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Comprehensive analysis of the effects of cooking conditions on the quality, sensory characteristics, and flavor profile of glutinous rice chicken, a Chinese traditional poultry meat product

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ABSTRACT

This study investigated the effects of cooking conditions on cooking loss, texture, and sensory attributes of glutinous rice chicken (GRC), a popular Chinese poultry dish. We compared the nutritional and sensory profiles of GRC prepared under optimal conditions (GRC-OP) with those of a commercial product (CG). Cooking time, power, and pressure significantly affected the shear force, hardness, and sensory qualities of GRC. The optimal parameters were determined using an orthogonal design: 20 min cooking time, 1000 watts power, and 60 kPa pressure. Gas chromatography/mass spectrometry and *E*-nose analyses showed that GRC-OP had a volatile profile similar to that of CG but with higher levels of specific compounds, including heptanal, 2-heptenal, octanal, hexanol, octanol, and 1-nonen-4-ol. GRC-OP also exhibited superior umami, salty, and rich tastes, and higher amino acid content, particularly Asp, Glu, Thr, Ser, Ala, Val, Met, and Ile. These findings provide crucial data for optimizing the quality and nutritional value of GRC in the meat industry.

1. Introduction

Poultry meat and products are rich in nutrients such as proteins, minerals, and vitamins, which are an indispensable part of the daily diet. According to previous studies (Przybylski et al., 2021; Xu et al., 2023), the cholesterol and saturated fatty acid contents in poultry meat are lower than those in red meat because of its low price, high nutritional value, and favorable sensory characteristics (Biswas et al., 2019; Goethals et al., 2019). Poultry meat and poultry products have attracted increasing attention from consumers. Glutinous rice chicken (GRC), a traditional meat product of the Yanbian Korean nationality, is highly regarded by consumers owing to its palatable taste and distinctive qualities. GRC is a Korean diet made by steaming and cooking rural free-range chicken and glutinous rice as the main processing materials and adding ingredients such as nourishing ginseng, red dates, and wolfberries. In addition to the oily aroma of chicken, diners can perceive the soft, waxy, and refreshing tastes of the other ingredients. Consequently, GRC can fulfill the gustatory needs of consumers and provide nutritional supplementation, representing a highly representative dietary option within traditional Korean culinary traditions. Most GRC products are produced through a traditional process that lacks standardization of processing technology. This often results in uneven quality of the final product with a high degree of yield instability, which in turn leads to a significant amount of waste in the production process.

Abbreviations: DBC, Dezhou braised chicken; *E*-nose, electronic nose; E-tongue, electronic tongue; FAA, free amino acid; FRCC, Chinese Fuliji red-cooked chicken; GRC, glutinous rice chicken; HS, headspace; SPME, solid-phase microextraction; TPA, texture profile analysis.

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The traditional manufacturing steps of GRC include steaming and cooking with rural free-range chicken and glutinous rice as the main processing materials, and adding ingredients such as nourishing ginseng, red dates, and wolfberries. The quality of cooked meat, particularly its flavor, is significantly affected by factors such as temperature and heating time (Yao et al., 2023). The cooking temperature and time are crucial factors in product processing because they significantly affect protein oxidation and denaturation. It is important to note that these factors should be carefully controlled to ensure optimal product quality. Subjecting chicken protein hydrolysate to temperatures above 60 °C for 20 min results in complete elimination of the >10,000 Da fraction (Cui et al., 2009), indicating extensive protein degradation. Similarly, in beef broth, free amino acids decrease at temperatures above 75 °C and cooking times exceeding 120 min (Pereira-Lima et al., 2000). Furthermore, longer cooking times lead to increased levels of glutamic acid, aspartic acid, lysine, and methionine, all of which are strongly associated with flavor. Thus, heat treatment affects protein degradation and hydrolysis, which significantly alters the flavor of meat products during processing. Xiong et al. (2020) evaluated the taste profile of traditional Chinese Fuliji red-cooked chicken (FRCC) in different processing steps, including raw, frying, stewing, vacuum packaging, and sterilization, by measuring sodium chloride (NaCl), sugar, free amino acids (FAAs), nucleotides, and flavor. Yao et al. (2022) used the headspace gas chromatography-ion mobility spectrometry (HS-GC-IMS) technique to identify the main volatile substances formed during the processing of Dezhou braised chicken (DBC). Zhu et al. (2019) also investigated the effects of cooking temperature (75, 80, 85, 90, 95, and 100 °C) and cooking time (10, 20, 30, 40, 50, 60, 90, and 120 min) on protein degradation, protein oxidation, and flavor formation in stewed chicken meat. Although many studies have been conducted on the quality characteristics and processing technologies of chicken products, both domestically and internationally, few have focused on optimizing the processing technology and quality of traditional Chinese GRC.

In this study, traditional processing technology for GRC was employed in conjunction with a pressure cooker. By controlling the cooking time, cooking temperature, and cooking pressure during the cooking process, a single-factor test was performed to investigate the influence of cooking conditions on the physicochemical properties and sensory evaluation of GRC, and an orthogonal test was conducted to obtain the optimal conditions. In addition, the aroma compounds of GRC were investigated and compared using HS-SPME-GC/MS, electronic nose, and electronic tongue methods. Based on the results, theoretical guidance can be provided for the realization of standardized, large-scale, and industrialized production of GRC products.

2. Materials and methods

2.1. Sample preparation

A simplified schematic of the study is shown in Fig. 1. Native chickens at 42 days of age and purchased from Yanji West Market (Yanji, Jilin, China) were used in this study. Briefly, qualified slaughtered native chickens were selected and dehaired, and the internal organs, bursa of Fabricius (chicken tip), and fat blocks were removed, followed by cleaning with distilled water. Subsequently, 2500–3000 mL of distilled water was poured into a pressure cooker, after which clean native chicken (approximately 2000 g–2500 g) was added. Additionally, 30 g of scallion, 20 g of onion, 10 g of ginger, 10 g of garlic, and 1 g of astragalus root were added to the pressure cooker, and cooked in an induction cooker at high heat (power 1600 W–2100 W) until boiling, and then cooled to low heat (500–1400 W). Glutinous rice was purchased from the Yanji West Market (Yanji, Jilin, China). The glutinous rice was washed and soaked in cold water for 3 h. Subsequently, the following ingredients were added to the pot: 850 g of glutinous rice, 30 g of red dates, 1 g of astragalus, 1 g of walnuts, 15 g of raisins, 7 g of dried cranberries, and 2 g of dried blueberries. Subsequently, 1300 g of chicken stock and steam were added for 35 min. Subsequently, the glutinous rice was stirred thoroughly. The final step in preparing the GRC was to place the cooked chicken on top of the glutinous rice. Chicken meat was bonded, ground, and sampled at a chicken-to-rice weight (7:4). Partial freezing of samples from the GRC to −80 °C was performed for the determination of nutrient content, *E*-nose, E-tongue, FAAS, and volatile flavor compounds. The remaining samples were used for texture profile analysis (TPA) and cooking loss measurements.

2.2. Single-factor and orthogonal experiments

A one-factor test program was developed based on cooking time, power, and pressure: (a) The cooking power was set at 1000 W (140 °C) and the cooking pressure was set at 70 kPa, and the effects on sensory quality, cooking loss, shear force, and texture of GRC were investigated when the cooking time was 15 min, 20 min, 25 min, 30 min, and 35 min. (b) The cooking time was set to 25 min and the cooking pressure was 70 kPa, and the effects on sensory quality, cooking loss, shear force, and texture of GRC were investigated when the cooking power was 500 W (100 °C), 800 W (120 °C), 1000 W (140 °C), 1200 W (160 °C), and 1400 W (180 °C). (c) The cooking time was set to 25 min and the cooking power was set to 1000 W (140 °C), and the effects on sensory quality, cooking loss, shear force, and texture of GRC were investigated when the cooking pressure was 50 kPa, 60 kPa, 70 kPa, 80 kPa, and 90 kPa.

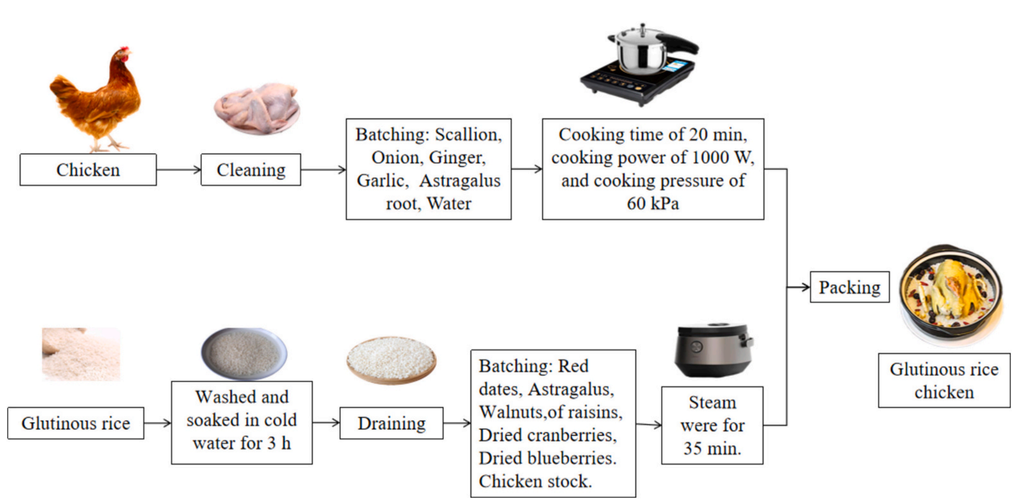

Fig. 1. Simplified schematic diagram of the preparation of glutinous rice chicken.

Table S1 lists the orthogonal test factors and their corresponding levels. Based on the results of the one-way test, three factors–cooking time (A), cooking power (B), and cooking pressure (C)–were selected for the L_9 (3^3) orthogonal test using the sensory composite score as the criterion.

2.3. Sensory evaluation

Sensory evaluation was performed by 10 trained and experienced professionals (five males and five females, aged 20–30 years) from the Food Research Centre of Yanbian University. The appearance, color, texture, smell, taste, and overall acceptability of the dishes were evaluated according to the Chinese national standards (QB/T 5471-2020). The scores for each aspect range from 1 to 20, with 20 being the best and 1 being the worst. The highest score for the sensory evaluation of the GRC products was 100. The sensory scoring standards are listed in Table S2.

Individuals participating in the sensory experiment were informed of the protocol and volunteered to participate. Before this study, the sensory analysis was approved by the College of Agriculture, Yanbian University, and all participants provided informed consent. All participants' rights and privacy were well protected, and consent was obtained for the collection and use of their personal information and related experimental data.

2.4. TPA

The TPA of each sample was measured using a texture analyzer (TMS-PLUS, FT, US) equipped with a 12.7 mm flat cylindrical probe. The samples were cut into cubes (1 × 1 × 1 cm) along the direction of the muscle fibers. The test speed was set to 4.0 mm/s, and the post-test speed was the default test speed in TPA mode. The trigger force was 0.07 N, and two consecutive cycles of 40 % compression were performed with 6 s between cycles. Shear force, hardness, springiness, cohesiveness, gumminess, and chewiness were recorded.

2.5. Cooking loss

The cooked samples were drained of excess liquid using a plastic net and weighed individually. Cooking loss was calculated as the weight difference between the uncooked and cooked samples and expressed as g/100 g. The average cooking loss value ($n = 3$) was then calculated and presented as the mean ± standard error.

2.6. Moisture, protein, fat, and sodium chloride contents

The moisture, protein, and sodium chloride contents of the GRC were measured according to the national standards GB5009.3-2016, GB5009.44-2016, and GB5009.5-2016, respectively. The fat content was determined according to the method described by Auriema et al. (2021) with the following modifications. Chicken meat (2 g) was added to 25 mL of trichloromethane-methanol solution (2:1, *v*/v) and homogenized for 1 min, after which 15 mL of trichloromethane-methanol solution was added, mixed well, and allowed to stand for 1 h before filtration. To the obtained filtrate, 8.8 mL of a mixed solution containing 7.3 g/L NaCl and 0.5 g/L $CaCl_2$ was added. The mixture was then centrifuged at 3000*g* for 15 min. The liquid at the top was discarded. The remaining liquid fraction was evaporated using a rotary evaporator and dried to a constant weight under a vacuum. The fat content was determined as the difference in weight between the flasks before and after spin distillation.

2.7. Volatile flavor compound analysis

The volatile flavor compounds in GRC were determined using solid-phase microextraction (SPME). This method was based on that described by Bi et al. (2021), with minor modifications. Volatile compounds were extracted from the headspace (HS) of the bacon samples by using SPME fiber (Shimadzu Corporation, Kyoto, Japan) coated with a 75 μm layer (Supelco, Bellefonte, PA, USA) of (DVB/CAR/PDMS). Two grams of the sample were transferred to a dedicated headspace vial, and the gas was equilibrated at 25 °C room temperature for 15 min. The sample was then extracted using a 75 μm PDMS/DVB fiber tip in a sand bath at 60 °C for 30 min.

Gas-phase conditions: Volatile substances were separated using a capillary column DB-5MS 30 m 0.25 mm, film thickness of 0.25 μm (Agilent Technologies, Santa Clara, CA, USA). The SPME fiber was desorbed and maintained in the injection port at 280 °C during the whole chromatographic run. The carrier gas was helium at 18.5 psi, resulting in a flow of 1 mL/min at 40 °C. The oven temperature was held at 40 °C for 3 min, increased from 40 °C to 120 °C at 5 °C/min, held at 120 °C for 5 min, and then increased from 120 °C to 230 °C at 10 °C/min with a final hold time of 5 min. Mass spectrometry conditions: MS operated in electron impact mode at an electron impact energy of 70 eV and 200 °C with an interface temperature of 280 °C and a collected data rate of 1 scan s-1 over a range of m/z 30–550. Compounds were characterized by searching the NIST08 and NIST08s spectral libraries, and for compounds with a qualitative match of >80, the relative content was calculated using the normalization method.

2.8. Electronic nose (E-nose) analysis

E-nose analysis (PEN3; Airsense, Germany) of the GRC was performed as described by You et al. (2023) with slight modifications. Briefly, approximately 5 g of meat was placed in a 20 mL clean *E*-nose injection vial, sealed, and gas-equilibrated for 15 min. The *E*-nose detection experiments were conducted with the following parameters: flush time, 120 s; sample preparation time, 5 s; detection time, 60 s; internal flow rate, 200 mL/min; and inlet flow rate, 200 mL/min. The *E*-nose contains 10 single-thick-film metal oxide sensors: W1C, W5S, W3C, W6S, W5C,W1S, W1W, W2S, W2W, and W3S. The results are reported as the average of three replicates.

2.9. Electronic tongue (E-tongue) analysis

The taste properties of GRC were determined using an E-tongue system (SA-402B; Insent, Tokyo, Japan). The method described by Lee et al. (2019) was used with slight modifications. About 9 g of meat sample was added to 90 mL of distilled, followed by homogenization and centrifugation at 4 °C, 10000*g* for 10 min. The supernatants were obtained from the samples and filtered. A sample measurement program (two-step wash) was used to determine the five tastes: umami, salty, sour, bitter, and astringent. Each group was replicated three times and each replicate was measured four times in parallel.

2.10. FAAs

The sample (3 g) was weighed, 30 mL of deionized water was added, homogenized in an ice bath for 1 min, and centrifuged at 10000*g* for 30 min at 4 °C. The supernatant was filtered. Ten milliliters of the filtrate were added to 20 mL of 4 % TCA and incubated at 37 °C for 30 min. The supernatant was collected and assayed on a 0.45 μm organic filter membrane. The whole process was performed at 0–4 °C. FAA were determined using an automated amino acid analyzer (L-8800, Hitachi, Tokyo, Japan).

2.11. Data analysis

The test data were categorized using Excel, and a one-way analysis of variance (ANOVA) was performed using SPSS 27 for GRC volatile flavors. Statistical significance was set at $p < 0.05$. At least three independent replicates were performed for each experiment, and the results were expressed as mean ± standard deviation (SD).

3. Results and discussion

3.1. Results of single-factor experiments

3.1.1. Effect of cooking time on cooking loss, TPA, and sensory quality of GRC

The effect of cooking time on the sensory properties of GRC is shown in Fig. 2A. As the cooking time increased, the sensory scores of GRC increased significantly at the beginning of 25 min and then decreased for cooking times longer than 25 min. At 15, 20, and 25 min, GRC had a delicate taste and better appearance than the others. When the cooking time was more than 25 min, the structure of the GRC began to loosen, and the meat became rotten, with deterioration of the texture. An insufficient cooking time prevents chicken proteins from being fully denatured, resulting in poor quality. However, overcooking negatively affects the tissue structure and flavor (Ge et al., 2021). Extended cooking times and high-temperature cooking can lead to the denaturation and decomposition of chicken proteins, respectively, which can negatively affect the quality of the final products (Boob et al., 2019). Table 1A shows the cooking loss and TPA of the GRC at different cooking times. The cooking loss of chicken meat gradually increased, reaching a maximum of 23.46 % at 30 min, and then decreased slightly to 23.16 % at 35 min. Similar findings were reported by Park et al. (2020), who found that a longer cooking time may contribute to higher cooking loss. Moreover, the shear force and hardness exhibited an overall increasing trend and then decreased after 30 min. There were no significant changes in springiness, cohesiveness, gumminess, or chewiness ($p < 0.5$). Based on sensory evaluation, the optimal cooking time for GRC was estimated to be between 15 and 25 min. Therefore, cooking times of 15, 20, and 25 min were selected for optimization in this study.

3.1.2. Effect of cooking power on cooking loss, TPA, and sensory quality of GRC

Fig. 2B shows the effect of cooking power on the sensory evaluation of GRC. As the cooking power increased from 800 to 1000 W, the GRC sensory scores exhibited a slight decline from 800 W to 1000 W. However, they generally demonstrated an upward trend, reaching a maximum value of 76.63 at 1200 W. GRC cooked at 500 W of cooking power had a lower sensory score, probably because of the lower temperature in the center of the chicken (Ma et al., 2023), which made it less palatable. The results showed that the sensory quality of chicken increased with a corresponding increase in cooking power, and the overall sensory quality score showed an increasing and then a decreasing trend. Table 1B shows the cooking loss and TPA of GRC at different cooking power levels. The cooking loss appeared to remain relatively stable when the cooking power was between 500 and 1000 W. However, it increased significantly above 1000 W, reaching a maximum of 23.28 % at 1400 W. There was no significant difference in cooking loss when the cooking power was 1200 W and 1400 W. The rate of cooking loss is a crucial indicator of the muscle water-holding capacity (WHC). When proteins are in a tight state, they have a limited capacity for network space, which results in low WHC. Conversely, when proteins in the expanded state have a large network space, this results in an enhanced WHC (Nawaz et al., 2019). In the current study, moisture loss occurred in GRC samples as a result of heated cooking, which agrees with the results of Pang et al. (2020), who indicated that during cooking, myosin and actin denatured and expelled the sarcoplasmic fluids from the muscle fibers, together with shrinkage of the perimysium, resulting in water loss from the meat tissue. Moreover, the shear force tends to increase, and the shear force of 1000 W–1400 W is significantly higher than that of 500 W and 800 W. And the hardness value of chicken meat first decreased and then increased with increasing cooking power, followed by a slight decrease at 1200 W. However, gumminess tended to decrease and then increase to a maximum at 1000 W, and there were no significant differences in springiness, cohesiveness, shear, and chewiness. In conclusion, the optimum cooking power was selected for

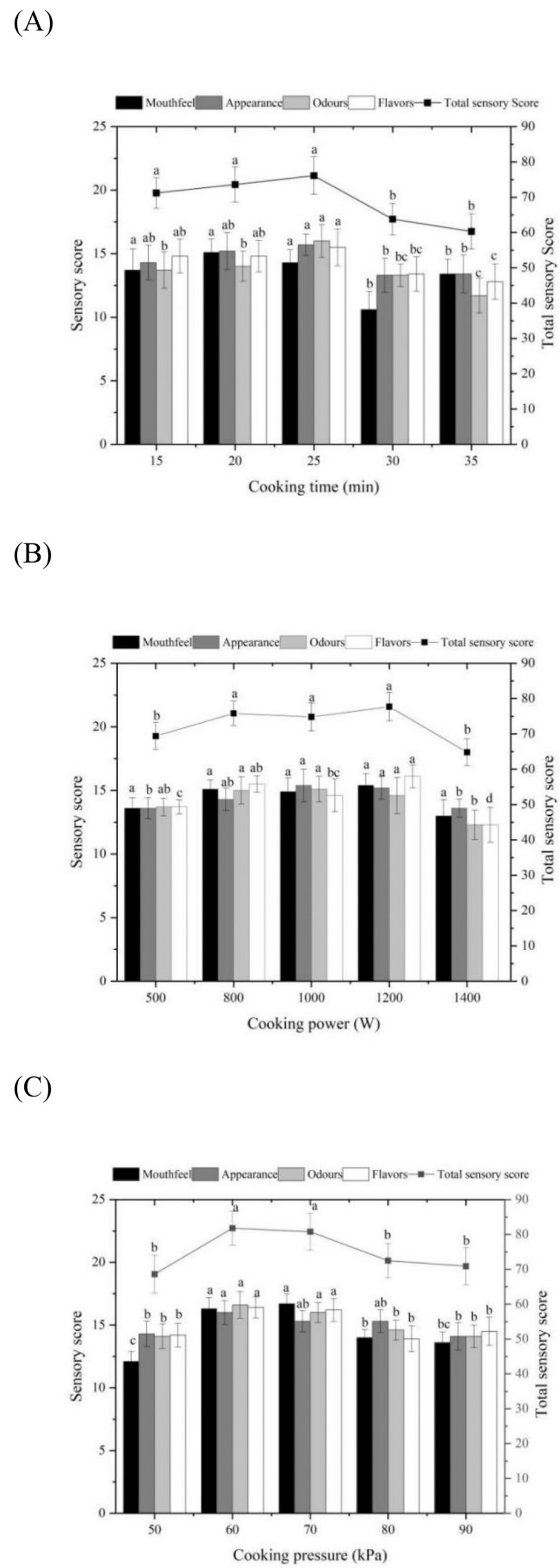

Fig. 2. Sensory score of GRC with different cooking parameters. (A) Sensory score of GRC with different cooking times. (B) Sensory score of GRC with different cooking powers. (C) Sensory score of GRC with different cooking pressures.

Table 1
(A) Texture profiles and cooking loss of GRC at different cooking times. (B) Texture profiles and cooking loss of GRC at different cooking powers. (C) Texture profiles and cooking loss of GRC at different cooking pressures.

(A)

Project	15 min	20 min	25 min	30 min	35 min
Shear force/N	45.13 ± 1.94^{c}	47.94 ± 1.83^{bc}	51.78 ± 1.72^{ab}	53.07 ± 2.62^{a}	49.33 ± 2.62^{ab}
Hardness/N	3.22 ± 0.56^{d}	3.61 ± 0.26^{cd}	4.68 ± 0.27^{ab}	4.88 ± 0.15^{a}	3.99 ± 0.62^{bc}
Springiness/mm	2.76 ± 0.40^{a}	3.14 ± 0.24^{a}	3.02 ± 0.45^{a}	2.82 ± 0.20^{a}	2.78 ± 0.07^{a}
Cohesiveness	0.44 ± 0.06^{a}	0.49 ± 0.02^{a}	0.45 ± 0.06^{a}	0.41 ± 0.06^{a}	0.43 ± 0.02^{a}
Gumminess	1.58 ± 0.31^{a}	1.57 ± 0.26^{a}	2.1 ± 0.37^{a}	2.0 ± 0.34^{a}	1.72 ± 0.34^{a}
Chewiness/mj	0.98 ± 0.3^{a}	1.1 ± 0.27^{a}	1.43 ± 0.39^{a}	1.26 ± 0.27^{a}	1.06 ± 0.19^{a}
Cooking loss/%	19.40 ± 1.51^{c}	20.41 ± 1.51^{bc}	22.16 ± 0.76^{ab}	23.46 ± 1.37^{a}	23.16 ± 1.41^{a}

(B)

Project	500 W	800 W	1000 W	1200 W	1400 W
Shear force/N	46.81 ± 1.77^{b}	47.66 ± 1.26^{b}	51.61 ± 1.11^{a}	52.83 ± 1.17^{a}	53.67 ± 1.34^{a}
Hardness/N	3.91 ± 0.52^{b}	3.44 ± 0.29^{c}	4.39 ± 0.26^{a}	3.86 ± 0.53^{b}	4.38 ± 0.29^{a}
Springiness/mm	2.98 ± 0.32^{a}	3.24 ± 0.19^{a}	2.94 ± 0.63^{a}	2.80 ± 0.03^{a}	3.00 ± 0.27^{a}
Cohesiveness	0.43 ± 0.08^{a}	0.39 ± 0.06^{a}	0.47 ± 0.1^{a}	0.47 ± 0.09^{a}	0.42 ± 0.06^{a}
Gumminess	1.70 ± 0.51^{b}	1.34 ± 0.17^{b}	2.05 ± 0.32^{a}	1.79 ± 0.11^{b}	1.85 ± 0.17^{b}
Chewiness/mj	1.15 ± 0.46^{a}	0.96 ± 0.1^{a}	1.37 ± 0.48^{a}	1.11 ± 0.07^{a}	1.23 ± 0.09^{a}
Cooking loss/%	19.90 ± 1.64^{b}	20.95 ± 1.39^{b}	20.25 ± 1.16^{b}	23.10 ± 0.86^{a}	23.28 ± 1.19^{a}

(C)

Project	50 kPa	60 kPa	70 kPa	80 kPa	90 kPa
Shear force/N	48.47 ± 3.18^{ab}	46.47 ± 1.46^{b}	46.03 ± 1.54^{b}	50.06 ± 3.58^{a}	51.41 ± 3.89^{a}
Hardness/N	3.71 ± 0.49^{b}	3.54 ± 0.17^{b}	3.58 ± 0.35^{b}	4.44 ± 0.18^{a}	4.47 ± 0.24^{a}
Springiness/mm	3.19 ± 0.3^{a}	2.88 ± 0.46^{a}	2.49 ± 0.05^{b}	2.8 ± 0.44^{a}	3.05 ± 0.24^{a}
Cohesiveness	0.57 ± 0.04^{a}	0.46 ± 0.13^{a}	0.3 ± 0.04^{b}	0.52 ± 0.02^{a}	0.5 ± 0.04^{a}
Gumminess	2.09 ± 0.21^{ab}	1.65 ± 0.47^{b}	1.06 ± 0.21^{c}	2.32 ± 0.02^{a}	2.24 ± 0.26^{a}
Chewiness/mj	1.49 ± 0.28^{a}	1.08 ± 0.48^{ab}	0.59 ± 0.11^{b}	1.45 ± 0.22^{a}	1.53 ± 0.31^{a}
Cooking loss/%	21.05 ± 1.27^{ab}	20.78 ± 0.96^{b}	21.05 ± 1.17^{ab}	22.03 ± 0.72^{a}	22.80 ± 1.04^{a}

Values are expressed as means ± standard deviation.
Different lowercase letters in the same column indicate significant differences among the different cooking pressures ($p < 0.05$).

orthogonal experiments at three levels: 800, 1000, and 1200 W.

3.1.3. *Effect of cooking pressure on cooking loss, TPA, and sensory quality of GRC*

The effects of cooking pressure on the sensory evaluation of GRC are shown in Fig. 2C. With increasing cooking pressure, the sensory scores of GRC gradually increased and then decreased, reaching a maximum value of 81.63 at 60 kPa. Although it was difficult to eliminate the fishy taste of chicken, a higher cooking pressure could change the spatial structure between myogenic fibers and reduce texture and chewiness. The decomposition of chicken flavor and aroma substances is accelerated under high cooking pressure, which adversely affects the chicken flavor (Orel et al., 2020). Table 1C shows the cooking loss and TPA of GRC under different cooking pressures. There was no significant difference in cooking loss at cooking pressures of 50 kPa–70 kPa. The shear force of chicken meat first decreased and then increased, and the trends in hardness, springiness, and chewiness were consistent with those of the shear force, all of which initially decreased and then increased. Cohesiveness and gumminess gradually decreased at 50 kPa–70 kPa, increased, and slightly decreased at 90 kPa. In conclusion, 60, 70, and 80 kPa were selected as the optimal small-fire cooking pressures for orthogonal experiments.

3.2. *Analysis of orthogonal experiment results*

Based on the single-factor results, an orthogonal test was performed to determine the optimal cooking conditions for GRC (Table S3). The results of the polarity analysis showed that $R_A > R_B > R_C$, and the order of influence of the three factors on the sensory evaluation of GRC was as follows: cooking time (A) > cooking power (B) > cooking pressure (C). According to the results of the orthogonal test analysis, the optimal processing conditions for the GRC were $A_2B_2C_1$.

3.3. *Comparison of cooking loss, textural properties, and sensory quality of the control group (CG) and the GRC under optimum cooking conditions (GRC-OP)*

The total sensory score of the GRC-OP group was 73.8, which was slightly higher than that of the CG score of 73.3 (Fig. 3A). Conversely, the optimized glutinous rice had a total sensory score of 73, which was marginally lower than that of the CG score of 74.9 (Fig. 3B). Despite these differences, the differences between the sensory scores of the two groups were not significant. This indicates that, in terms of sensory evaluation, there was no significant difference between the glutinous rice in the two groups. In essence, it may be said that the product achieves a replication of the traditional flavor of GRC. In addition, the texture of GRC-OP was enhanced, whereas the appearance and taste scores exhibited a slight decline compared with those of CG. However, the odor quality was enhanced. Table 2A shows the cooking loss and textural properties of the CG and GRC-OP samples. GRC-OP showed a higher cooking loss than the CG, but no significant difference was observed. Furthermore, lower shear force and hardness values were detected in CG ($p > 0.05$). Springiness, gumminess, and chewiness were higher in the GRC-OP group than those in the CG. The cohesiveness of GRC-OP was lower than that of CG. The observed differences in the results may be attributed to the higher temperature during the cooking of GRC-OP compared to that of the CG, which resulted in the denaturation of actin and myosin and gelatinization of collagen in chickens, leading to a slightly higher shear force and hardness of GRC-OP compared to those of the CG; however, there was no significant difference. In conclusion, the sensory qualities of CG and GRC-OP were similar. The industrialized GRC process effectively replicates the sensory qualities of traditional GRC production processes.

3.4. *Analysis of comparative moisture, protein, fat, and sodium chloride results*

The analysis of the basic nutritional composition provided a better understanding of the properties of the samples. The moisture, protein, fat, and sodium chloride contents of the GRC samples were investigated. As shown in Table 2B, the moisture content of GRC-OP was slightly higher ($p < 0.05$) than that of CG. Normally, a lower moisture content in chicken meat results in higher relative dry matter content and total nutrient content, whereas a higher moisture content leads to more tender and succulent meat, which enhances palatability (Borela et al., 2022). The higher moisture content observed in the GRC-OP samples may be attributed to the shorter cooking time of GRC-OP, which resulted in a higher collagen content that retained more moisture (Cai et al., 2019). After optimizing the cooking power, the appropriate power was selected, the cooking temperature was varied appropriately to slow the

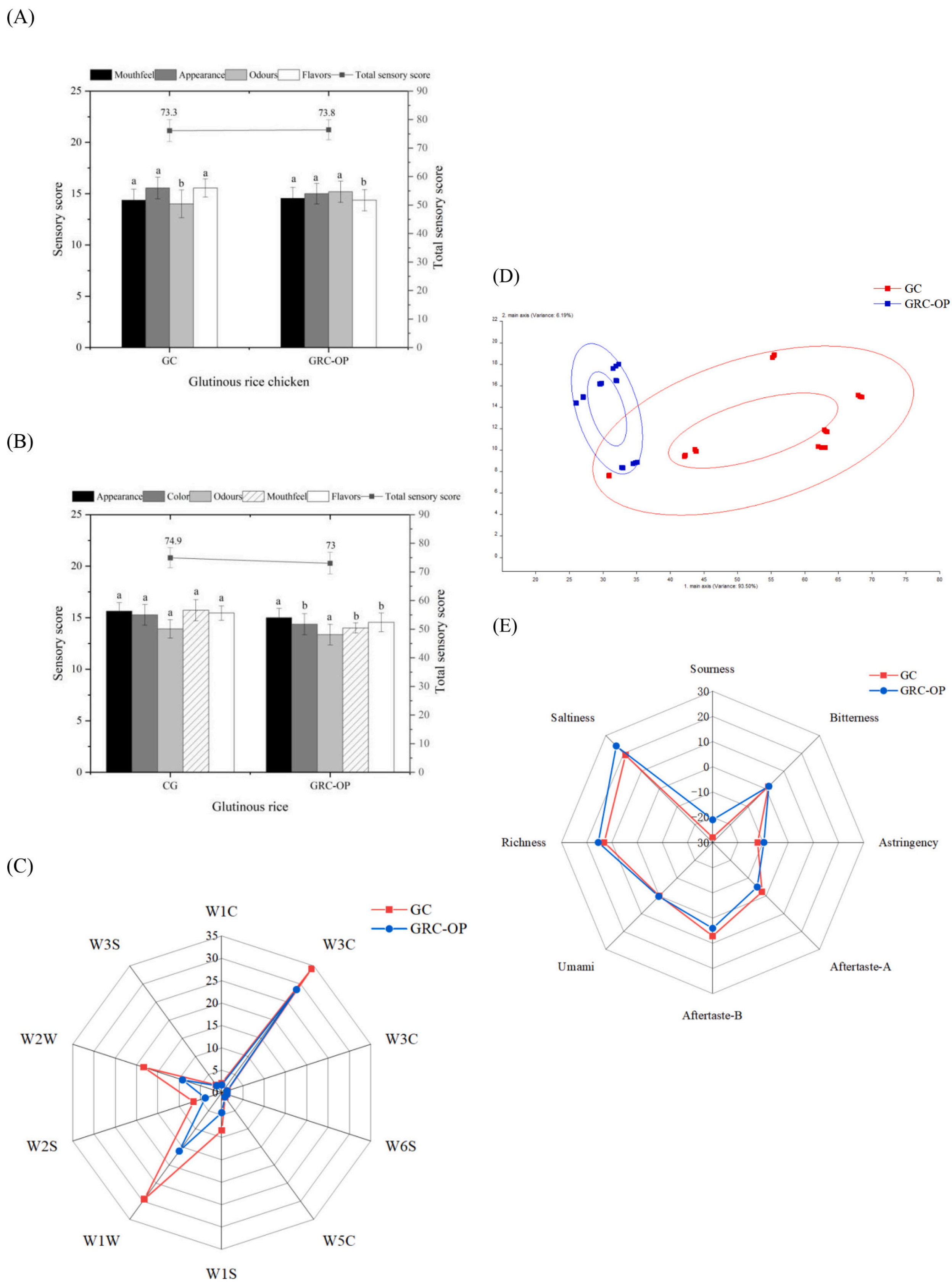

Fig. 3. Sensory evaluation comparison with CG and GRC-OP. (A) Sensory evaluation comparison of chicken. (B) Sensory evaluation comparison of glutinous rice. (C) Spider plot for taste attributes from electronic nose (*E*-nose) analysis of CG and GRC-OP. (D) PCA of E-nose data. (E) Spider plot for taste attributes from electronic tongue analysis of CG and GRC-OP.

Table 2
(A) Texture profiles, cooking loss, and basic nutritional components of CG and GRC-OP. (B) Basic nutritional components of CG and GRC-OP.

(A)		
Project	CG	GRC-OP
Shear force/N	47.05 ± 0.71[a]	47.36 ± 1.02[a]
Hardness/N	3.41 ± 0.75[b]	4.1 ± 0.09[a]
Springiness/mm	2.7 ± 0.58[a]	2.96 ± 0.02[a]
Cohesiveness	0.51 ± 0.08[a]	0.47 ± 0.08[a]
Gumminess	1.76 ± 0.52[a]	1.94 ± 0.39[a]
Chewiness/mj	47.05 ± 0.71[a]	47.36 ± 1.02[a]
Cooking loss/%	22.82 ± 1.05[a]	23.52 ± 0.96[a]
(B)		
Nutritional content	Control	GRC-OP
Moisture/%	65.99 ± 0.60[b]	66.89 ± 0.12[a]
Fat/%	9.02 ± 0.44[a]	7.98 ± 0.2[b]
Protein/%	26.00 ± 1.09[a]	26.16 ± 0.73[a]
Sodium chloride/%	0.55 ± 0.13[a]	0.72 ± 0.04[a]

Values are expressed as means ± standard deviation.
Different lowercase letters in the same column indicate significant differences between the different cooking methods ($p < 0.05$).

rate of water dissipation, and the water-binding capacity was slightly higher than that of CG.

Sodium chloride content during GRC processing has a direct impact on chicken quality. The higher cooking power and pressure of GCR-OP compared with those of CG resulted in a gradual increase in the sodium chloride content of GRC. This enhances the flavor of chicken, suppresses off-flavors, and imparts a salty taste (Chen et al., 2019).

The total fat content results indicated that the fat content of GRC-OP was lower than that of the GC. This is because the initial heating process for GC required a longer cooking time, resulting in a greater rate of water loss than fat loss. Once the water loss reaches a certain threshold, the thermal degradation rate of fat surpasses the water loss rate (Semjon et al., 2020). This phenomenon results in a reduction in the proportion of fat, which, in turn, leads to a lower fat content in GCR-OP than in GC. It is generally accepted that meat with lower fat content is more acceptable in a balanced diet (Djinovic-Stojanovic et al., 2019). The protein content of chicken broth can be increased by optimizing cooking time, pressure, and power. This results from the fact that the small molecules in the broth penetrate the chicken, which in turn increases the protein content of the broth and the decomposition products of the chicken. However, this process impedes the dissolution of proteins, which in turn results in the GRC proteins and other proteins being less dissolved, and the final proteins being higher than those in the CG. ($p > 0.05$) (Guan et al., 2024). The moisture content of the GRC was 53.16 %, fat content was 4.26 %, and protein content was 4.64 %, which is in accordance with the national standards. Compared with CG, the water content of GRC-OP increased, and the sodium chloride and protein contents increased slightly.

3.5. E-nose analyses

For the present study, the E-nose response values in CG and GRC-OP are shown in Fig. 3C. The data points of the two sample groups differed significantly, indicating that the E-nose effectively differentiated between the sample groups. The W5S (sensitive to nitrogen oxides), W1S (sensitive to methyl), W1W (sensitive to sulfides), and W2W (sensitive to organic sulfides) sensors positively affected the CG and GRC-OP responses ($p < 0.05$), suggesting that aromatic sulfide and nitrogen oxide compounds were generated in CG and GRC-OP. Nevertheless, the response values of the four sensors to the GRC-OP were lower than those of the CG. The presence of nitrogen oxides and sulfides in cooked meat imparts an overall flavor (Xin et al., 2022). The results indicated that the NOx and sulfides in GRC-OP were lower than those in CG, and this phenomenon was found to be related to spices. In contrast, the response values for W2S (alcohol-sensitive) decreased ($p < 0.05$), and no significant differences were detected in the response values for W1C, W3C, W6S, W5C, and W3S ($p > 0.05$).

PCA is an effective method for classifying samples according to differences in flavor. As shown in Fig. 3D, PC1 and PC2 accounted for 99.69 % of total variance. In PC2, there was minimal disparity between the CG and GRC-OP, whereas in PC1, there was a discernible discrepancy. The electronic nose data collection points for the CG and GRC-OP exhibited a certain degree of aggregation. This can be observed in the overlap and proximity of certain data collection points. This indicates that the difference in volatile odor information between the CG and GRC-OP was relatively minor. The discernible differences in flavor components suggested that the aromas of the two groups of samples exhibited a certain degree of similarity. Overall, the PCA results suggested that the *E*-nose properly characterized CG and GRC-OP, with small differences in volatile odors and some differences in aroma components. However, the differences in the aroma between the two groups of samples were not significant.

3.6. E-tongue analyses

The E-tongue can present complex taste indicators in a numerical format (Jung et al., 2023). In addition, it is possible to compare taste differences between the CG and GRC-OP based on numerical differences in taste metrics. The results showed that the response values for sourness, astringency, and aftertaste A were lower than the tasteless point. The bitterness, saltiness, aftertaste, umami, and richness values were higher than those of the tasteless points (Fig. 3E). The salinity and richness of GRC-OP were higher than those of GC, and aftertaste-B was slightly lower than that of GC; however, there was no significant difference in the umami and bitterness of CG and GRC-OP. In conclusion, GRC-OP demonstrated an improvement in salinity and richness compared to GC, whereas bitterness, umami, and aftertaste-B attributes remained consistent.

3.7. Analysis of volatile flavor compounds

A total of 54 volatile compounds were identified by GC, including seven alcohols, 11 aldehydes, three ketones, 28 alkanes, and one olefin. A total of 50 volatile compounds were identified in the GRC-OP, including eight alcohols, 10 aldehydes, three ketones, 27 alkanes, and one olefin. The contents of each volatile compound are listed in Table 3. There were no significant differences in the flavor composition. The observed variations in flavor were not statistically significant and exhibited high similarity between the samples.

Aldehydes exert a profound influence on the aroma of cooked meat, particularly branched and high-content small-molecule aldehydes, which impart a better flavor (Ramalingam et al., 2019). Aldehydes play a significant role in the overall aroma of GRC because of their low threshold values (Jiang et al., 2022) and grass and fat flavors. Moreover, pentanal, hexanal, heptanal, 2-gengxiquan, octanal, (E)-2-octenal, nonanal, (Z)-4-decenal,(E,E)-2,4-decadienal are formed from oxidation of unsaturated fatty acids or thermal oxidative decomposition of lipids in food (Han et al., 2023). The slight decrease in hexanal content in GRC-OP compared to that in GC and the non-detection of tridecanal and 2,4-decadienal in GRC-OP were attributed to the addition of spices, as well as the effects of cooking temperature and cooking time. The amount of remaining aldehydes increased in GRC-OP compared to that in the GC sample.

Alcohols are primarily derived from the oxidation and degradation of lipids, which impart pleasant fruity and floral odors (Bi et al., 2021). The GRC-OP had a slightly lower mass fraction of 1-octen-3-ol than that in GC. However, the mass fractions of pentanol, hexanol, cyclooctanol, and 1-heptanol were higher in the GRC-OP than in the GC. 1-Octen-3-ol is a typical volatile flavor compound derived from linoleic acid oxidation

Table 3
Volatile compounds in CG and GRC-OP.

RI	Compounds	Relative content /%	
		GC	GRC-OP
707	Valeraldehyde	0.26 ± 0.15[a]	0.38 ± 0.19[a]
806	Hexanal	42.55 ± 3.96[a]	37.83 ± 3.4[b]
905	Heptanal	1.36 ± 0.29[a]	1.78 ± 0.25[a]
913	2-Heptenal	ND	0.77 ± 0.17
1005	Octanal	1.6 ± 0.4[b]	2.22 ± 0.14[a]
1013	(E)-2-Octenal	0.63 ± 0.04[b]	1.05 ± 0.23[a]
1104	Nonanal	3.12 ± 0.25[a]	3.92 ± 0.67[a]
1212	(z)-4-Decenal	0.33 ± 0.07[a]	0.29 ± 0.05[a]
1204	Decanal	0.42 ± 0.04[a]	0.49 ± 0.14[a]
1502	Tridecanal	0.14 ± 0.01	ND
1220	(E, E) -2,4-Decadienal	0.18 ± 0.01[a]	0.25 ± 0.14[a]
1220	2,4-decadienal	0.47 ± 0.04	ND
1088	2,3-Octanedione	13.15 ± 0.61[a]	12.51 ± 0.83[a]
853	2-Heptanone	0.54 ± 0.14[a]	0.34 ± 0.15[b]
1119	4,6,6-Trimethylbicyclo[3.1.1]hept-3-en-2-one	0.62 ± 0.19[a]	0.6 ± 0.12[a]
960	1-heptanol	ND	0.4 ± 0.09
969	1-octen-3-ol	6.6 ± 0.53[a]	4.32 ± 0.89[b]
761	Pentanol	0.79 ± 0.02[b]	0.91 ± 0.07[a]
860	Hexanol	0.24 ± 0.17[a]	0.35 ± 0.24[a]
1147	Cyclooctanol	0.66 ± 0.05[b]	0.94 ± 0.04[a]
1059	Octanol	0.39 ± 0.04[b]	0.68 ± 0.12[a]
1068	1-Nonen-4-ol	0.48 ± 0.02[b]	0.67 ± 0.11[a]
1393	2-Butyl-1-octanol	0.29 ± 0.09[a]	0.31 ± 0.08[a]
1512	Pentadecane	0.16 ± 0.05[a]	0.26 ± 0.09[a]
1185	2,4-Dimethyl-undecane	0.44 ± 0.14[a]	0.42 ± 0.19[a]
1185	4,6-Dimethyl-undecane	1 ± 0.25[a]	0.74 ± 0.32[a]
1249	4-Methyld-odecane	0.29 ± 0.05[a]	0.34 ± 0.17[a]
1185	3,8-Dimethyl-undecane	0.51 ± 0.07[a]	0.5 ± 0.34[a]
1711	Heptadecane	ND	0.48 ± 0.21
1249	6-Ethyl-undecane	0.37 ± 0.01[a]	0.25 ± 0.10[a]
1448	5-Methyl-tetradecane	0.28 ± 0.17[a]	0.21 ± 0.08[a]
1753	2,6,11,15-Tetramethylhexa-decane	0.22 ± 0.1	ND
1285	4,6-Dimethyl-dodecane	0.29 ± 0.11	ND
1185	2,6-Dimethyl-undecane	0.6 ± 0.5[a]	0.59 ± 0.24[a]
1249	2-Methyldo-decane	1.29 ± 0.43[a]	1.1 ± 0.44[a]
1249	3-Methyldo-decane	ND	0.76 ± 0.4
1313	Tridecane	1.41 ± 0.65[a]	1.44 ± 0.52[a]
1285	2,4-Dimethyl-dodecane	0.29 ± 0.14[a]	0.18 ± 0.04[a]
4103	3,5,24-Trimethyltetra-decane	0.18 ± 0.06	ND
1150	Undecane,5-methy-	0.46 ± 0.22[a]	0.31 ± 0.04[a]
1612	Hexadecane	0.37 ± 0.04[a]	0.33 ± 0.2[a]
1519	2,6,10-Trimethyltetra-decane	ND	0.2 ± 0.06
1320	2,6,10-Trimethyl-dodecane	0.14 ± 0.01[a]	0.15 ± 0.01[a]
1349	5-Methyltridecane	0.19 ± 0.09	ND
967	1-Butenyl-cyclopentane	0.16 ± 0.04	ND
1249	4-Ethyl-undecane	0.42 ± 0.13	ND
2243	4-Methyl-docosane	ND	0.22 ± 0.01
1446	2-Bromo-dodecane	0.21 ± 0.08[a]	0.17 ± 0.03[a]
1413	Tetradecane	0.47 ± 0.05[a]	0.49 ± 0.05[a]
1150	2-Methyl-undecane	0.67 ± 0.13[a]	0.58 ± 0.04[a]
1150	3-Methyl-undecane	0.58 ± 0.1[a]	0.57 ± 0.12[a]
1852	2,6,10,14-Tetramethyl-heptadecane	2.97 ± 0.93[a]	2.85 ± 0.82[a]
1150	4-Ethyl-decane	0.46 ± 0.12[a]	0.43 ± 0.06[a]
1185	2,7-Dimethyl-undecane	ND	0.53 ± 0.08
1320	2,7,10-Trimethyl-dodecane	0.39 ± 0.26[a]	0.29 ± 0.13[a]
1628	1-Iodododecane	0.2 ± 0.01[a]	0.25 ± 0.08[a]
868	3-Ethyl-2-methyl-1,3-hexadiene	0.32 ± 0.15	ND
1274	5-Hexyl-3,3-dimethyl-1-cyclopentene	ND	0.14 ± 0.01
1040	2-Pentylfuran	1.15 ± 0.13	ND
1334	O-Decyl-hydroxylamine	0.52 ± 0.06	ND
2596	4-Hexadecylanilin	0.27 ± 0.05	ND
1301	Methoxyphenyl-oxime	0.44 ± 0.28[a]	0.19 ± 0.06[b]

ND: not detected or below the detection limit.
Values are expressed as means ± standard deviation.
Different lowercase letters in the same column indicate significant differences between the different cooking methods ($p < 0.05$).

and has a mushroom/metallic odor (Ding et al., 2020).

Three ketones were identified in both GC and GRC-OP. The relative mass fraction of ketones in GRC-OP did not change significantly compared with that in GC. Most ketones contribute little to the flavor profile (Zhou et al., 2022). 2-Heptanone is produced by the degradation of unsaturated fatty acids and mainly contributes to the fatty flavor (Cao et al., 2020). 2,3-Octanedione has a creamy and nutty aroma, which is primarily derived from the re-oxidation or interaction of unsaturated fatty acid hydroperoxides (Ma et al., 2020).

In total, 28 and 27 alkanes were identified in the GC and GRC-OP samples, respectively. These factors did not significantly affect the flavor of chicken meat. However, the synergistic effect of multiple alkanes may contribute to the overall flavor of chicken meat. The relative mass fractions of the alkanes were similar and did not undergo significant changes, which was consistent with the electronic nose results.

In conclusion, 54 and 50 volatile flavor substances were detected in GC and GRC-OP, respectively. The differences in the types and relative mass fractions of volatile flavor substances were not significant, indicating that GRC-OP has flavors similar to those of GC, with aldehydes contributing more to the overall flavor.

3.8. FAAs

FAAs serve as precursors for numerous volatile flavor compounds and are involved in the Maillard reaction, which produces specific flavors during meat processing (Qiu et al., 2024). The composition and content of FAA in GC and GRC-OP are listed in Table S4. Seventeen FAA were quantified and identified by gas chromatography (GC) and GRC-OP. The total FAA of the GC and GRC-OP were found to be 325.79 mg/100 g and 332.42 mg/100 g, respectively. The total amount of FAA in GRC-OP was slightly higher than that in GC ($p > 0.05$).

Glu and aspartic acid Asp have an umami taste; Arg, Leu, Ile, Val, Phe, Cys, His, and Met have a bitter taste; Ala, Gly, Pro, Thr, and Ser have a sweet taste; and individual amino acids also have sour and salty tastes (Roobab et al., 2023). In this study, the levels of Glu and Asp in GRC-OP were slightly higher than those in the GC. Bitter amino acids, such as valine, methionine, isoleucine, leucine, and tyrosine, were present at levels below their thresholds, which may be important contributors to the bright taste of GRC. Although arginine is bitter, it increases the value of adding flavor complexity and enhances freshness (Guo et al., 2019). The concentration of arginine in GRC was increased by optimizing the production process. Except for isoleucine and histidine, the contents of other aromatic amino acids in the GRC did not change significantly. The total fresh and bitter amino acid contents in GRC-OP were slightly higher than those in GC, which was consistent with the *E*-tongue results.

4. Conclusion

The objective of this study was to investigate the effects of cooking process parameters on the quality and sensory properties of GRC to maintain the distinctive characteristics of traditional poultry meat products. The results showed that cooking conditions, including cooking time, power, and pressure, significantly affected shear force, hardness, and sensory characteristics. Through single-factor and orthogonal experiments in the cooking stage, the optimum cooking conditions for GRC were found to be a cooking time of 20 min, cooking power of 1000 W, and cooking pressure of 60 kPa. Furthermore, 50 volatile flavor compounds, including 27 alkanes, 10 aldehydes, and eight alcohols, were detected in GRC after optimization, with Glu and Asp being the most abundant FAA. The results of this study provide important information for the development of high quality properties and nutritional abilities of traditional GRCs in the meat manufacturing industry.

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CRediT authorship contribution statement

Cenyue Zhang: Writing – original draft, Formal analysis. **Juan Wang:** Writing – original draft, Formal analysis. **Ziting Ma:** Writing – review & editing. **Changcheng Zhao:** Writing – original draft, Methodology, Formal analysis. **Chunxiang Piao:** Methodology, Formal analysis. **Mingxun Cui:** Writing – original draft. **Hongmei Li:** Writing – original draft, Formal analysis, Data curation. **Tingyu Li:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Formal analysis, Conceptualization. **Baide Mu:** Funding acquisition, Formal analysis. **Guanhao Li:** Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no competing financial interests or personal relationships that may have influenced the work reported in this study.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fochx.2024.101868.

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