viscosity of Different Hydrocolloids at the Same Concentration. Table 1 shows the apparent viscosity values of different hydrocolloids at the same concentration (0.3% w/v). Obvious differences in apparent viscosity values among different hydrocolloids could be observed. It had been calculated that the apparent viscosity value of the agar solution was 26 times higher than that of the gelatin solution, which illustrated that the apparent viscosity of different hydrocolloids at a constant concentration were quite different. Akhtar et al. [9] investigated the influence of the shear-thinning nature of a viscosity-controlling hydrocolloid system on the sensory perception of taste, thickness, and creaminess of model oil-in-water dairy emulsions. Maltodextrin and xanthan were used to adjust the apparent viscosity of the systems separately. It found that emulsions containing the two different hydrocolloids show distinctly different rheological behavior over the shear-rate range tested. The apparent viscosity of xanthan gum is significantly different from maltodextrin under the same shear rate. For ready-to-eat meat, which was injected with hydrocolloids,

the excessive apparent viscosity of hydrocolloid solutions might lead to an unnatural appearance. Therefore, the apparent viscosity of hydrocolloid solutions needed to be taken into account when hydrocolloids were added to meat products. A preexperiment of the apparent viscosity of hydrocolloids showed that the consumers preferred to choose the meat products that the added hydrocolloids had a moderate apparent viscosity (approximately 1.0 Pa·s). Thus, the paper investigated the influence of hydrocolloids at the same apparent viscosity on the eating quality of porcine meat. The concentrations of different hydrocolloids for the injection were selected based on the apparent viscosity.

3.1.2. Concentrations of Different Hydrocolloids at Same Apparent Viscosity Values. Table 1 shows the apparent viscosity values of different hydrocolloids. The apparent viscosity values of different hydrocolloids ranged from 1.03 Pa·s to 1.12 Pa·s, which was significantly higher than that of deionized water ($p < 0.05$). Moreover, no significant difference was observed among different hydrocolloids, meaning that these hydrocolloids had the similar fluidity ($p < 0.05$). Therefore, the values of 0.45% (w/v), 0.20% (w/v), 0.13% (w/v), and 1.40% (w/v) were chosen as the concentration of xanthan gum, carrageenan, agar and gelatin solutions, respectively. Sharma et al. [10] investigated the effect of selected hydrocolloids on the texture of pureed carrots. It turned out that the apparent viscosity values of three groups which separately added xanthan, carrageenan, and gelatin had no significant differences under the same rate, but the concentration of each sample was disparate obviously.

3.2. Effects of Different Hydrocolloids on the Eating Quality of Pork

3.2.1. Color. The results of the color analysis of pork samples are displayed in Table 2. Each row of the table shows the values of L^*, a^*, and b^* of porcine meat before and after the injection of hydrocolloids and the value of total color difference (ΔE^*). Statistical results revealed that no significant changes of L^*, a^*, and b^* of all groups were observed ($p > 0.05$). The value of ΔE^* of the control group was 0.56, and that of water-injected and all hydrocolloid-injected groups fluctuated in the range of 1.61~2.99. The color change of control group was described as "slight," and that of water-injected and all hydrocolloid-injected groups were classified as "noticeable" according to the color difference class [7].

Each column in Table 2 reveals the differences in L_0^*, a_0^*, b_0^*, L_1^*, a_1^*, b_1^*, and ΔE^* among control, water-injected, and all hydrocolloid-injected groups. In comparison with the control group, the values of L_0^*, a_0^*, b_0^*, L_1^*, a_1^*, and b_1^* of water-injected and all hydrocolloid-injected groups showed no significant differences, whereas the ΔE^*values of water-injected, gelatin-injected, and xanthan gum-injected groups increased significantly ($p < 0.05$). This may be due to the fact that the values of a^* were related to the concentration of myoglobin and the degree of myoglobin denaturation. Myoglobin is a kind of water-soluble protein that mainly distributed in the sarcoplasm of muscular fibers [11]. The number of myoglobin in the muscles might decrease with the loss of deionized water or hydrocolloid solutions after the injection of water or hydrocolloids, which caused ΔE^* difference of pork samples.

3.2.2. Texture Properties. The results of the texture properties of pork samples are displayed in Table 3. No significant changes were observed in gelatin group compared with the control, while the other groups changed significantly, which demonstrated that hydrocolloid types affected the taste of porcine meat. For xanthan gum, agar, and carrageenan groups, the values of hardness, gumminess, and chewiness increased significantly ($p < 0.05$). After the injection, the hardness of xanthan gum group, agar group, and carrageenan group increased 10.50%, 17.02%, and 11.23%, respectively; the gumminess increased 23.12%, 19.13%, and 19.97%, respectively; the chewiness increased 29.40%, 18.87%, and 24.79%, respectively. Ayadi et al. [12] studied the influence of carrageenan addition on the properties of Turkey meat sausages, explaining the increase of hardness and chewiness of carrageenan group might result from the interaction of carrageenan—muscle proteins.

3.2.3. Cooking Loss. As shown in Figure 1, the cooking loss of the control group was confirmed to be the lowest (22.05%). Water-injected and all hydrocolloid-injected groups revealed a greater cooking loss than the control ($p < 0.05$). However, there were no significant differences among all hydrocolloid-injected groups ($p > 0.05$), meaning that the cooking loss was not influenced by the types of hydrocolloids.

3.2.4. Moisture Content. As shown in Figure 2, the moisture contents of water-injected and all hydrocolloid-injected pork were significantly higher than those of the control group ($p < 0.05$), while no significant differences were observed between water-injected and all hydrocolloid-injected pork ($p > 0.05$). Moreover, the statistical results indicated that the moisture content was not affected by the types of hydrocolloids.

3.3. Study of the Water Distribution by LF-NMR. As shown in Figure 3, four peaks were observed in samples through the multiexponential fitting of the CPMG decay curves, which was similar to the spectra of hydrocolloid-injected prawns [5, 13]. Water in meat or meat products can be classified as follows: strongly bound water (water strongly bound to protein), weakly bound water (water weakly bound to protein), immobilized water (water trapped within myofibrils), and free water (water in the fluid surrounding the cell) in the light of fluidity differences [14, 15]. The relaxation times of these four peaks (as shown in Figure 3) were expressed as T_{2b} (0.1–1 ms), T'_{2b} (1–10 ms), T_{21} (10–100 ms), and T_{22} (100–1000 ms), which were considered as strongly bound water, weakly bound water, immobilized water, and free water, respectively [15]. The fastest fraction, the

Table 2: Effects of different hydrocolloids on color assessment of porcine meat.

	L_0^*	L_1^*	a_0^*	a_1^*	b_0^*	b_1^*	ΔE^*
Control	46.04 ± 3.50	45.91 ± 3.42	4.01 ± 0.91	4.25 ± 0.89	3.19 ± 0.30	3.61 ± 0.15	0.56 ± 0.12^a
Water	46.05 ± 2.83	48.19 ± 1.69	5.08 ± 1.07	5.02 ± 0.20	3.88 ± 1.29	4.11 ± 0.23	2.50 ± 1.11^b
Gel	45.74 ± 2.86	47.91 ± 2.70	4.00 ± 0.88	4.21 ± 1.01	3.33 ± 0.49	3.64 ± 0.79	2.26 ± 0.59^b
Xan	45.33 ± 0.87	48.13 ± 1.93	4.12 ± 0.80	4.07 ± 0.84	3.37 ± 0.34	3.38 ± 0.64	2.99 ± 1.13^b
Car	47.30 ± 3.72	47.85 ± 1.66	4.36 ± 0.47	4.43 ± 1.00	3.85 ± 0.91	3.81 ± 0.72	2.10 ± 0.34^{ab}
Aga	45.32 ± 1.24	46.71 ± 1.12	4.63 ± 0.17	4.57 ± 0.80	3.45 ± 0.63	3.13 ± 0.73	1.61 ± 1.07^{ab}

Note. Different uppercase letters in a row indicate significant differences between before and after injection ($p < 0.05$); different lowercase letters in a column indicate significant differences among different treatments ($p < 0.05$).

Table 3: Effects of different hydrocolloids in intramuscular injection on texture properties of porcine meat.

	Hardness	Springiness	Cohesiveness	Gumminess	Chewiness	Resilience
Control	13856.30 ± 808.79^a	0.57 ± 0.00	0.61 ± 0.02	8388.77 ± 506.73^a	4669.10 ± 488.65^a	0.24 ± 0.01
Xan	15311.26 ± 1258.57^b	0.58 ± 0.02	0.62 ± 0.03	10327.84 ± 1087.19^b	6041.83 ± 797.63^b	0.25 ± 0.01
Gel	13086.60 ± 567.12^a	0.53 ± 0.05	0.62 ± 0.02	8087.66 ± 291.38^a	4288.44 ± 405.76^a	0.24 ± 0.01
Aga	16214.69 ± 434.65^b	0.55 ± 0.03	0.62 ± 0.01	9993.90 ± 441.76^b	5550.35 ± 339.76^b	0.24 ± 0.00
Car	15412.77 ± 1001.57^b	0.58 ± 0.03	0.62 ± 0.01	10064.35 ± 597.71^b	5826.92 ± 232.80^b	0.24 ± 0.00
Water	15475.39 ± 474.64^b	0.57 ± 0.00	0.63 ± 0.01	9778.07 ± 472.32^b	5550.31 ± 175.39^b	0.24 ± 0.01

Note. Different superscripts in a row indicate significant differences ($p < 0.05$).

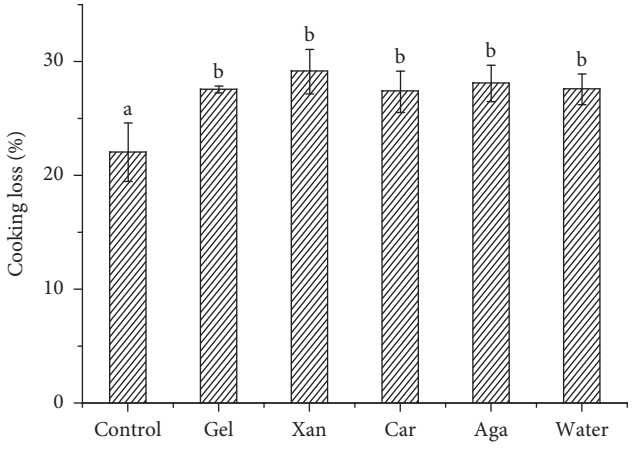

Figure 1: Effects of different hydrocolloids in intramuscular injection on the cooking loss of porcine meat.

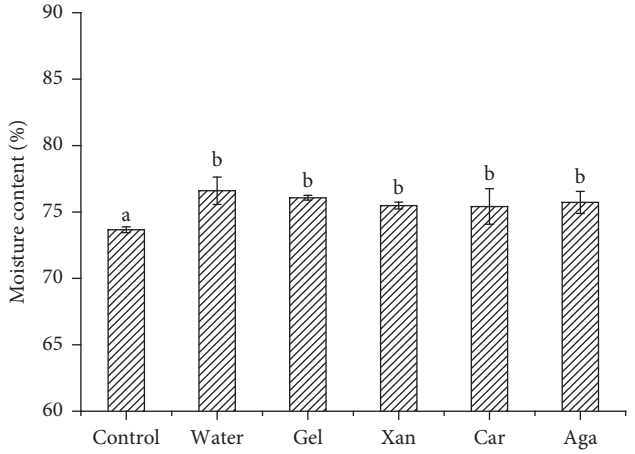

Figure 2: Effects of different hydrocolloids in intramuscular injection on the moisture content of porcine meat.

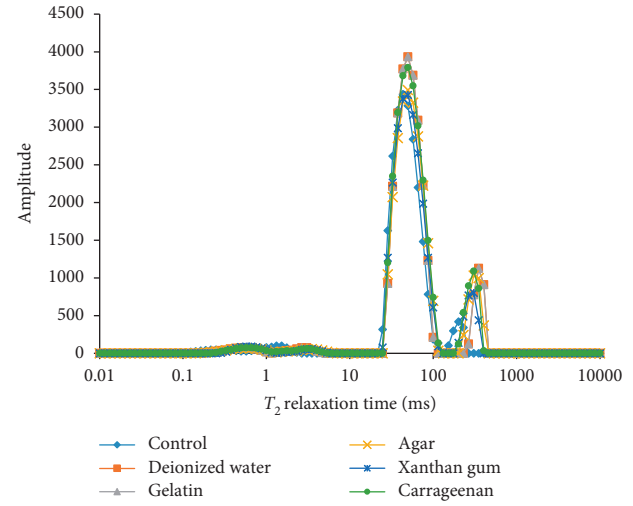

Figure 3: Distribution of multiexponentially fitted T_2 relaxation time spectra of normal, water-injected, and hydrocolloid-injected pork.

relaxation times within the range of 0–10 ms included two peaks (T_{2b} and T'_{2b}), captured about 5 percent of the total signal. T_{21}, the major fraction, the relaxation time within the range of 30–60 ms, captured 80 percent of the total signal; and T_{22}, the slowest fraction, the relaxation time within the range of 100–400 ms, captured 15 percent of the total signal [16, 17].

T_2 relaxation times of pork samples are displayed in Table 4. No remarkable differences could be observed for the T_{2b} and T'_{2b} values of all hydrocolloid-injected pork samples compared with the control group, which illustrated that the strongly bound water and the weakly bound water were not affected by the treatment of hydrocolloid injection. Moreover, both T_{21} and T_{22} values of all hydrocolloid-injected groups were significantly increased ($p < 0.05$), suggesting the

Table 4: Effects of different hydrocolloids in intramuscular injection on T_2 relaxation times of water molecules in porcine meat.

	Control	Xan	Car	Gel	Aga	Water
T_{2b}	0.35 ± 0.10	0.39 ± 0.09	0.45 ± 0.04	0.47 ± 0.02	0.47 ± 0.09	0.45 ± 0.09
T'_{2b}	1.80 ± 0.39^{a}	2.28 ± 0.38^{ab}	2.38 ± 0.62^{ab}	2.98 ± 0.78^{ab}	2.68 ± 0.47^{ab}	3.15 ± 0.85^{b}
T_{21}	43.29 ± 0.00^{a}	47.61 ± 2.16^{b}	48.19 ± 0.76^{bc}	49.05 ± 1.25^{bc}	48.57 ± 1.10^{bc}	50.60 ± 1.43^{c}
T_{22}	212.07 ± 13.51^{a}	265.29 ± 19.82^{b}	286.52 ± 9.07^{b}	340.58 ± 22.68^{c}	290.88 ± 11.43^{b}	292.24 ± 1.82^{b}

Note. Different superscripts in a row indicate significant differences ($p < 0.05$).

Table 5: Effects of different hydrocolloids in intramuscular injection on the proportion of peak area of water molecules in porcine meat.

	Control	Xan	Car	Gel	Aga	Water
P_{2b}	2.27 ± 0.22^{a}	2.07 ± 0.20^{ab}	1.83 ± 0.24^{b}	2.24 ± 0.28^{ab}	2.16 ± 0.16^{ab}	2.02 ± 0.18^{ab}
P'_{2b}	1.79 ± 0.20^{a}	1.40 ± 0.31^{b}	1.28 ± 0.09^{b}	1.22 ± 0.20^{b}	1.16 ± 0.17^{b}	1.06 ± 0.12^{b}
P_{21}	91.41 ± 0.66^{a}	86.35 ± 2.21^{b}	85.79 ± 1.22^{b}	84.83 ± 2.98^{b}	86.51 ± 2.20^{b}	84.07 ± 2.08^{b}
P_{22}	4.27 ± 0.84^{a}	9.71 ± 2.52^{b}	10.52 ± 1.48^{b}	11.36 ± 3.11^{b}	9.83 ± 2.37^{b}	12.32 ± 2.36^{b}

Note. Different superscripts in a row indicate significant differences ($p < 0.05$).

mobility of immobilized and free water was increased [5]. The comparison of hydrocolloid-injected groups and water-injected group indicated that T_{21} values of the xanthan gum group were obviously lower than that of water-injected group ($p < 0.05$), while T_{22} values of the gelatin group were significantly higher than that of the water-injected group ($p < 0.05$). Furthermore, the comparison among different hydrocolloids showed that the T_{22} values of the gelatin group were significantly higher than those of xanthan gum, carrageenan, and agar groups ($p < 0.05$), illustrating that the relaxation time was influenced by different hydrocolloids.

The peak area proportions of different groups are shown in Table 5. It could be seen that P_{2b}, P'_{2b}, P_{21}, and P_{22} of all groups shared 1.83–2.27%, 1.06–1.79%, 84.07–91.41%, and 4.27–12.32% of total peak areas, respectively. Compared with the control group, P_{2b}, P'_{2b}, P_{21}, and P_{22} of hydrocolloid-injected group changed 0.11–0.44%, 0.39–0.63%, 4.90–6.58%, and 5.44–7.09%, respectively. It was obvious that P_{21} and P_{22} changed significantly after hydrocolloid injection. The values of P_{21} of all hydrocolloid-injected groups were significantly lower than that of control group ($p < 0.05$), while P_{22} increased significantly ($p < 0.05$), meaning that the injection of hydrocolloid solutions improved the water content of free water. In addition, the effect of hydrocolloid types on the peak area proportion of hydrocolloid-injected pork could be neglected, since no significant difference was discovered in P_{2b}, P'_{2b}, P_{21}, and P_{22}.

3.4. Adulteration Analysis of Pork Samples by PCA Method. In order to identify the hydrocolloid-injected pork from the control, LF-NMR data were processed by the PCA method. The purpose of the PCA method was to reduce the dimensionality of the NMR data set with a large number of intercorrelated variables and retained as much of the original data as possible at the same time [18]. The scores of scatter plots of PCA were calculated by LF-NMR data to identify possible differences among pork samples. The scatter plots of the control, water-injected, and hydrocolloid-injected pork groups are shown in Figure 4.

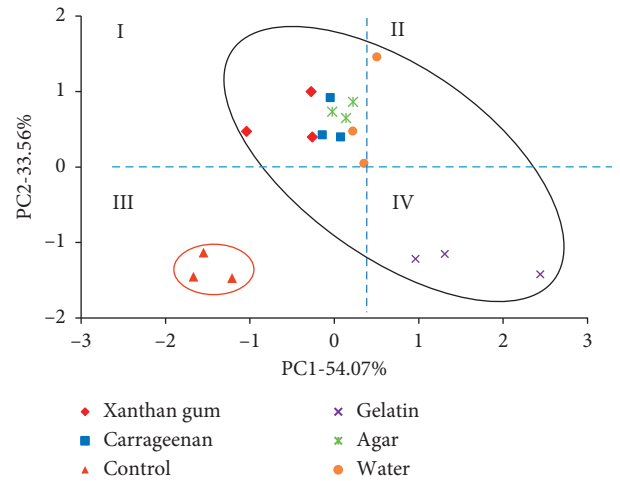

Figure 4: PCA scores for pork samples injected with different hydrocolloid solutions.

The results indicated that two significant components that totally explained 87.63% of the total variance were obtained. Factor 1 and factor 2 explained 54.07% and 33.56% of the total variance, respectively. As shown in Figure 4, the dot set of the control group was distributed in Part III, and gelatin group was clustered in Part IV, while xanthan gum, carrageenan, agar, and water groups were gathered at the border of Part I and Part II. This illustrated that hydrocolloid-injected pork could be clearly differentiated from the control based on the difference of LF-NMR data. The overlapping regions in the scatter plot map might be attributable to the similarity in water distribution of the pork samples. Overall, the results proved that LF-NMR combined with the PCA method could tell apart hydrocolloid-injected pork from the noninjected.

4. Conclusion

In this paper, the effects of different hydrocolloid solutions on the eating quality of porcine meat were studied based on LF-NMR. The results showed that the total color

difference (ΔE^*), cooking loss, and moisture content of porcine meat were significantly increased after the injection of hydrocolloid solutions ($p < 0.05$). Texture analysis indicated that the hardness, gumminess, and chewiness of porcine meat were affected by the injection of different hydrocolloids. Four distinct peaks corresponding to strongly bound water, weakly bound water, immobilized water, and free water in hydrocolloid-injected pork were observed by LF-NMR. The relaxation time of immobilized water increased after the injection of hydrocolloids, while the peak area proportion decreased significantly ($p < 0.05$). In addition, the relaxation time and peak area proportion of free water increased significantly when injecting hydrocolloids into pork ($p < 0.05$). PCA results showed that hydrocolloid-injected pork could be successfully distinguished from the control. In summary, LF-NMR combined with PCA can be used as an effective method for the analysis and detection of hydrocolloid-injected pork.

Data Availability

The data used to support the findings of this study are included within the article.

Disclosure

Shengmei Gai and Zhonghui Zhang are co-first authors.

Conflicts of Interest

There are no conflicts of interest regarding the publication of this article.

Acknowledgments

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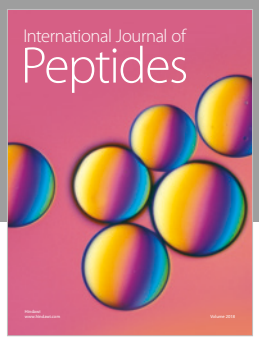

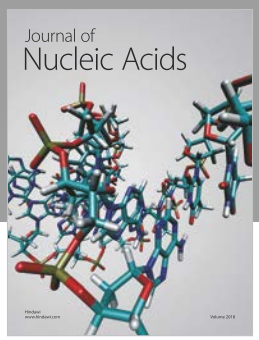

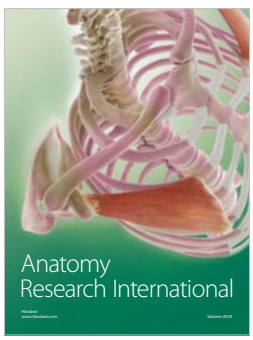

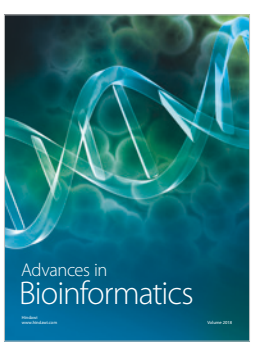

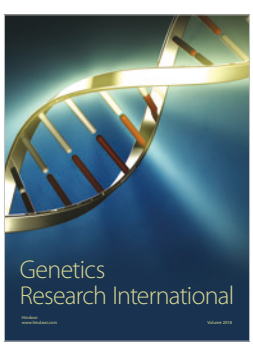

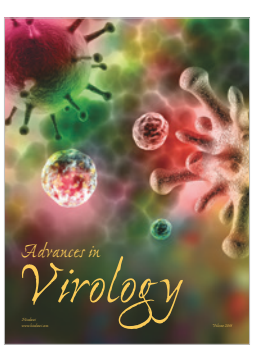

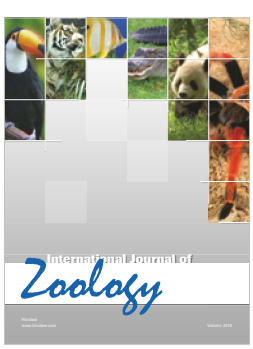

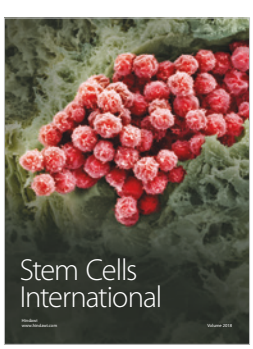

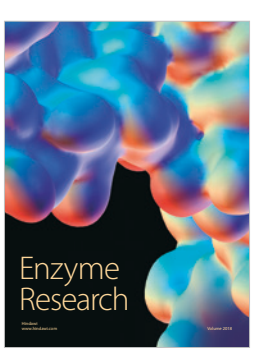

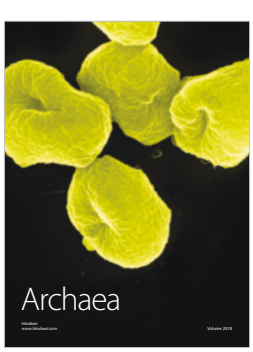


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