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Effects of maternal vitamin D_3 status on quality characteristics of pork batters in offspring pigs during cold storage

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Abstract

Seventy-two offspring pigs (150 d) from 27 sow (9 sows per group) fed different vitamin D_3 levels were used to evaluate the effects of maternal vitamin D_3 status and postmortem cold storage on cooking loss, color, texture profile analysis (**TPA**), low-field nuclear magnetic resonance (**LF-NMR**) T_2 relaxation times and dynamic rheological of gel properties of chilled pork batters in offspring pigs. Sows were allotted to low, normal, and high dietary vitamin D_3 groups which contained 200 (**LD**), 800 (**ND**), and 3200 (**HD**) IU of vitamin D_3/kg basal diet, respectively. Results showed that HD group had higher a* value, hardness, cohesiveness, springiness, chewiness, and storage modulus (G') values, while had lower cooking loss, L* value, T_{21} and T_{22} relaxation time compared with LD group during postmortem cold storage period ($P < 0.05$). In addition, cold storage time increased cooking loss and b* values of LD and ND groups, TPA parameters, T_{22} relaxation time and G' values of all experimental groups, while decreased a* and L* values of LD and ND groups ($P < 0.05$). The results revealed that maternal high-dose vitamin D_3 levels influenced these indicators of chilled pork batters in offspring pigs, which improved the quality attributes during postmortem cold storage.

Keywords: vitamin D_3; offspring pigs; pork batters; cold storage; quality attributes.

Practical Application: Vitamin D_3 affects the quality of pork batters.

1 Introduction

Previous studies found that maternal nutrition status during pregnancy influenced the development of fetal muscle, and postnatal health of offspring through regulating the environment in the uterus (Godfrey & Barker, 2000; Musser et al., 2004; Zhu et al., 2006). The development of skeletal muscle in the early to mid-gestation period has an important influence on the number and composition of offspring muscle fibers in cattle (Zhu et al., 2006). And other researcher observed that maternal nutritional (energy) restriction during late pregnancy decreased the expression of genes in muscle of offspring calves, which indicated that alterations in the intra-uterine environment could change prenatal development and muscle development (Sanglard et al., 2018; Costa et al., 2021). In the lipid metabolism, vitamin D has potential nutritional regulation in animals (Wang et al., 2016). Maternal vitamin D_3 levels affected intramuscular adipocyte commitment and differentiation in piglets by regulating adipogenesis related genes expression (Guo et al., 2020a). Maternal vitamin D deficiency during pregnancy promoted the proliferation and differentiation of pre-adipocytes, and resulted in offspring obesity (Wen et al., 2018). In addition, maternal vitamin D levels during late pregnancy also affects the development of offspring muscle (Harvey et al., 2014). For example, this study found that prenatal and postnatal skeletal muscle development in offspring pigs was thought to rise maternal vitamin D levels, possibly due to the involvement of vitamin D_3 in the myogenic signaling pathway in the expression of muscle transcription factors (Zhou et al., 2016). Intramuscular fat (**IMF**) deposition affects meat quality of animals, and appropriate amount of IMF can promote the taste, juiciness and tenderness of meat, which enhancing the meat quality (Li et al., 2020b). Therefore, IMF is important for meat palatability, and adipocytes in embryonic stage can provide deposition site for increasing IMF content in later fattening stage (Tong et al., 2008; Du et al., 2010). Our previous work demonstrated that maternal vitamin D_3 supplementation significantly boosted IMF accumulation and meat quality in offspring pigs (Guo et al., 2020a; 2020b). Therefore, adjustment of maternal nutritional status is considered to be an effective method to increase adipogenesis in fetal muscle, and enhance marbling of offspring (Du et al., 2013). Enhancing evidence showed that the condition of postmortem storage has also become an important factor affecting meat quality, and pork batters can reduce the rate of fat and protein oxidation when stored at low temperature (Pomponio & Ruiz-Carrascal, 2017). In addition, pork can effectively improve the ability of myofibrillar protein hydrolysis and increase flavor and water retention in the process of postmortem ripening (Li et al., 2009). There is no doubt

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about the influence of maternal vitamin D_3 supplementation on pork quality of offspring. Nonetheless, little is known about how maternal vitamin D_3 supplementation affects the quality of offspring minced pork during storage. Therefore, the purpose of this study was to explore the effects of maternal vitamin D_3 levels on cooking loss, meat color, texture properties, low-field NMR T_2 relaxation time and dynamic rheological properties of chilled pork batters of offspring during postmortem storage.

2 Materials and methods

2.1 Animals and diets

All handling protocols related to animals were approved by the Henan Institute of Science and Technology Institutional Animal Care and Use Committee (No. 2020HIST013, Xinxiang, P.R. China). All offspring pigs used in this study originated from sows fed various vitamin D_3 levels (during pregnancy), all diets and experimental design for sows and their offspring pigs as described in our previous companion reports (Guo et al., 2020b; Guo et al., 2021) Sows during pregnancy were previously added 200 (**LD**), 800 (**ND**), and 3200 (**HD**) IU of vitamin D_3 per kg diet, respectively. While their offspring pigs were fed the same vitamin D_3 diet, and the feeding experiment lasted for 150 days.

2.2 Tissue collection

Six offspring pigs per each group (2 offspring pigs per replicate, randomly selected) were slaughtered based on body weight and gender (Miao et al., 2009). After slaughtering, the carcass was split longitudinally. The *longissimus* dorsi muscle was divided into three parts and refrigerated at 4 °C for 0, 24 and 48 h, respectively. Muscle sample was grinded using a meat grinder (6 mm), and weighed 200 g, added 20% ice water and 2% NaCl to each sample.

2.3 Cooking loss measurement

Samples of pork batters were separately packed with a plastic bag and kept in 85 °C water for 20 min. Samples of cooked pork batters were chilled to room temperature for 30 min. Wipe off the surface exudates with absorbent paper. The cooking loss was calculated according to the percentage weigh ratio of pork batters before and after cooking (Choi et al., 2016) (Equation 1).

$$Cooking\ loss\ (\%) = (M_b - M_a)/M_b \quad (1)$$

In this equation, M_b and M_a represent the weight of pork batters before and after cooking (Zhang et al., 2019).

2.4 Color measurement

The exudates from the surface of cooked pork batters are wiped off using absorbent paper. After storage in refrigerator at 4 °C for 0, 24 and 48 h, the color of pork batters in offspring pigs was determined with a colorimeter (Konica Minolta CR 410, Sensing Inc, Osaka, Japan). The meat color contained lightness (L*), redness (a*) and yellowness (b*) value, respectively (Jia et al., 2012).

2.5 TPA (Texture profile analysis)

The cooked pork batters were stored in refrigerator at 4 °C for 0, 24 and 48 h, and then sorted into cylinders with a diameter of 2 cm and a height of 3 cm. And then, the texture of the samples was determined using P/36R probe. Each sample was measured three times in parallel, and then the average values of springiness, hardness, chewiness, and cohesiveness were analyzed.

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

LF-NMR imaging analyzer (NMI20-040V-I, Suzhou Newmai Analytical instrument Co., Ltd.) was used to determine the transverse relaxation times of cooked pork batters of offspring pigs according to the previously reported methods (Zhang et al., 2019; Straadt et al., 2007). Briefly, cooked pork batters in offspring pigs were sorted into cylinders with a diameter of 1.5 cm and a height of 3 cm, and each cylinder was put into a cylindrical tube with a diameter of 1.5 cm and a height of 5 cm. The Carr-Purcell-Meiboom-Gill pulse sequence was used to determine the transverse relaxation time (T_2) of LF-NMR at 32 °C, 200 μs (between 90°and 180° pulse), and 22.4 MHz resonance frequency. In total 2000 echoes (contain 8 scans) were obtained from each sample, and the scan interval time was 3 s. Meanwhile, each meat sample was measured three times in parallel, the average value of relaxation time was calculated.

2.7 Dynamic rheological measurement

The MCR301 Dynamic Rheometer (HAAKE MARS Rotary, Thermo Scientific co., Germany) with a 50 mm parallel steel plate geometry (0.5 mm gap) was used to determine dynamic rheological difference. Briefly, the raw pork batters were placed between the flat parallel plates which coated with a layer of silicone oil, and were performed at a rate 2 °C/min from 20 °C to 80 °C. An oscillatory mode of 10% was carried out to shear the samples at a fixed frequency of 0.1 Hz. Each sample was measured three times in parallel, and the change of storage modulus (G') with temperature was determined during the heating (Kang et al., 2017; Zhu et al., 2019).

2.8 Statistical analysis

In the present study, statistical analysis was performed with the one-way Analysis of Variance (ANOVA) procedures of SPSS 17.0 (SPSS, Inc., Chicago, IL, USA). All treatment means were considered significant differences at $P < 0.05$ by Duncan's multiple range tests. Data were presented as mean ± standard error of the means (SEM).

3 Results

3.1 Changes of cooking loss of pork batters in offspring pigs

As shown in Table 1, cooking loss of pork batters in offspring pigs derived from HD group was lower than that derived from LD and ND groups at 0, 24 and 48 h postmortem storage ($P < 0.05$),

while there were no differences in cooking loss between LD and ND groups ($P > 0.05$). Meanwhile, offspring pigs born to ND and LD groups had lower cooking loss of pork batters at 0 h compared with that at 48 h postmortem storage ($P < 0.05$). No significant differences in cooking loss of pork batters of HD group were found among all storage times ($P > 0.05$). Our research found that the cooking loss of ND and LD groups was lower at 0 h than at 48 h postmortem cold storage.

3.2 Changes of color of pork batters in offspring pigs

As shown in Table 2, pork batters of HD group had higher a* values, while lower L* values compared with LD group at 0, 24 and 48 h postmortem storage ($P < 0.05$). Compared with 48 h postmortem storage, the a* and L* values of pork batters of ND and LD groups were higher at 0 h postmortem storage ($P < 0.05$). However, no significant differences in a* and L* values of pork batters were determined in HD group at all postmortem storage times ($P > 0.05$). b* values of pork batters in HD and ND groups were lower than that in LD group at all postmortem storage times ($P < 0.05$). Compared with 0 h postmortem storage, the b* values of pork batters in ND and LD groups were higher at 48 h postmortem storage ($P < 0.05$), while no significant differences in b* value of pork batters in HD group were measured at all storage times ($P > 0.05$).

3.3 Changes of TPA of pork batters in offspring pigs

As shown in Table 3, hardness, and chewiness of pork batters in ND group were lower than those in HD group, and were higher than those in LD group at all postmortem storage times ($P < 0.05$). Meanwhile, springiness and cohesiveness of pork batters in HD group were higher than that in LD group at all postmortem cold storage times ($P<0.05$). Compared with 0 h, all experimental groups (LD, ND and HD) had higher springiness, hardness, chewiness, and cohesiveness of pork batters at 24 and 48 h postmortem cold storage ($P < 0.05$).

3.4 Changes of LF-NMR of pork batters in offspring pigs

As shown in Table 4 and Figure 1, there were three characteristic peaks in the T_2 relaxation time map of pork batters in offspring pigs. There were no significant differences in T_{2a} relaxation time of pork batters among all groups during postmortem storage

Table 1. Effects of maternal vitamin D_3 status on cooking loss of pork batters in offspring pigs during postmortem storage.

Item	Groups			SEM	*P*-value
	LD	ND	HD		
0 h	13.38^{Ba}	12.61^{Ba}	10.29^{b}	0.693	0.043
24 h	14.66^{ABa}	13.84^{ABa}	11.37^{b}	0.838	0.031
48 h	15.76^{Aa}	14.96^{Aa}	11.63^{b}	0.561	0.026
SEM	0.876	0.932	0.541	-	-
P-value	0.034	0.047	0.066	-	-

In the same column, values with different capital superscripts mean significant difference ($P < 0.05$). In the same line, values with different small letter superscripts mean significant difference ($P < 0.05$). LD, low vitamin D_3 group. ND, normal vitamin D_3 group. HD, high vitamin D_3 group.

Table 2. Effects of maternal vitamin D_3 status on color of pork batters in offspring pigs during postmortem storage.

Item	Groups			SEM	*P*-value
	LD	ND	HD		
Lightness (L^*)					
0 h	79.44^{Aa}	78.72^{Aab}	75.14^{b}	1.811	0.045
24 h	78.34^{ABa}	77.63^{ABab}	75.60^{b}	2.193	0.039
48 h	77.06^{Ba}	75.54^{Bab}	74.83^{b}	1.547	0.041
SEM	1.633	1.766	2.441	-	-
P-value	0.027	0.036	0.077	-	-
Redness (a^*)					
0 h	4.96^{Ab}	5.08^{Aab}	5.37^{a}	0.152	0.013
24 h	3.61^{ABb}	3.96^{ABab}	4.66^{a}	0.339	0.048
48 h	3.42^{Bb}	3.67^{Bab}	4.32^{a}	0.207	0.024
SEM	0.293	0.344	0.413	-	-
P-value	0.022	0.018	0.053	-	-
Yellowness (b^*)					
0 h	9.51^{Ba}	8.33^{Bb}	8.18^{b}	0.352	0.043
24 h	9.98^{ABa}	8.91^{ABb}	8.63^{b}	0.579	0.032
48 h	10.87^{Aa}	9.73^{Ab}	8.84^{b}	0.424	0.015
SEM	0.873	0.698	0.732	-	-
P-value	0.036	0.013	0.061	-	-

In the same column, values with different capital superscripts mean significant difference ($P < 0.05$). In the same line, values with different small letter superscripts mean significant difference ($P < 0.05$). LD, low vitamin D_3 group. ND, normal vitamin D_3 group. HD, high vitamin D_3 group.

Table 3. Effects of maternal vitamin D_3 status on TPA of pork batters in offspring pigs during postmortem storage.

Item	Groups			SEM	*P*-value
	LD	ND	HD		
Hardness, N					
0 h	38.19^{Ac}	43.39^{Ab}	50.15^{Aa}	1.873	0.041
24 h	33.20^{Bc}	37.33^{Bb}	42.74^{Ba}	1.795	0.045
48 h	33.14^{Bc}	35.84^{Bb}	37.03^{Ca}	1.532	0.038
SEM	1.006	1.704	1.014	-	-
P-value	0.025	0.029	0.012	-	-
Springiness					
0h	0.941^{Ab}	1.189^{Aab}	1.360^{Aa}	0.004	0.003
24h	0.866^{Bb}	0.930^{Bab}	1.051^{Ba}	0.006	0.018
48 h	0.813^{Bb}	0.828^{Bab}	0.841^{Ca}	0.012	0.027
SEM	0.011	0.063	0.019	-	-
P-value	0.023	0.034	0.012	-	-
Cohesiveness					
0 h	0.491^{Ab}	0.539^{Aab}	0.599^{Aa}	0.009	0.004
24 h	0.416^{Bb}	0.436^{Bab}	0.480^{Ba}	0.004	0.003
48 h	0.414^{Bb}	0.425^{Bab}	0.449^{Ca}	0.006	0.013
SEM	0.034	0.029	0.014	-	-
P-value	0.031	0.022	0.004	-	-
Chewiness, N·mm					
0 h	15.45^{Ac}	19.63^{Ab}	23.68^{Aa}	0.554	0.022
24 h	10.15^{Bc}	13.57^{Bb}	18.58^{Ba}	0.538	0.043
48 h	9.75^{Bc}	12.09^{Bb}	14.53^{Ca}	0.117	0.048
SEM	0.884	0.691	1.135	-	-
P-value	0.033	0.025	0.011	-	-

In the same column, values with different capital superscripts mean significant difference ($P < 0.05$). In the same line, values with different small letter superscripts mean significant difference ($P < 0.05$). LD, low vitamin D_3 group. ND, normal vitamin D_3 group. HD, high vitamin D_3 group.

Table 4. Effects of maternal vitamin D_3 status on LF-NMR of pork batters in offspring pigs during postmortem storage.

Item	Groups			SEM	*P*-value
	LD	ND	HD		
T_{2a}, ms					
0 h	0.054^{a}	0.054^{a}	0.052^{a}	0.001	0.207
24 h	0.052^{a}	0.054^{a}	0.052^{a}	0.001	0.173
48 h	0.054^{a}	0.054^{a}	0.052^{a}	0.001	0.196
SEM	0.001	0.001	0.001	-	-
P-value	0.211	0.198	0.242	-	-
T_{21}, ms					
0h	15.19^{a}	14.88^{ab}	13.25^{b}	0.801	0.039
24h	15.47^{a}	14.88^{ab}	14.68^{b}	0.663	0.022
48 h	14.88^{a}	14.48^{ab}	13.68^{b}	0.512	0.047
SEM	0.713	0.601	0.858	-	-
P-value	0.061	0.274	0.127	-	-
T_{22}, ms					
0 h	231.01^{a}	191.95^{Bb}	191.46^{Bb}	5.416	0.025
24 h	232.52^{a}	193.51^{Bb}	192.20^{Bb}	3.426	0.031
48 h	233.76^{a}	205.95^{Ab}	200.92^{Ab}	6.191	0.029
SEM	9.853	6.627	5.032	-	-
P-value	0.092	0.046	0.041	-	-

In the same column, values with different capital superscripts mean significant difference ($P < 0.05$). In the same line, values with different small letter superscripts mean significant difference ($P < 0.05$). LD, low vitamin D_3 group. ND, normal vitamin D_3 group. HD, high vitamin D_3 group.

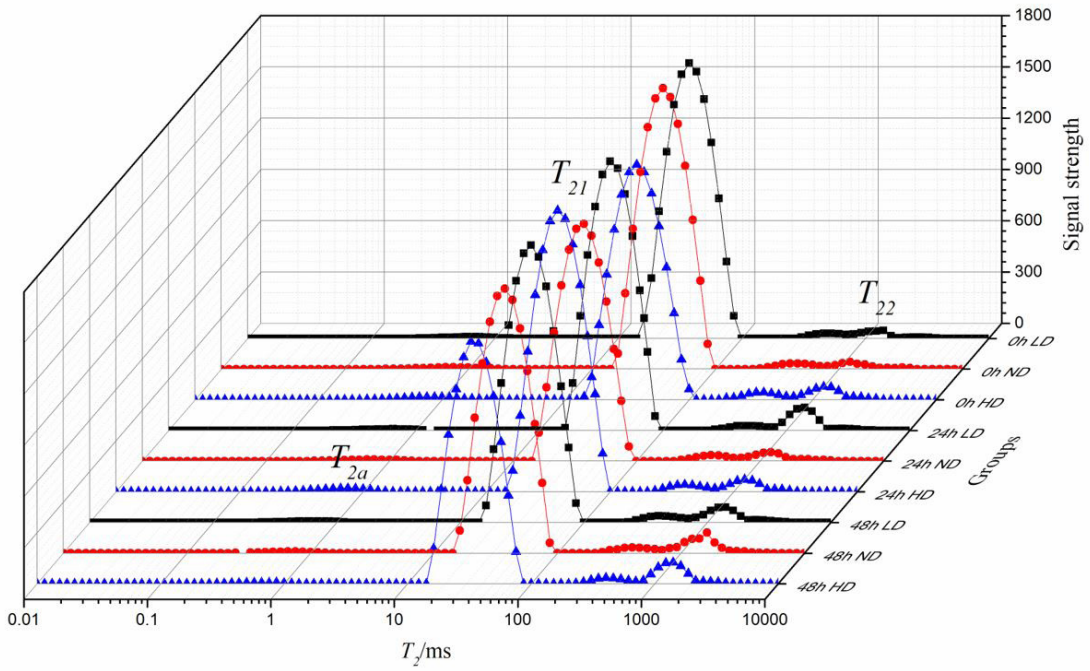

Figure 1. Three-dimensional T_2 relaxation time plot of pork batters in offspring pigs from LD, ND and HD groups during postmortem storage.LD, low vitamin D_3 group. ND, normal vitamin D_3 group. HD, high vitamin D_3 group. T_{2a}, binding water relaxation. T_{21}, immobile water relaxation time. T_{22}, free water relaxation time.

times ($P > 0.05$). Whereas, T_{21} relaxation time of pork batters of offspring pigs in HD group at 0, 24 and 48 h postmortem were significantly lower than those in LD groups ($P < 0.05$). In addition, T_{22} relaxation time of pork batters in LD group were higher than that in HD and ND groups at 0, 24 and 48 h ($P < 0.05$). Meanwhile, The T_{22} relaxation time of pork batters of offspring pigs in all groups at 48 h was significantly higher than that at 0 and 24 h postmortem cold storage ($P < 0.05$). There were no differences in T_{21} relaxation time of pork batters at 0, 24 and 48 h postmortem cold storage in the same group ($P > 0.05$).

3.5 Changes of dynamic rheological of pork batters in offspring pigs

The dynamic rheological properties of pork batters of offspring pigs during postmortem cold storage are shown in Figure 2. All experimental groups had similar the typical dynamic rheological curve of pork batters, which when the temperature from 20 °C to 41 °C, G' decreased slightly, and then increased slightly with the temperature increasing from 42 °C to 50 °C. G' values moderately reduced from 54 °C to 57 °C, then G' values of pork batters rapidly increased up to 80 °C. Meanwhile, under the same postmortem storage time, G' values of pork batters in HD group were higher than that in LD and ND ($P < 0.05$). In addition, at the same group, G' values of pork batters of offspring pigs at 48 h were higher than those at 0 and 24 h postmortem cold storage ($P < 0.05$).

4 Discussion

In the present study, it was found that there was an interaction between maternal vitamin D_3 levels and postmortem cold storage on cooking loss, meat color, texture properties, LF-NMR T_2 relaxation time and dynamic rheological properties of pork batters in offspring pigs. These results revealed that maternal vitamin D_3 level and postmortem storage impacted the quality of pork batters in offspring pigs via adjusting meat quality indices.

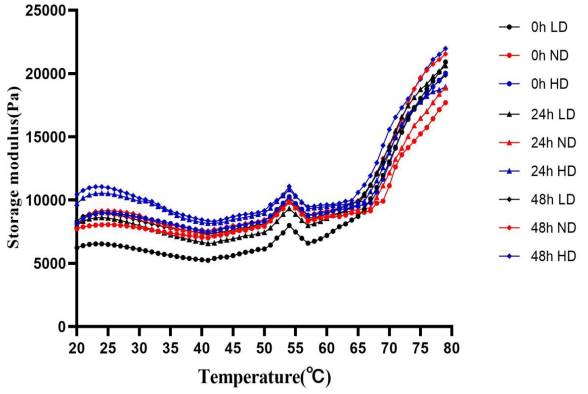

Figure 2. Dynamic rheological G' plot of pork batters in offspring pigs from LD, ND and HD groups during postmortem storage.LD, low vitamin D_3 group. ND, normal vitamin D_3 group. HD, high vitamin D_3 group.

Our research found that the cooking loss of ND and LD groups was lower at 0 h than at 48 h postmortem cold storage. These results suggested that water holding capacity (**WHC**) of pork batters was affected by postmortem cold storage. The results are in accordance with previous reports (Añón & Calvelo, 1980), in which it was found that freezing or frozen storage decrease

the WHC of meat, and the cooking loss of meat was increased during cold storage (Xu et al., 2012; Hong et al., 2015). These results may be due to the destruction of muscle tissue structure during postmortem cold storage, resulting in the reduction of water protein interaction, which reduces the WHC of meat (Cheng et al., 2020). Previous study has demonstrated that the decrease in WHC of meat may be related to the decrease of pH value, the denaturation of proteins and the destruction of muscle fiber structure during cold storage (Leygonie et al., 2012). Meanwhile, no differences in cooking loss of pork batters were observed in HD group during whole postmortem cold storage times, which suggested that maternal high-dose vitamin D_3 addition decreased the cooking loss, and increased juiciness of pork batters in offspring pigs at all postmortem cold storage times. The reason may be that maternal high-dose vitamin D_3 addition inhibited the decline of cooking loss by reducing the decline of pH value in meat samples, and improving the juiciness of pork batters in offspring pigs (Guo et al., 2021). In addition, the cooking loss in LD and ND groups was higher than that in HD group at 0 h, 24 h and 48 h postmortem cold storage, which indicated that maternal high-dose vitamin D_3 addition could improve the water retention of pork batters of offspring pigs. The reason may be that maternal high-dose vitamin D_3 supplementation decrease cooking loss of offspring pigs by regulating pH values, muscle fiber structure and the denaturation of proteins during postmortem cold storage (Leygonie et al., 2012; Guo et al., 2021).

Growing evidence have demonstrated that one of the most important sensory attributes of fresh pork is color, which affects consumers' purchase of red meat (Cheng et al., 2020; Risvik, 1994). In our study, offspring pigs in HD group had higher a^* values of pork batters than the offspring pigs in LD group at 0, 24 and 48 h postmortem cold storage. The results revealed that maternal high-dose vitamin D_3 supplementation can maintained the stability of redness of *longissimus* dorsi muscles of offspring pigs. These results are consistent with the meat color change trend of offspring pigs during postmortem cold storage times (Guo et al., 2021). The possible reason is that maternal high-dose vitamin D_3 supplementation can protect the phospholipid content against lipid peroxidation of pork batters in offspring pigs, and improved the color stability (Kumar et al., 2015). Similar results were found by pervious researcher (Duffy et al., 2018), who observed that on storage for 7 days, dietary 25-OH-D_3 supplementation may maintain the color stability of muscle samples with an increased redness by delaying the lipid peroxidation of muscle samples. Meanwhile, the value of L* and b* of pork batters in HD group were lower than those in LD group at 0, 24 and 48 h postmortem cold storage, which indicated that maternal high-dose vitamin D_3 levels inhibit lightness and yellowness of pork batters in offspring pigs and prolong the postmortem cold storage time. Similar results were observed by a previous report (Wiegand et al., 2002), that found dietary vitamin D_3 supplementation (125,000 μg) at 7 to 14 days postmortem decreased L* values of pigs compared with the control group. Another study also observed that vitamin D_3 supplementation (2000 μg) lowered L* values of pork (Wilborn et al., 2004). However, vitamin D_3 supplementation did not affect b* values of pork (Wiegand et al., 2002; Wilborn et al., 2004). Inconsistent research results might be due to the species or age, dosage of vitamin D_3, and duration of feeding vitamin D_3 supplementation. In addition, there were no differences in L* and a* values of HD group at 0, 24 and 48 h postmortem cold storage, which indicated that maternal high-dose vitamin D_3 addition inhibited the decrease of L* and a* values, and prolonged retail display of pork batters of offspring pigs at postmortem cold storage times. However, pork batter shows a decrease in redness value with prolonged refrigeration due to lipid oxidation increasing the number of free radicals, resulting in an increase in the rate of oxidation of myoglobin (Li et al., 2020a).

The texture of meat is usually considered to be the most important quality attributes that affecting consumer acceptance (Lee et al., 2011; Wang et al., 2013). The springiness, hardness, chewiness, and cohesiveness of pork batters was increased by animal fat and sesame oil (Kang et al., 2017). In the present study, the springiness, hardness, chewiness, and cohesiveness of pork batters of HD group were higher than that of LD group at postmortem cold storage times, which indicated that maternal high-dose vitamin D_3 supplementation improved texture properties of pork batters in offspring pigs. These results may be due to the increase of IMF content in offspring pigs by maternal high-dose vitamin D_3 supplementation (Guo et al., 2020a). The underlying mechanism still need to be proven by further investigation. In addition, our study found that the hardness, chewiness, springiness and cohesiveness of pork batters in offspring pig from all groups decreased with postmortem cold storage time. Similar results also were observed by pervious researcher (Cheng et al., 2020), who found that textural properties of beef decreased with storage time, which was supported by the decrease in water holding capacity. In addition, Liu et al. believed that the decrease in patty textural qualities was induced by a high freezing temperature (−8 °C) and long freezing time (Li et al., 2020a). These results suggested that TPA parameters of pork batters were influenced by cold storage time. The reason may be that the cooking loss of pork batters increases with storage time (as shown in Table 1), and finally decreased the TPA parameters. Previous studies also found similar trends in sheep and camel muscles (Martínez-Arellano et al., 2013; Maqsood et al., 2015). The decrease of textural properties may be also caused by the degradation of porcine muscle by microorganisms and the endogenous enzyme (Cheng et al., 2020). However, other study observed that the TPA parameters of beef meat increased during storage period from 1 to 10 d (Trabelsi et al., 2019). Lund et al. (2007) also found that the hardness of porcine longissimus dorsi was increased during chill storage. The reason may be caused by the development of protein oxidation products in muscle samples during cold storage (Srinivasan et al., 1996). Inconsistent results in TPA parameters might be due to species, the temperature, and times of cold storage.

LF-NMR T_2 relaxation time usually could be used to characterize water fluidity and distribution of meat, which was helpful to comprehend the effects of autopsy and chilling on WHC in meat (Straadt et al., 2007). Pervious study has demonstrated that T_{2a}, T_{21} and T_{22} indicates the binding water combined with protein, water in the muscle fiber network, and free water, respectively (McDonnell et al., 2013). In this study, there was no differences in T_{2a} of pork batters in offspring pigs

were measured during cold storage in all-experimental groups, which indicated that binding water of pork batters of offspring pigs was not influenced by maternal vitamin D_3 levels during cold storage period from 0 to 48 h postmortem. In addition, HD group had lower T_{21} and T_{22} of pork batters than LD group at 0, 24 and 48 h postmortem cold storage. Moreover, compared with bound water and non-flowing water, free water has the highest content. This is consistent with the findings of Luo et al. (2021), which are attributed to cell membrane rupture. These results suggested that maternal high-dose vitamin D_3 addition could inhabit water mobility, increase juiciness, and improve the quality of pork batters in offspring pigs during cold storage period. Our research also observed that offspring pigs in LD, ND and HD groups had higher T_{22} of pork batters at 48 h than those at 0 and 24 h postmortem cold storage, which indicated that water mobility was affected by postmortem cold storage.

The dynamic rheological properties are usually used to evaluate heat induced myofibrillar proteins gelation, which reflect the quality of protein. In the present study, offspring pigs from all groups had similar heating curve, and G' values increased slowly from 42 °C to 50 °C, which indicated that the denaturation and gelation of pork batters were occurred (Kang et al., 2017; Xiong & Brekke, 1990; Ali et al., 2015). From 54 °C to 57 °C, G' values of pork batters had a moderate decrease, similar results were observed by previous research (Kang et al., 2017; Álvarez et al., 2012). And then, the G' values of pork batters rapidly increased up to 80 °C, which may be that the viscous sol becomes an elastic gel network. In addition, HD group had higher G' value compared with ND and LD groups at the same postmortem cold storage time, which suggested that maternal high-dose vitamin D_3 addition could improve protein network and texture of pork batters in offspring pigs. Whereas, the underlying mechanism still need to be proven by further investigation. Meanwhile, our study also found that at the same group, G' values of pork batters of offspring pigs were lower at 0 h than that at 24 and 48 h postmortem cold storage, which suggested that postmortem cold storage times also affected the protein network and texture of pork batter. Similar results were also observed in pork batters (Wang et al., 2018), which indicated that the gel characteristics or pork batters were decreased with cold storage time.

5 Conclusion

Maternal vitamin D_3 status and cold storage time influenced cooking loss, meat color, texture properties, low-field NMR T_2 relaxation time and dynamic rheological properties of pork batters, and changed the quality attributes of pork batters in offspring pigs.

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References

Ali, S., Zhang, W. G., Rajput, N., Khan, M. A., Li, C. B., & Zhou, G. H. (2015). Effect of multiple freeze-thaw cycles on the quality of chicken breast meat. *Food Chemistry*, 173, 808-814. http://dx.doi.org/10.1016/j.foodchem.2014.09.095. PMid:25466093.

Álvarez, D., Xiong, Y. L., Castillo, M., Payne, F. A., & Garrido, M. D. (2012). Textural and viscoelastic properties of pork frankfurters containing canola-olive oils, rice bran, and walnut. *Meat Science*, 92(1), 8-15. http://dx.doi.org/10.1016/j.meatsci.2012.03.012. PMid:22503483.

Añón, M. C., & Calvelo, A. (1980). Freezing rate effects on the drip loss of frozen beef. *Meat Science*, 4(1), 1-14. http://dx.doi.org/10.1016/0309-1740(80)90018-2. PMid:22055482.

Cheng, S., Wang, X., Yang, H., Lin, R., Wang, H., & Tan, M. (2020). Characterization of moisture migration of beef during refrigeration storage by low-field NMR and its relationship to beef quality. *Journal of the Science of Food and Agriculture*, 100(5), 1940-1948. http://dx.doi.org/10.1002/jsfa.10206. PMid:31846075.

Choi, M. J., Min, S. G., & Hong, G. P. (2016). Effects of pressure-shift freezing conditions on the quality characteristics and histological changes of pork. *Lebensmittel-Wissenschaft + Technologie*, 67, 194-199. http://dx.doi.org/10.1016/j.lwt.2015.11.054.

Costa, T. C., Du, M., Nascimento, K. B., Galvão, M. C., Meneses, J. A., Schultz, E. B., Gionbelli, M. P., & Duarte, M. S. (2021). Skeletal muscle development in postnatal beef cattle resulting from maternal protein restriction during mid-gestation. *Animals*, 11(3), 860. http://dx.doi.org/10.3390/ani11030860. PMid:33803518.

Du, M., Huang, Y., Das, A. K., Yang, Q., Duarte, M. S., Dodson, M. V., & Zhu, M. J. (2013). Meat science and muscle biology symposium: manipulating mesenchymal progenitor cell differentiation to optimize performance and carcass value of beef cattle. *Journal of Animal Science*, 91(3), 1419-1427. http://dx.doi.org/10.2527/jas.2012-5670. PMid:23100595.

Du, M., Tong, J., Zhao, J., Underwood, K. R., Zhu, M., Ford, S. P., & Nathanielsz, P. W. (2010). Fetal programming of skeletal muscle development in ruminant animals. *Journal of Animal Science*, 88(Suppl. 13), E51-E60. http://dx.doi.org/10.2527/jas.2009-2311. PMid:19717774.

Duffy, S. K., Kelly, A. K., Rajauria, G., Jakobsen, J., Clarke, L. C., Monahan, F. J., Dowling, K. G., Hull, G., Galvin, K., Cashman, K. D., Hayes, A., & O'Doherty, J. V. (2018). The use of synthetic and natural vitamin D sources in pig diets to improve meat quality and vitamin D content. *Meat Science*, 143, 60-68. http://dx.doi.org/10.1016/j.meatsci.2018.04.014. PMid:29715661.

Godfrey, K. M., & Barker, D. J. (2000). Fetal nutrition and adult disease. *The American Journal of Clinical Nutrition*, 71(Suppl. 5), 1344S-1352S. http://dx.doi.org/10.1093/ajcn/71.5.1344s. PMid:10799412.

Guo, L. P., Miao, Z. G., Ma, H. J., & Melnychuk, S. (2020a). Effects of maternal vitamin D_3 during pregnancy on FASN and LIPE mRNA expression in offspring pigs. *The Journal of Agricultural Science*, 158(1-2), 128-135. http://dx.doi.org/10.1017/S0021859620000210.

Guo, L. P., Miao, Z. G., Ma, H. J., & Melnychuk, S. (2020b). Effects of maternal vitamin D_3 concentration during pregnancy on adipogenic genes expression and serum biochemical index in offspring piglets. *Journal of Animal and Feed Sciences*, 29(2), 125-131. http://dx.doi.org/10.22358/jafs/124041/2020.

Guo, L. P., Miao, Z. G., Ma, H. J., & Melnychuk, S. (2021). Effects of maternal vitamin D_3 status on quality traits of longissimus dorsi muscle in offspring pigs during postmortem storage. *Livestock Science*, 243, 104372. http://dx.doi.org/10.1016/j.livsci.2020.104372.

Harvey, N. C., Moon, R. J., Sayer, A., Ntani, G., Davies, J. H., Javaid, M. K., Robinson, S. M., Godfrey, K. M., Inskip, H. M., & Cooper, C. (2014). Maternal antenatal vitamin D status and offspring muscle

development: findings from the Southampton Women's Survey. *The Journal of Clinical Endocrinology and Metabolism*, 99(1), 330-337. http://dx.doi.org/10.1210/jc.2013-3241. PMid:24178796.

Hong, G. E., Kim, J. H., Ahn, S. J., & Lee, C. H. (2015). Changes in meat quality characteristics of the sous-vide cooked chicken breast during refrigerated storage. *Korean Journal for Food Science of Animal Resources*, 35(6), 757-764. http://dx.doi.org/10.5851/kosfa.2015.35.6.757. PMid:26877635.

Jia, N., Kong, B., Liu, Q., Diao, X., & Xia, X. (2012). Antioxidant activity of black currant (Ribes nigrum L.) extract and its inhibitory effect on lipid and protein oxidation of pork patties during chilled storage. *Meat Science*, 91(4), 533-539. http://dx.doi.org/10.1016/j.meatsci.2012.03.010. PMid:22483714.

Kang, Z. L., Zhu, D. Y., Li, B., Ma, H. J., & Song, Z. J. (2017). Effect of pre-emulsified sesame oil on physical-chemical and rheological properties of pork batters. *Food Science and Technology*, 37(4), 620-626. http://dx.doi.org/10.1590/1678-457x.28116.

Kumar, Y., Yadav, D. N., Ahmad, T., & Narsaiah, K. (2015). Recent trends in the use of natural antioxidants for meat and meat products. *Comprehensive Reviews in Food Science and Food Safety*, 14(6), 796-812. http://dx.doi.org/10.1111/1541-4337.12156.

Lee, Y. S., Youm, G., Owens, C. M., & Meullenet, J. F. (2011). Optimization of consumer acceptability and sensory characteristics for marinated broiler breast meat. *Journal of Food Science*, 76(8), S478-S484. http://dx.doi.org/10.1111/j.1750-3841.2011.02355.x. PMid:22417605.

Leygonie, C., Britz, T. J., & Hoffman, L. C. (2012). Impact of freezing and thawing on the quality of meat: review. *Meat Science*, 91(2), 93-98. http://dx.doi.org/10.1016/j.meatsci.2012.01.013. PMid:22326063.

Li, C., Wu, J., Zhang, N., Zhang, S., Liu, J., Li, J., Li, H. M., Feng, X. C., Han, Y. Q., Zhu, Z. Y., Xu, X. L., & Zhou, G. H. (2009). Effects of boning method and postmortem aging on meat quality characteristics of pork loin. *Animal Science Journal*, 80(5), 591-596. http://dx.doi.org/10.1111/j.1740-0929.2009.00677.x. PMid:20163625.

Li, F. F., Zhong, Q., Kong, B., Wang, B., Pan, N., & Xia, X. (2020a). Deterioration in quality of quick-frozen pork patties induced by changes in protein structure and lipid and protein oxidation during frozen storage. *Food Research International*, 133, 109142. http://dx.doi.org/10.1016/j.foodres.2020.109142. PMid:32466938.

Li, X., Fu, X., Yang, G., & Du, M. (2020b). Review: enhancing intramuscular fat development via targeting fibro-adipogenic progenitor cells in meat animals. *Animal*, 14(2), 312-321. http://dx.doi.org/10.1017/S175173111900209X. PMid:31581971.

Lund, M. N., Lametsch, R., Hviid, M. S., Jensen, O. N., & Skibsted, L. H. (2007). High-oxygen packaging atmosphere influences protein oxidation and tenderness of porcine longissimus dorsi during chill storage. *Meat Science*, 77(3), 295-303. http://dx.doi.org/10.1016/j.meatsci.2007.03.016. PMid:22061781.

Luo, J., Li, M., Zhang, Y., Zheng, M., & Ling, C. M. (2021). The low-field NMR studies the change in cellular water in tilapia fillet tissue during different drying conditions. *Food Science & Nutrition*, 9(5), 2644-2657. http://dx.doi.org/10.1002/fsn3.2221. PMid:34026078.

Maqsood, S., Abushelaibi, A., Manheem, K., & Kadim, I. T. (2015). Characterisation of the lipid and protein fraction of fresh camel meat and the associated changes during refrigerated storage. *Journal of Food Composition and Analysis*, 41, 212-220. http://dx.doi.org/10.1016/j.jfca.2014.12.027.

Martínez-Arellano, I., Severiano-Pérez, P., Fernandez, F. J., & Ponce-Alquicira, E. (2013). Changes in the physicochemical and sensory characteristics in raw and grilled ovine meat. *Journal of the Science of Food and Agriculture*, 93(7), 1743-1750. http://dx.doi.org/10.1002/jsfa.5964. PMid:23401049.

McDonnell, C. K., Allen, P., Duggan, E., Arimi, J. M., Casey, E., Duane, G., & Lyng, J. G. (2013). The effect of salt and fibre direction on water dynamics, distribution and mobility in pork muscle: a low field NMR study. *Meat Science*, 95(1), 51-58. http://dx.doi.org/10.1016/j.meatsci.2013.04.012. PMid:23648432.

Miao, Z. G., Wang, L. J., Xu, Z. R., Huang, J. F., & Wang, Y. R. (2009). Developmental changes of carcass composition, meat quality and organs in the Jinhua pig and Landrace. *Animal*, 3(3), 468-473. http://dx.doi.org/10.1017/S1751731108003613. PMid:22444318.

Musser, R. E., Davis, D. L., Dritz, S. S., Tokach, M. D., Nelssen, J. L., Minton, J. E., & Goodband, R. D. (2004). Conceptus and maternal responses to increased feed intake during early gestation in pigs. *Journal of Animal Science*, 82(11), 3154-3161. http://dx.doi.org/10.2527/2004.82113154x. PMid:15542461.

Pomponio, L., & Ruiz-Carrascal, J. (2017). Oxidative deterioration of pork during superchilling storage. *Journal of the Science of Food and Agriculture*, 97(15), 5211-5215. http://dx.doi.org/10.1002/jsfa.8403. PMid:28452152.

Risvik, E. (1994). Sensory properties and preferences. *Meat Science*, 36(1-2), 67-77. http://dx.doi.org/10.1016/0309-1740(94)90034-5. PMid:22061453.

Sanglard, L. P., Nascimento, M., Moriel, P., Sommer, J., Ashwell, M., Poore, M. H., Duarte, M. S., & Serão, N. V. L. (2018). Impact of energy restriction during late gestation on the muscle and blood transcriptome of beef calves after preconditioning. *BMC Genomics*, 19(1), 702. http://dx.doi.org/10.1186/s12864-018-5089-8. PMid:30253751.

Srinivasan, S., Xiong, Y. L., & Decker, E. A. (1996). Inhibition of protein and lipid oxidation in beef heart surimi-like material by antioxidants and combinations of pH, NaCl, and buffer type in the washing media. *Journal of Agricultural and Food Chemistry*, 44(1), 119-125. http://dx.doi.org/10.1021/jf950385i.]

Straadt, I. K., Rasmussen, M., Andersen, H. J., & Bertram, H. C. (2007). Aging-induced changes in microstructure and water distribution in fresh and cooked pork in relation to water-holding capacity and cooking loss - a combined confocal laser scanning microscopy (CLSM) and low-field nuclear magnetic resonance relaxation study. *Meat Science*, 75(4), 687-695. http://dx.doi.org/10.1016/j.meatsci.2006.09.019. PMid:22064034.

Tong, J., Zhu, M. J., Underwood, K. R., Hess, B. W., Ford, S. P., & Du, M. (2008). AMP-activated protein kinase and adipogenesis in sheep fetal skeletal muscle and 3T3-L1 cells. *Journal of Animal Science*, 86(6), 1296-1305. http://dx.doi.org/10.2527/jas.2007-0794. PMid:18344293.

Trabelsi, I., Ben Slima, S., Ktari, N., Triki, M., Abdehedi, R., Abaza, W., Moussa, H., Abdeslam, A., & Salah, R. B. (2019). Incorporation of probiotic strain in raw minced beef meat: study of textural modification, lipid and protein oxidation and color parameters during refrigerated storage. *Meat Science*, 154, 29-36. http://dx.doi.org/10.1016/j.meatsci.2019.04.005. PMid:30981132.

Wang, B., Yang, Q., Harris, C. L., Nelson, M. L., Busboom, J. R., Zhu, M. J., & Du, M. (2016). Nutrigenomic regulation of adipose tissue development - role of retinoic acid: A review. *Meat Science*, 120, 100-106. http://dx.doi.org/10.1016/j.meatsci.2016.04.003. PMid:27086067.

Wang, C. Y., Wang, R., Kuang, Z. L., Lu, X. J., Ma, H. J., & Song, Z. J. (2018). Effect of the different cold storage time on gel properties of chilled pork batters. *Science and Technology of Food Industry*, 39, 76-79.

Wang, D., Dong, H., Zhang, M. H., Liu, F., Bian, H., Zhu, Y. Z., & Xu, W. M. (2013). Changes in actomyosin dissociation and endogenous enzyme activities during heating and their relationship with duck meat tenderness. *Food Chemistry*, 141(2), 675-679. http://dx.doi.org/10.1016/j.foodchem.2013.04.034. PMid:23790834.

Wen, J., Hong, Q., Wang, X., Zhu, L., Wu, T., Xu, P., Fu, Z. Y., You, L. H., Wang, X., Ji, C. B., & Guo, X. R. (2018). The effect of maternal vitamin D deficiency during pregnancy on body fat and adipogenesis in rat offspring. *Scientific Reports*, 8(1), 365. http://dx.doi.org/10.1038/s41598-017-18770-4. PMid:29321608.

Wiegand, B. R., Sparks, J. C., Beitz, D., Parrish, F. C. Jr., Horst, R. L., Trenkle, A. H., & Ewan, R. C. (2002). Short-term feeding of vitamin D_3 improves color but does not change tenderness of pork-loin chops. *Journal of Animal Science*, 80(8), 2116-2121. PMid:12211380.

Wilborn, B. S., Kerth, C. R., Owsley, W. F., Jones, W. R., & Frobish, L. T. (2004). Improving pork quality by feeding supranutritional concentrations of vitamin D_3. *Journal of Animal Science*, 82(1), 218-224. http://dx.doi.org/10.2527/2004.821218x. PMid:14753364.

Xiong, Y. L., & Brekke, C. J. (1990). Thermal transitions of salt-soluble proteins from pre- and postrigor chicken muscles. *Journal of Food Science*, 56(6), 1540-1543. http://dx.doi.org/10.1111/j.1365-2621.1990.tb03563.x.

Xu, Y., Huang, J. C., Huang, M., Xu, B. C., & Zhou, G. H. (2012). The effects of different chilling methods on meat quality and calpain activity of pork muscle longissimus dorsi. *Journal of Food Science*, 77(1), C27-C32. http://dx.doi.org/10.1111/j.1750-3841.2011.02440.x. PMid:22260101.

Zhang, M., Xia, X., Liu, Q., Chen, Q., & Kong, B. (2019). Changes in microstructure, quality and water distribution of porcine longissimus muscles subjected to ultrasound-assisted immersion freezing during frozen storage. *Meat Science*, 151, 24-32. http://dx.doi.org/10.1016/j.meatsci.2019.01.002. PMid:30682660.

Zhou, H., Chen, Y., Lv, G., Zhuo, Y., Lin, Y., Feng, B., Fang, Z. F., Che, L. Q., Li, J., Xu, S. Y., & Wu, D. (2016). Improving maternal vitamin D status promotes prenatal and postnatal skeletal muscle development of pig offspring. *Nutrition*, 32(10), 1144-1152. http://dx.doi.org/10.1016/j.nut.2016.03.004. PMid:27209214.

Zhu, M. J., Ford, S. P., Means, W. J., Hess, B. W., Nathanielsz, P. W., & Du, M. (2006). Maternal nutrient restriction affects properties of skeletal muscle in offspring. *The Journal of Physiology*, 575(Pt 1), 241-250. http://dx.doi.org/10.1113/jphysiol.2006.112110. PMid:16763001.

Zhu, M. M., Peng, Z. Y., Lu, S., He, H. J., Kang, Z. L., Ma, H. J., Zhao, S. M., & Wang, Z. R. (2019). Physicochemical properties and protein denaturation of pork longissimus dorsi muscle subjected to six microwave-based thawing methods. *Foods*, 9(1), 26-42. http://dx.doi.org/10.3390/foods9010026. PMid:31881759.