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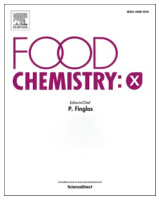

Dietary inulin supplementation improves meat quality and off-flavor of duck meat referring to regulated muscle fiber types and antioxidant capacity

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ABSTRACT

This study aimed to evaluate the effects of dietary inulin (0–30 g/kg) on duck meat, muscle fiber types, meat quality, antioxidant ability, Low-field nuclear magnetic resonance, amino acid and off-flavor. These results indicated that inulin promoted the conversion of type II to type I muscle fibers. Compared with the control group, supplementation with 20 g/kg inulin reduced ($P < 0.05$) the shear force and pressure water loss by 17.9 N and 1.9 %, respectively. Inulin increased the pH_{24h} and the redness of duck meat. Low-field nuclear magnetic resonance confirmed that inulin increased the immobile water content and enhanced water retention in duck meat. Additionally, inulin enhanced antioxidant capacity and reduced the degree of lipid oxidation. Inulin increased the content of umami and sweet amino acids by 2.63 %, which affects the flavor of duck meat. Notably, dietary inulin reduced the content of volatile off-flavor substances and improved the flavor of duck meat. In summary, dietary inulin may be an effective strategy for producing high quality duck meat and removing duck off-flavor.

1. Introduction

As a high-nutrition food, duck meat is valued for its high protein content, low-melting fatty acid content, and rich vitamin B and vitamin E content, and good digestibility (Quaresma et al., 2024; Sun et al., 2023). Moreover, the compendium of materia medica records that duck meat benefits from nourishing the stomach and kidney and aids recovery after illness. Duck meat and its products are rapidly developing in the global market, with their health, nutritional value, and market potential gradually gaining popularity (Biswas et al., 2019; Ibrahim et al., 2023). Unfortunately, constrained by suboptimal breeding environments, outdated husbandry techniques, and the prohibition of antibiotic use, ducks exhibit reduced immunity and increased susceptibility to diseases during rearing, ultimately leading to a decline in the edible quality of duck meat (Gul & Alsayeqh, 2023; Liu et al., 2023). Furthermore, duck meat commonly presents drawbacks such as tough texture and excessive off-flavor (Biswas et al., 2019). However, as the desire for high-quality meat products grows among consumers, the existing quality of duck meat fails to satisfy the market demand (Sun, Zhao, Zhao, & Sun, 2023). Duck meat is often used as pet food instead of being consumed by humans, which constitutes a considerable loss of animal protein resources, given the substantial challenges in global meat production (Sun, Zhao, Zhao, & Sun, 2023; Utari, Warly, Hermon, & Evitayani., 2023; Wang et al., 2024). Consequently, it is imperative to resolve the problem of the poor edible quality in duck meat.

Muscle fibers, the fundamental units of skeletal muscle, significantly affect meat quality owing to their biochemical characteristics (Joo, Kim, Hwang, & Ryu, 2013; Mo et al., 2023). Based on the contractile properties of muscle fibers following electrical stimulation, muscle fibers can be categorized into two main types: type I (slow-twitch) and type II (fast-twitch) (Schiaffino & Reggiani, 2011). In contrast to type II muscle fibers, type I muscle fibers possess a greater myoglobin content, which

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results in a more pronounced red hue in the meat. Several previous studies have demonstrated a positive correlation between type I muscle fibers content and meat quality, including the tenderness and water-holding capacity (WHC) of animal muscles (Joo et al., 2013; Li et al., 2022; Mo et al., 2023). Besides, Li, Liu, Zhang, Xie, and Shan (2022) found that the levels of taste-active amino acids were positively correlated with type I muscle fibers in meat, thereby enhancing the taste characteristics. Thus, augmenting type I muscle fibers may be a feasible approach to effectively promote duck meat quality.

Many researchers believe that incorporating natural bioactive compounds with immunomodulatory and antioxidative properties into feed is a viable approach for enhancing the meat quality of animal muscles (Ban et al., 2024; Defaix et al., 2024; Li, Liang, et al., 2022). Inulin, a natural plant polysaccharide, is considered a highly valuable prebiotic and dietary fiber, owing to its excellent antioxidant capacity and resistance to gastric digestion (Illippangama, Jayasena, Jo, & Mudannayake, 2022; Sun, Zhang, & Sun, 2024). Some previous studies have illustrated that inulin can significantly enhance the antioxidant capacity of animals, thereby improving the quality of their muscles (Bucław, 2019; Defaix et al., 2024). Moreover, inulin influences the transformation of different types of muscle fiber in skeletal muscles (Wang et al., 2019). Sun et al. (2024) reported that inulin can increase type I muscle fibers in muscles. Thus, based on these findings, it is reasonable to infer that the improvement of duck meat quality may be due to the increasing the content of type I muscle fiber and antioxidant capacity by dietary inulin. Nonetheless, to the best of our knowledge, there is a scarcity of literature investigating the effects of dietary inulin on muscle fiber types, meat quality, and antioxidant capacity of duck meat.

Hence, we investigated the effects of dietary supplementation with different concentrations of inulin (0–30 g/kg) on meat quality, off-flavor, muscle fiber types, and antioxidant ability of duck meat. This study provides a novel approach for promoting meat quality and reducing the off-flavor of duck meat.

2. Materials and methods

2.1. Materials

Inulin (Average polymerization degree and weight-average molecular weight was 9 and 1460 g/mol, respectively) was provided from Qilu Biotechnology Co. Ltd. (Jinan, China). ATP disodium salt was obtained from Beijing Solarbio Science & Technology Co.,Ltd. (Beijing, China). Tris(hydroxymethyl)aminomethane, $CaCl_2$, cobalt nitrate, anhydrous ethanol and TCA was purchased from China National Pharmaceutical Chemicals Co., Ltd. (Shanghai, China). All the reagents were of analytical grade.

2.2. Samples preparation

A total of 240 healthy male Cherry Valley ducks of one-day-old age were provided by Shandong Shengyao Biotechnology Company, and these ducks were randomly distributed into one control and three dietary inulin treatment groups (INU10, INU20, and INU30), each with six replicate pens housing 10 ducks per pen. The control group was fed a basal diet (Table S1), and the three dietary inulin groups were supplemented with inulin (10, 20, and 30 g/kg) based on the weight of the basal diet. All ducks were maintained in a similar and controlled environment, with free access to food and water. At 35 days, the duck was hung upside down on the hooks and stunned with electric shock before bleeding from the neck. Subsequently, the process involved scalding for feather removal, wax dipping and dewaxing; removal of the viscera, tongues, and feet; and rinsing to obtain a white strip duck. Finally, the duck was segmented, and fresh duck breast was collected for subsequent analysis of relevant indicators.

2.3. ATPase histochemical stain

Duck meat tissue sections were prepared using a cryostat microtome at −20 °C (CRYOSTAR NX50, Thermo Scientific Company, America). Fresh tissue cryo-sections were dried, and the tissue areas were encircled with an immunohistochemical pen. Sections were incubated in buffer solution 1 (0.165 M Tris(hydroxymethyl)aminomethane, 0.018 M $CaCl_2$, pH 10.4) for 5 min. After decanting buffer solution 1, buffer solution 2 (0.165 M Tris(hydroxymethyl)aminomethane, 0.018 M $CaCl_2$, 2.73 mM ATP disodium salt, pH 9.4) was incubated for 30 min. Thereafter, the sections were stained with a 2 % $CaCl_2$ solution (2 min each, three times). The sections were then stained for 5 min using a cobalt nitrate solution and washed with deionized water (20 s each, three times). Sections were dehydrated using anhydrous ethanol and covered with neutral resin. Subsequently, the sections were observed at 200 × under a light microscope (ECLIPSE E100, Nikon Corporation, Japan) and analyzed using Image Pro Plus 6.0 software.

2.4. Meat quality

At 15 min after slaughter, the pH value and color of fresh duck breast meat were measured using a pH meter (Seven2Go- S2, Mettler-Toledo, Switzerland) and a colorimeter (CR-400, 8 mm diameter aperture, Illuminant A, standard observer position 10°, Konica Company., Japan), respectively. Prior to measurements, the pH meter and colorimeter were calibrated using standard solutions (pH 4.0 and 7.0) and a white plate, respectively. The probe of pH meter was needle-type solid probe, inserted 2 cm deep into the meat for measurement. After the meat samples were stored at 4 °C for 24 h, pH and meat color were measured again.

The shear force and pressure water loss of the samples were determined following the method of Sun, Zhao, Zhao, and Sun (2023). Briefly, each sample was placed in a vacuum-sealed package and cooked in water bath immersion at 80 °C until the center temperature reached 70 °C. The cooked duck breasts were cooled to room temperature before being stored overnight at 4 °C. Each cooked duck breast was cut into long strips (2 × 2 × 4 cm^3) to measure shear force using a texture analyzer (TA-3000, Saicheng Instrument Company, Jinan, China) with a 25 kg load transducer. The pressure water loss was determined using a strain pressure meter (YYW-2, Turang Equipment Company, Nanjing, China). The duck meat sample was cut into cuboids (2 × 2 × 2 cm^3) and placed into the strain pressure meter. The pressure was set to 5 kg and kept for 5 min.

2.5. Antioxidant ability

The antioxidant capacity of the duck meat was evaluated by measuring the degree of lipid oxidation, total antioxidant capacity (T-AOC), total superoxide dismutase (T-SOD), catalase (CAT), and glutathione peroxidase (GPx). Lipid oxidation was assessed through thiobarbituric acid-reactive substance (TBARS) method by employing Xu et al. (2023). The antioxidant enzyme activity was measured using the commercial assay kit (Nanjing Jiancheng Bioengineering Institute, Nanjing, China), respectively.

2.6. Low-field nuclear magnetic resonance (LF-NMR)

The LF-NMR was measured following the procedure of Sun, Zhao, Ma, et al. (2023) using an NMR analyzer (NMI20-040 V-I; Niumag Analytical Instrument Corporation, Suzhou, China). The duck meat (1 × 1 × 2 cm^3) was placed into the analyzer. Subsequently, the samples were determined using the CPMG sequence, the FID sequence was calibrated using a standard oil sample before the measurement.

2.7. Amino acid content

Amino acid content was determined using the method described by Guo et al. (2021). Briefly, 5 g of duck meat was placed in a beaker containing ionexchanged water (pre-cooled to 4 °C), 5 mL of 10 % TCA solution was added, then homogenized (3 × 10 s, 3000 rpm) and centrifuged (8000 ×*g*, 10 min) to obtain a precipitate sample. The sample was washed five times with 5 % TCA solution and filtered through a 0.45 μm filter membrane. Samples were analyzed at 39 °C using an automatic amino acid analyzer (L-8900, Hitachi, Kyoto, Japan).

2.8. Volatile flavor compounds

The procedure described by Sun, Zhao, Zhao, and Sun (2023) was followed. Duck meat (5 g) was cut into minced pieces and placed into a headspace bottle. 10 μL of 1,2-dichlorobenzene (0.05 μg·μL-1) was added as an internal standard. The meat sample was incubated at 60 °C for 30 min to release the aroma. The coated fiber was then inserted into the GC inlet, and desorbed for 10 min at 250 °C for subsequent analysis by a gas chromatography–mass spectrometry (Trace1310 TSQ 8000 Evo, Thermo Scientific Company, America). GC–MS analysis was conducted using an HP-5 MS capillary column (30 m × 0.25 mm, 0.25 μm) and high-purity helium as the carrier gas at a flow rate of 1 mL min^{-1} with a 10:1 split ratio. The temperature program included the following steps: First, temperature was held at 50 °C for 5 min, was gradually increased to 130 °C at a rate of 2 °C/min, and further increased to 250 °C at a rate of 10 °C/min. Finally, the temperature was maintained at 250 °C for 10 min to ensure complete desorption of flavor compounds. Mass spectrometry was performed with the interface temperature set at 250 °C.

2.9. Statistical analysis

The experimental data were obtained from 6 independent experiments and statistically analyzed using one-way ANOVA with SPSS 26.0. Differences between treatments were identified using Duncan's multiple range tests in post hoc test. The data are presented as the mean ± standard error and plotted using Origin 2024. The experiments were repeated six times, with significance set at $P < 0.05$.

3. Results and discussion

3.1. Muscle fiber type

Muscle fiber type is closely related to meat quality (Sun et al., 2024). Joo et al. (2013) believed that meat quality was essentially determined by muscle fiber characteristics, and it was feasible to control the quality of fresh meat by manipulating these characteristics. Fig. 1 displays the changes of inulin on muscle fiber type. The control group had a type I muscle fiber area ratio of 67.32 %, whereas the treatment groups had ratios of 70.14 %, 71.46 %, and 70.35 %, respectively. The results indicate that inulin can increase type I muscle fiber content and decrease type II muscle fiber content in duck meat. The impact of inulin on muscle fiber types may be related to its function as a dietary fiber. Han et al. (2020) reported that a high dietary fiber diet reduced type II muscle fibers in pork, which was consistent with our findings. In addition, previous studies have found that a higher content of type I muscle fibers in meat could improve tenderness, juiciness and redness (Joo et al., 2013; Sun et al., 2024; Wen et al., 2022); the results of meat quality (Table 1) in this study confirmed these findings.

3.2. Meat quality

The pH change in the muscle is associated with lactic acid produced by glycolysis after animal slaughter. Substantial accumulation of lactic acid can cause the pH to decrease (Zhang, Mao, Li, Luo, & Hopkins, 2019). Meanwhile, the changes in pH can affect the physical properties of meat, including tenderness, water-holding capacity, and meat color (Utari et al., 2023). As shown in Table 1, dietary inulin supplementation had no significant difference ($P > 0.05$) on pH at 15 min post-slaughter. However, the pH at 24 h post-slaughter in the three treatment groups was higher than ($P < 0.05$) that in the control group, although there were no significant differences among the three treatment groups. Type I muscle fibers have a lower glycogen content than type II muscle fibers (Joo et al., 2013). Glycogen undergoes glycolysis to produce lactic acid in the muscles (Han et al., 2020). Hence, the accumulation of lactic acid in type I muscle fibers is lower than that in type II muscle fibers (Joo et al., 2013). In this study, inulin increased type I muscle fibers which reduced lactic acid accumulation, thereby decreasing pH reduction. Moreover, pH is closely related to meat quality, and a significant drop in

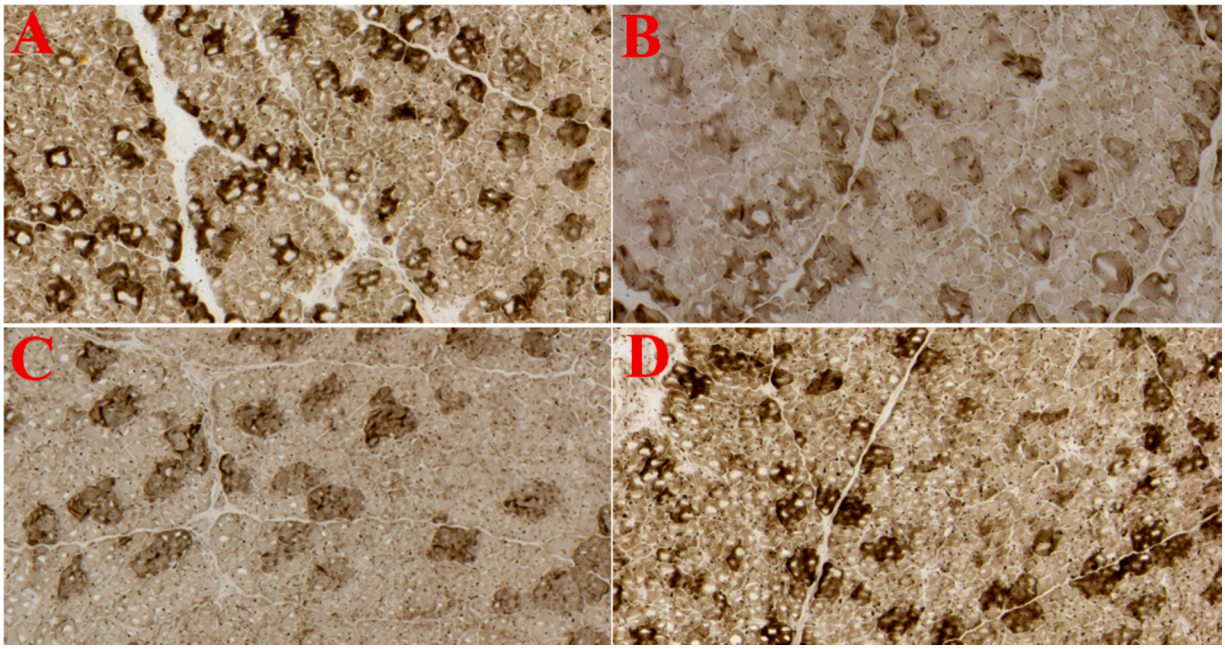

Fig. 1. Effect of dietary inulin on the muscle fiber types in duck meat. A: Control group; B: INU10 group; C: INU20 group; D: INU30 group.

Table 1
Effect of dietary inulin on meat quality in duck meat.

	Control	INU10	INU20	INU30
pH_{15min}	5.79 ± 0.03a	5.92 ± 0.04a	5.83 ± 0.06a	5.93 ± 0.06a
pH_{24h}	5.13 ± 0.04b	5.33 ± 0.03a	5.39 ± 0.04a	5.37 ± 0.02a
Shear force (N)	42.94 ± 0.74a	32.53 ± 0.64b	25.04 ± 0.44d	29.91 ± 0.46c
Pressure water loss (%)	17.79 ± 0.42a	16.70 ± 0.46ab	15.89 ± 0.43b	16.27 ± 0.39b
L^*_{15min}	39.11 ± 0.47a	36.21 ± 0.30b	35.83 ± 0.17b	36.64 ± 0.23b
a^*_{15min}	13.43 ± 0.33b	14.55 ± 0.31a	15.19 ± 0.14a	14.60 ± 0.21a
b^*_{15min}	8.75 ± 0.19a	7.62 ± 0.18b	6.97 ± 0.12c	7.34 ± 0.10bc
L^*_{24h}	49.24 ± 1.11a	43.68 ± 0.45b	40.78 ± 0.52c	42.85 ± 0.22bc
a^*_{24h}	15.47 ± 0.19c	17.05 ± 0.09b	18.25 ± 0.18a	17.21 ± 0.32b
b^*_{24h}	10.49 ± 0.13a	9.79 ± 0.05bc	9.63 ± 0.05c	9.91 ± 0.04b

The letters a–c indicate significant differences ($P < 0.05$) among different groups.

pH after animal slaughter can degrade meat quality (Zhang et al., 2019). Table 1 illustrates the impact of inulin on the shear force and pressure water loss in duck meat. The shear force and pressure water loss of all treatment groups were significantly lower than those in the control group, demonstrating that dietary inulin enhanced the tenderness and WHC of duck meat. In addition, the INU20 group showed the lowest shear force and pressure water loss, suggesting that a dose of 20 g/kg is an appropriate level of dietary inulin supplementation. The current results were consistent with those of Grela, Swiatkiewicz, Florek, Bakowski, and Skiba (2021) who reported inulin improved the tenderness and water retention of pork. Furthermore, Hwang, Kim, Jeong, Hur, and Joo (2010) found that an increase in type I muscle fibers could improve tenderness, aligning with the results of this study. Joo et al. (2013) suggested that higher type I muscle fibers could result in higher WHC and juiciness of meat, which was confirmed by our results.

The meat color serves as the most direct impression of meat quality for consumers, which directly affects their purchasing decisions (Sun, Zhao, Zhao, & Sun, 2023). The impact of inulin on color is delineated in Table 1. After slaughter 15 min, the L^* of the treatment groups were significantly lower than ($P < 0.05$) those of the control group; however, there were no significant difference among the three inulin groups. At 24 h post-slaughter, L^* in the three dietary inulin groups is significantly lower than the control group, respectively, with a notable decrease of 17.18 % in the INU20 group. The higher L^* is due to the increased light reflection resulting from the exudation of moisture from the meat (Jin et al., 2021). Dietary inulin could enhance the WHC by increasing the immobile water content (Fig. 3). Thus, dietary inulin reduces L^* by enhancing the WHC of duck meat. Wang et al. (2023) found that dietary plant polysaccharides supplementation led to a lower L^*, which was consistent with our results. In comparison with the control group, the a^*_{15min} and a^*_{24h} shows significant increase ($P < 0.05$), with INU20 exhibiting the highest values at 15.19 and 18.25, respectively. Changes in a^* are related to myoglobin (Mb) content in muscle (Turgut, Işıkçı, & Soyer, 2017). Type I muscle fibers contain more Mb, leading to meat redness (Li, Liang, et al., 2022), which is consistent with the muscle fibers results (Fig. 1) in this study. In addition, the rate of oxygen consumption in meat is an important factor for meat color (Joo et al., 2013). Jin et al. (2021) believed that the antioxidant capacity of muscle was positively correlated with redness in duck meat, which was supported by the antioxidant ability results (Fig. 2) in this study. However, Wang et al. (2019) reported that dietary inulin did not improve the redness of pork, which may be related to low level of dietary supplementation. In this study, the b^* at 15 min post-slaughter for the three treatment groups are lower than the control group. Furthermore, the $b^*$of the control group is higher than INU20, INU10, and INU30 groups by 7.15 %, 8.93 %, and 8.58 % at 24 h post-slaughter, respectively. These results demonstrate that dietary inulin can reduce meat yellowness. b^* is positively correlated with the degree of lipid oxidation (Sun, Zhao, Zhao, & Sun, 2023). Therefore, the reduction in b^* was related to the decreased post-slaughter muscle lipid oxidation by inulin, as confirmed by the TBARS

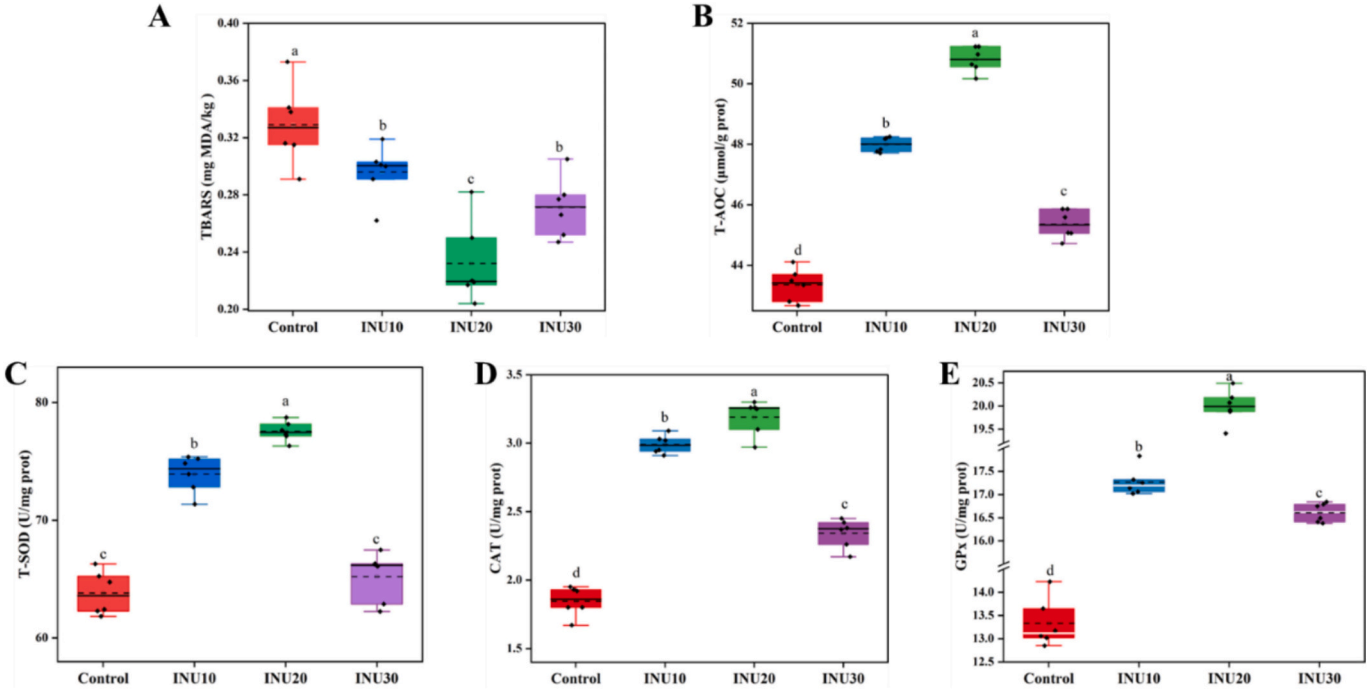

Fig. 2. Effect of dietary inulin on the antioxidant capacity in duck meat. A: TBARS; B: T-AOC; C: T-SOD; D: CAT; E: GPx. The letters a–d indicate significant differences ($P < 0.05$) among different groups.

results (Fig. 2A). Overall, dietary supplementation with inulin resulted in a redder appearance of duck meat, providing a better visual effect.

3.3. Antioxidant ability

Oxidative reactions occur in animal muscles after slaughter and lead to a decline in meat quality (Zhang et al., 2019). Consequently, the antioxidant capacity of muscles is closely related to meat quality. As presented in Fig. 2A, dietary inulin significantly reduced TBARS values in duck meat compared to the control, with the maximum reduction occurring in the INU20 group (29.49 %). There was no significant difference ($P > 0.05$) in the TBARS values between the INU10 and INU30 groups. TBARS represents the malondialdehyde content in meat and is negatively correlated with antioxidant capacity (Sun, Zhao, Zhao, & Sun, 2023). Therefore, inulin delayed the lipid oxidation and promoted the antioxidant capacity of duck meat. These results are similar to those of Grela et al. (2021), who reported that dietary supplementation with inulin significantly reduced the TBARS value in pork. Moreover, the expression of antioxidant enzymes in post-slaughter meat reflects its antioxidant capacity (Wang et al., 2023). Fig. 2B-E displays the effect of dietary inulin supplementation on T-AOC, T-SOD, CAT, and GPx in duck meat. The trends in variation across the four indicators were similar. Dietary inulin supplementation improved the activity of T-AOC, T-SOD, CAT, and GPx in duck meat, with the INU20 group exhibiting the best antioxidant capacity, which consistent with results on tenderness and water-holding capacity. A previous study reported that dietary inulin increased the expression levels of GPx, CAT, T-AOC, and T-SOD in pork (Wang et al., 2019), which was similar to our results. Wang et al. (2023) believed that the activity of antioxidant enzymes positively correlated with qualities such as tenderness and WHC; this viewpoint confirmed by the results of this study.

3.4. LF-NMR

Fig. 3 depicted the effect of inulin on water distribution in duck meat. As presented in Fig. 3A, three peaks were detected, reflecting the changes and contents of the three water states in the meat. T_{2b} represents bound water, T_{21} represents immobile water, and T_{22} represents free water. The peak areas corresponding to the three types of water are denoted as PT_{2b}, PT_{21}, and PT_{22}. As depicted in Fig. 3B, there were no significant differences in T_{2b} in different groups, and the peak areas PT_{2b} (Fig. 3C) has same result, demonstrating that dietary inulin did not affect the distribution and content of bound water in duck meat. In terms of immobile water, the T_{21} of the INU20 group was the smallest, showing a significant difference ($P < 0.05$) compared to the control group. The peak area results illustrate that PT_{21} of the INU20 group is significantly higher than control, suggesting that 20 g/kg inulin supplementation to diet affects proton migration of duck meat, reducing water mobility and retaining immobile water. Conversely, the INU20 group exhibited the lowest amount of free water, indicating inulin can reduce the content of free water in meat. Previous studies have found that a higher content of free water content indicates higher water loss, whereas higher immobile water content indicates better water retention (Kong et al., 2022; Sun et al., 2024; Wang et al., 2023). Free water is often derived from the transformation of bound water and immobile water in the meat. Hence, these results suggested that inulin effectively mitigated the transformation of immobile water into free water, consequently augmenting the WHC. Wang et al. (2023) reported that dietary polysaccharides reduced the content of free water in chicken, while increasing immobile water, which was consistent with our results. Furthermore, some studies have suggested that lipid oxidation disrupted cell membrane integrity, leading to the increase of water loss (Cheng et al., 2016; Xia, Kong, Liu, & Liu, 2009). In this study, inulin effectively inhibited lipid oxidation (Fig. 2A), increased the content of immobile water, and enhanced water retention in duck meat.

3.5. Amino acid content

Amino acid content is a pivotal indicator for assessing the nutrition and flavor of meat (Wang et al., 2023). As depicted in Table 2, there were no differences ($P > 0.05$) in the total amino acid content among all the groups. However, some amino acids which are related to flavor showed significant differences. Dietary inulin increased ($P < 0.05$) the umami and sweet amino acids, such as Asp, Glu, and Ala, and reduced

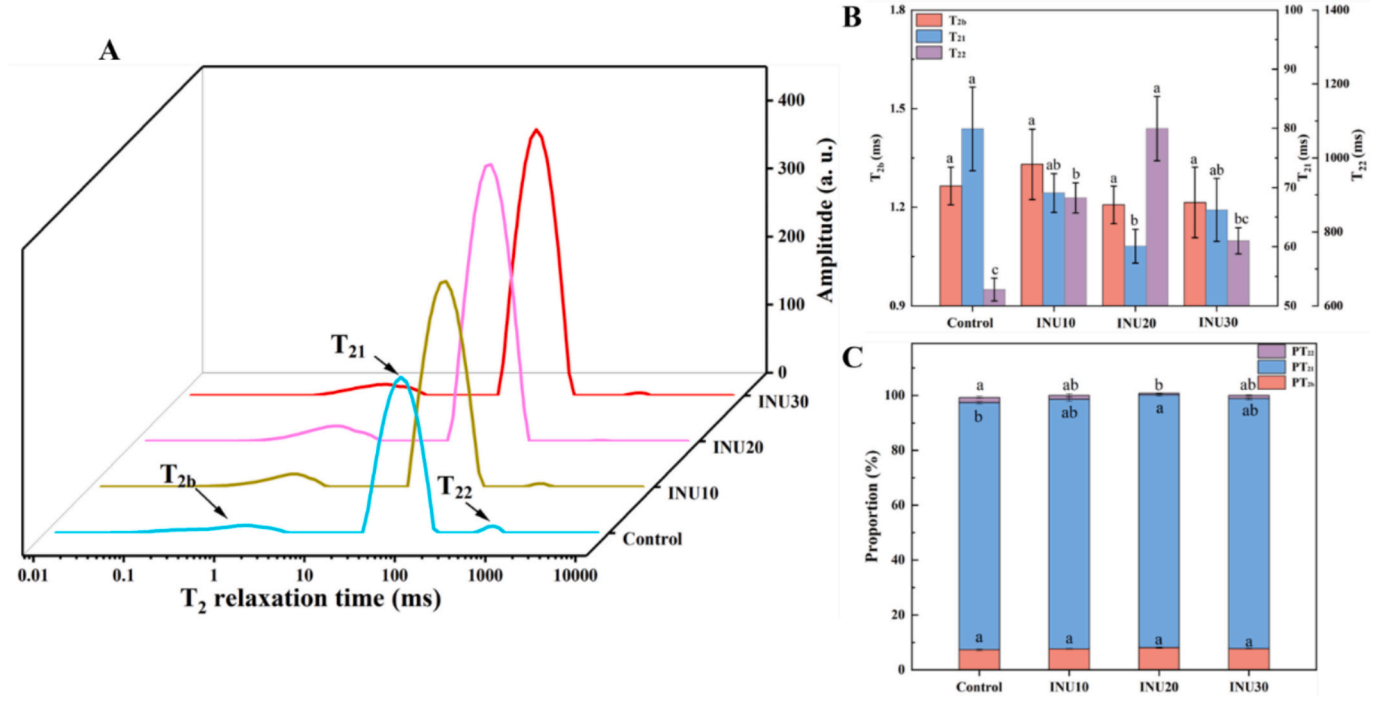

Fig. 3. The curves of the LF-NMR T_2 relaxation times (A), relaxation times T_2 (B) and the peak area ratio PT_2 (C) of duck meat with different levels of dietary inulin supplementation. The letters a–c indicate significant differences ($P < 0.05$) among different groups.

Table 2
Effect of dietary inulin on amino acids content in duck meat.

Amino acid (%)	Samples				
	Control	INU10	INU20	INU30	Taste
Asp	5.71 ± 0.36c	6.33 ± 0.42bc	7.24 ± 0.41a	6.58 ± 0.50ab	umami
Thr	4.18 ± 0.16a	4.01 ± 0.17ab	3.73 ± 0.13bc	3.65 ± 0.15c	sweet
Ser	3.02 ± 0.21a	2.66 ± 0.19b	2.79 ± 0.17ab	2.90 ± 0.13ab	sweet
Glu	10.55 ± 1.43a	12.42 ± 1.74a	12.37 ± 1.45a	12.62 ± 1.68a	umami
Gly	2.57 ± 0.08a	2.42 ± 0.07ab	2.24 ± 0.05bc	2.17 ± 0.05c	sweet
Ala	3.66 ± 0.15b	4.16 ± 0.18ab	4.28 ± 0.23a	3.91 ± 0.14ab	sweet
Val	3.13 ± 0.19a	1.55 ± 0.20b	2.97 ± 0.17a	1.71 ± 0.19b	bitter
Met	2.06 ± 0.15a	1.78 ± 0.17ab	1.62 ± 0.11b	1.87 ± 0.15ab	bitter
Ile	3.62 ± 0.03a	3.59 ± 0.08a	3.31 ± 0.08b	2.98 ± 0.13c	bitter
Leu	5.57 ± 0.19c	6.03 ± 0.14b	6.43 ± 0.16a	6.67 ± 0.15a	bitter
Tyr	3.38 ± 0.05a	3.14 ± 0.09b	2.87 ± 0.17c	3.36 ± 0.09a	tasteless
Phe	3.15 ± 0.02a	3.23 ± 0.07a	3.18 ± 0.04a	3.20 ± 0.03a	bitter
Lys	7.11 ± 0.32a	6.46 ± 0.24ab	5.90 ± 0.31c	6.37 ± 0.43b	tasteless
His	2.75 ± 0.03a	2.62 ± 0.02b	2.47 ± 0.05c	2.80 ± 0.03a	bitter
Arg	4.46 ± 0.16a	4.47 ± 0.17a	4.39 ± 0.13a	4.46 ± 0.15a	bitter
Pro	4.04 ± 0.12a	3.90 ± 0.13ab	3.71 ± 0.11b	3.61 ± 0.08b	sweet
Total	68.46 ± 1.09a	68.21 ± 2.01a	68.35 ± 3.15a	67.72 ± 3.12a	

The letters a–c indicate significant differences ($P < 0.05$) among different groups.

some bitter amino acids, such as Met, Ile and His. Moreover, inulin decreased the content of tasteless amino acids such as Tyr and Lys. These results indicate that dietary inulin affects the amino acid composition to change the nutritional value and flavor of duck meat. Asp, Glu and Ala are precursors in meat that can form pleasant volatile flavors (Xu et al., 2019). Notably, Glu is a component of the commonly used flavor enhancer monosodium glutamate, which buffers and neutralize unpleasant tastes in food (Yan et al., 2018). Hence, an increase in these amino acids can reduce the off-flavor of duck meat. It has been demonstrated that His and Tyr are easily broken down into biogenic amines, leading to strong fishy odors and spoilage (Sun, Zhao, Zhao, & Sun, 2023). In addition, Li et al. (2022b) reported that type I muscle fibers were positively correlated with the levels of taste-active amino acids in pig. In this study, the group (INU20) with a higher type I muscle fibers content, showed more umami and sweet amino acids, which is consistent with the finding of Li et al. (2022b). Hence, dietary inulin improves the flavor of duck meat by adjusting the amino acid composition.

3.6. Volatile flavor compounds

The off-flavor of duck meat significantly affects consumer purchase desire (Sun et al., 2023b), so making it essential to evaluate the volatile flavor compounds. As depicted in Table 3, eight types of aldehydes were identified; seven types of hydrocarbons (alkanes and alkenes), alcohols, and esters were each detected, and ketones, furans, and acids were found in two, one, and five types, respectively.

Aldehydes are closely associated with the off-flavor of duck meat (Sun et al., 2023b). In comparison to the control group, dietary inulin significantly reduced ($P < 0.05$) the total content of aldehydes in duck meat, especially in the INU10 and INU20 groups, which decreased by 27.96 % and 26.36 %, respectively. Moreover, inulin reduced the levels of hexanal, octanal, nonanal, (Z)-2-nonenal, (E)-2-octenal, and benzaldehyde in the duck meat. Among these aldehydes, hexanal, octanal, nonanal, and (E)-2-octenal are recognized as sources of the off-flavor in duck meat (Zhao et al., 2024; Zhen et al., 2022). Benzaldehyde, which has a bitter almond flavor, is a product of amino acid degradation (Watanabe et al., 2015). Overall, dietary inulin can significantly reduce aldehydes associated with off-flavor, thereby improving the flavor of duck meat.

As presented in Table 3, there were significant differences in hydrocarbons (alkanes and alkenes) among all the groups. Inulin reduced ($P < 0.05$) the hydrocarbons content of duck meat. However, owing to the high flavor thresholds of hydrocarbons, their contribution to flavor is minor (Zhao et al., 2024). Furthermore, the detection of hydrocarbons is highly unstable. The control group detected four kinds of hydrocarbons, whereas INU10, INU20 and INU30 detected four, six, and five types, respectively. Some compounds such as 1,2-epoxytetradecane, 3,5-dimethyl-1-hexene and pentyl-cyclopropane, were detected in only one or two groups. Ventanas, Mustonen, Puolanne, and Tuorila (2010) reported that alkanes and alkenes are intermediates in the synthesis of certain heterocyclic compounds, leading to their lower detection levels, which can explain the aforementioned phenomenon. Jin et al. (2021) described that dietary resveratrol increased the content of alkanes and alkenes in duck meat, which was inconsistent with our results. These contradictory results may be due to different dietary additives and the instability of hydrocarbons detection.

Most alcohols have high thresholds and contribute little to meat flavor (Sun et al., 2023b). In this study, dietary inulin reduced the total alcohols content. Alcohols generation is related to the degradation of peroxides formed by lipid oxidation (Jin et al., 2021). Dietary inulin reduced the level of lipid oxidation (Fig. 2A) in duck meat, which may explain the observed decrease in alcohols contents. Among the alcohols, 1-octen-3-ol is noteworthy for its earthy, mushroom-like odor and low flavor threshold, significantly contributing to the off-flavor of duck meat (Sun et al., 2023b). Ketones are intermediate in the synthesis of some heterocyclic compounds. 2-Heptanone has been reported to be associated with the off-flavor of duck meat (He et al., 2020). Inulin significantly reduced the content of 2-heptanone, indicating that inulin reduces the off-flavor of duck meat. Compared to the control, the content of 2,3-octanedione was reduced in the INU10 and INU20 groups. This result was similar to the finding of Jin et al. (2021), who found that resveratrol reduced the 2,3-octanedione concentration in duck meat.

Low quantities of esters, acids, and furans were also detected in this study. Esters and acids have high flavor thresholds and contribute minimally to the flavor of duck meat (Sun et al., 2023b). Esters are formed by the esterification of aldehydes, alcohols, and acids (Fu et al., 2022). As shown in Table 3, inulin reduced the total content of esters, which was likely related to its significant reduction in aldehydes and alcohols. Compared to the control, the total acid content increased in the INU20 group, significantly dropped in the INU30 group, and showed no significant difference in the INU10 group. The increase in the acid content may be due to the conversion of some aldehydes by aldehyde dehydrogenase (Guo et al., 2021). 2-Pentyl-furan provides a pleasant fruity aroma (Liu et al., 2014). The 2-pentyl-furan in the INU20 group was higher than the control group, indicating that dietary inulin improving the flavor of duck meat. The degradation of fat in duck meat post-slaughter is a major pathway for producing volatile compounds (Fu et al., 2022). In the present study, lipid oxidation was significantly inhibited (Fig. 2A), which might explain the reduced total volatile content in the dietary inulin group. Lipid oxidation is directly related to the levels of reactive oxygen species (ROS) and lipoxygenase (LOX) enzymes (He et al., 2020). Previous studies have reported that inulin reduced the ROS production and the LOX enzymes expression (Lachowicz, Świeca, & Pejcz, 2020). In addition, the characteristic off-

Table 3
Effect of dietary inulin on volatile flavor compounds in duck meat.

Volatile compounds (ng/g)	Control	INU10	INU20	INU30	CAS ID
Aldehydes					
Hexanal	19.25 ± 0.85a	12.21 ± 0.39c	11.38 ± 0.42c	13.38 ± 0.47b	66–25-1
Octanal	21.51 ± 0.55a	16.23 ± 0.77b	14.89 ± 0.32c	15.54 ± 0.34bc	124–13-0
Nonanal	38.42 ± 1.16a	25.87 ± 0.97d	27.74 ± 0.57c	30.49 ± 1.03b	124–19-6
Dodecanal	0.00 ± 0.00c	0.00 ± 0.00c	2.34 ± 0.07a	1.46 ± 0.05b	112–54-9
2-Undecenal	6.97 ± 0.10c	7.33 ± 0.28bc	7.56 ± 0.20b	8.31 ± 0.18a	2463-77-6
(Z)-2-Nonenal	5.65 ± 0.36a	3.79 ± 0.14b	3.98 ± 0.22b	3.77 ± 0.09b	60,784–31-8
(E)-2-Octenal	8.10 ± 0.39a	6.37 ± 0.47b	5.51 ± 0.28c	5.97 ± 0.14bc	2548-87-0
Benzaldehyde	3.97 ± 0.20a	2.97 ± 0.09bc	2.71 ± 0.14c	3.09 ± 0.26b	100–52-7
Total	103.81 ± 2.34a	74.78 ± 1.60c	76.45 ± 1.08c	82.02 ± 1.63b	
Hydrocarbons					
Hexadecane	4.21 ± 0.10c	5.37 ± 0.09a	2.49 ± 0.16d	4.87 ± 0.22b	544–76-3
1,2-epoxytetradecane	3.78 ± 0.14a	0.00 ± 0.00c	1.23 ± 0.03b	0.00 ± 0.00c	3234-28-4
3,5-dimethyl-1-hexene	0.00 ± 0.00b	0.00 ± 0.00b	2.24 ± 0.10a	0.00 ± 0.00b	7423-69-0
1-Nonene	8.98 ± 0.64b	8.44 ± 0.37b	10.32 ± 0.48a	6.31 ± 0.55c	124–11-8
Cyclopropane, pentyl-	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00b	1.24 ± 0.07a	2511-91-3
Dodecane,2,6,11-trimethyl-	0.00 ± 0.00d	1.25 ± 0.13b	1.97 ± 0.06a	0.57 ± 0.03c	31,295–56-4
Octadecane, 6-methyl-	9.34 ± 1.24a	2.04 ± 0.07c	1.57 ± 0.22c	3.38 ± 0.39b	10,544–96-4
Total	25.98 ± 1.55a	17.10 ± 0.66c	19.82 ± 0.91b	16.38 ± 1.17c	
Alcohols					
1-Nonanol	3.37 ± 0.12b	2.99 ± 0.24c	3.67 ± 0.18a	1.91 ± 0.10d	143–08-8
1-Octen-3-ol	33.54 ± 2.31a	25.87 ± 3.34b	26.27 ± 1.74b	24.39 ± 1.65b	3391-86-4
1-Hexanol	16.68 ± 2.27b	18.89 ± 1.46b	12.54 ± 2.01b	20.27 ± 2.56a	111–27-3
6-Methyl-5-hepten-2-ol	6.34 ± 1.01a	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00b	1569-60-4
2-Methyl-1-hexadecanol	5.21 ± 0.47a	3.67 ± 0.33b	0.00 ± 0.00c	4.27 ± 0.50b	22,104–78-5
1-Pentanol	46.97 ± 3.58a	32.48 ± 4.21c	39.71 ± 1.68b	50.88 ± 3.03a	71–41-0
(E)-2-Octen-1-ol	10.78 ± 1.69a	6.97 ± 0.55b	7.21 ± 0.87b	7.93 ± 1.21b	18,409–17-1
Total	122.89 ± 3.73a	90.87 ± 3.94c	89.40 ± 5.52c	109.65 ± 3.86b	
Esters					
Dodecyl acrylate	1.25 ± 0.03b	4.37 ± 0.14a	0.00 ± 0.00c	0.00 ± 0.00c	2156-97-0
Dodecanoic acid, ethyl ester	0.00 ± 0.00c	0.00 ± 0.00c	3.61 ± 0.23a	2.19 ± 0.11b	106–33-2
Nonanoic acid, ethyl ester	0.00 ± 0.00c	1.32 ± 0.08b	3.97 ± 0.07a	0.00 ± 0.00c	123–29-5
Decanoic acid, ethyl ester	5.32 ± 0.48a	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00b	110–38-3
Octanoic acid, ethyl ester	6.47 ± 0.19a	0.00 ± 0.00b	0.00 ± 0.00b	0.00 ± 0.00b	106–32-1
Hexanoic acid, ethyl ester	4.97 ± 0.12b	5.55 ± 0.18a	5.47 ± 0.24a	4.81 ± 0.14c	123–66-0
Total	18.01 ± 0.34a	11.24 ± 0.25c	13.05 ± 0.25b	7.00 ± 0.17d	
Ketones					
2-Heptanone	15.67 ± 1.88a	8.31 ± 0.83b	6.24 ± 0.61c	9.29 ± 1.45b	110–43-0
2,3-Octanedione	101.57 ± 8.49b	85.37 ± 5.47c	89.96 ± 8.30bc	114.57 ± 5.39a	585–25-1
Total	117.27 ± 6.78a	93.58 ± 3.83b	96.17 ± 8.20b	123.85 ± 3.49a	
Furan					
2-Pentyl-furan	5.57 ± 0.58c	8.79 ± 0.24b	10.32 ± 0.24a	4.31 ± 0.26d	3777-69-3
Acids					
Octanoic acid	8.31 ± 0.38b	6.27 ± 0.61c	9.39 ± 0.55a	3.54 ± 0.52d	124–07-2
Nonanoic acid	1.06 ± 0.05c	2.34 ± 0.11b	5.47 ± 0.31a	5.71 ± 0.29a	112–05-0
Dodecanoic acid	0.00 ± 0.00d	1.39 ± 0.10b	2.28 ± 0.13a	0.90 ± 0.07c	143–07-7
Decanoic acid	5.67 ± 0.37a	3.21 ± 0.28b	2.67 ± 0.11c	3.68 ± 0.32b	334–48-5
Pentadecanoic acid	0.00 ± 0.00b	3.14 ± 0.14a	0.00 ± 0.00b	0.00 ± 0.00b	1002-84-2
Total	15.04 ± 0.77bc	16.35 ± 1.02b	19.81 ± 1.08a	13.83 ± 1.19c	
Total	408.58 ± 7.63a	312.71 ± 6.85d	325.02 ± 3.35c	357.05 ± 6.53b	

The letters a–d indicate significant differences ($P < 0.05$) among different groups.

flavor substances in ducks are mainly nonanal, octanal, heptanal, decanal, pentanal, hexanal, *(E)*-2-octenal, *(E)*-2-heptenal, 2-methyl-butanal, p-cresol, 3-methyl-butanal, 2-heptanone, and 1-octene-3-ol (Pu et al., 2022; Zhao et al., 2024). Although not all of the above substances were detected in this study, the content of the detected off-flavor compounds (Table 3) significantly decreased after dietary inulin supplementation. This may be related to the inulin enhancing the antioxidant capacity of ducks, thereby inhibiting the oxidation of duck meat, especially lipid oxidation. Wang et al. (2023) suggested that the improvement in flavor was related to lipid oxidation. Therefore, inulin significantly inhibited lipid oxidation in this study, which might lead to improvements of duck meat flavor.

4. Conclusion

This study investigated the impact of dietary inulin supplementation (0–30 g/kg) on muscle fiber types, meat quality, antioxidant ability, and off-flavor in duck meat. Dietary inulin supplementation, especially at 20 g/kg, significantly improved meat quality, including tenderness, WHC, and color. Inulin increased the immobile water content in duck meat, thereby reducing moisture loss. Moreover, dietary inulin adjusted the amino acid composition by increasing the umami and sweet amino acids

content, which affects the nutritional value and flavor of duck meat. Inulin decreased the content of off-flavor compounds of duck meat. These changes in duck meat might be attributed to dietary inulin augmenting the proportion of type I muscle fibers and enhancing the antioxidant capacity. In summary, dietary inulin may be an effective strategy for producing high quality duck meat and removing duck off-flavor. Further study can reveal the relevant mechanisms from perspectives of metabolomics and gut microbiome.

CRediT authorship contribution statement

Hailei Sun: Writing – original draft, Methodology, Data curation, Conceptualization. **Jia Wang:** Writing – original draft, Methodology. **Jina Han:** Writing – review & editing, Investigation. **Xiaolong Li:** Methodology, Data curation. **Juan Zhao:** Resources. **Yimin Zhang:** Writing – review & editing, Resources, Conceptualization. **Jingxin Sun:** Funding acquisition.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fochx.2024.102148.

Data availability

Data will be made available on request.

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