Further insight into the role of Ca^{2+} in broiler pale, soft and exudative-like (PSE) meat through the analysis of moisture by TGA and strong cation elements by ICP-OES

Arlan S. Freitas^{1,2} · Leila M. Carvalho³ · Adriana L. Soares⁴ · Marta S. Madruga³ · Arnoud C. S. Neto⁵ · Rafael H. Carvalho⁴ · Elza I. Ida⁴ · Mario Estevez⁶ · Massami Shimokomaki¹

Revised: 30 April 2018 / Accepted: 21 May 2018 / Published online: 19 June 2018
© Association of Food Scientists & Technologists (India) 2018

Abstract This study evaluated moisture content of broiler breast PSE meat by thermal gravimetric analysis and strong cation elements by inductively coupled plasma optical emission spectrometry. The weight changes were monitored within the temperature interval 9–750 °C and the most severe changes were observed at 9–160 °C (1A). This remarkable transition was attributed to water loss of about 64.74% in normal samples while PSE samples lost about 61.16%. There was, therefore, approximately 4.0% lower moisture in PSE meat samples in relation to normal meat. The analysis of cation elements showed significant differences ($p < 0.05$), with normal samples having 13.0% higher $\sum[\text{Ca}^{2+}] + [\text{Mg}^{2+}] + [\text{Na}^+] + [\text{K}^+]$ than PSE meat samples while $[\text{Ca}^{2+}]$ in PSE meat was 10.81% higher than in the normal counterparts. We provided further evidence of the role of Ca^{2+} excess within the muscle sarcomere during the onset of PSE meat.

Keywords Glycolysis · Minerals · PSE meat · Heat stress · Meat quality

Introduction

Stress is a common term for describing a set of physiological reactions to physical, psychological or other types of impulses capable of disturbing homeostasis (Mitchell and Kettlewell 1998). Endogenous thermal stress promotes a higher intracellular phospholipase A_2 (PLA_2) activity in the presence of micromolar elevation in intracellular Ca^{2+} (Soares et al. 2003) with this phenomenon being proposed to trigger the molecular mechanisms leading to the onset of pale, soft and exudative (PSE) meat. In addition, damage in calcium efflux from the sarcoplasmic reticulum to the sarcoplasm by calcium channel proteins is linked to this meat quality problem (Werner et al. 2005). In fact, Ca^{2+} overload leads to increased glycolysis rate through activation of adenosine monophosphate-activated protein kinase and to increased lactate production (Hardie 2003). High temperatures during PSE onset leads to increased formation of reactive oxygen species, deregulated intracellular Ca^{2+} levels, and a series of metabolic changes that affect meat quality (Carvalho et al. 2017; Feng et al. 2008). Physiologically, the birds are strongly affected by several factors especially for long distance journeys and long periods in lairage without food, increasing the heat stress on-board and inducing PSE meat (Freitas et al. 2017) and consequently, losing the Water Holding Capacity (WHC). As a result, meat becomes soft and its surface appears wet and pale (Hughes et al. 2014; Jiang et al. 2016; Wilhelm et al. 2010).

Thermogravimetric analysis (TGA) is the most common technique employed for investigating the kinetics of sample in combustion, pyrolysis, drying and others (Cai and Liu 2007). It has recently been introduced to meat and bone meal (MBM) to be destroyed due to the possibility of being the responsible for the transmission of the bovine

✉ Mario Estevez
mariovet@unex.es

¹ Graduate Program in Animal Science, Department of Animal Science, Agricultural Sciences Center, Londrina State University, Londrina, Paraná, Brazil

² Maranhão Federal Institute, São Luís, Maranhão, Brazil

³ Paraíba Federal University, João Pessoa, Paraíba, Brazil

⁴ Department of Food Technology, Londrina State University, Londrina, Brazil

⁵ Guaraves Alimentos, Guarabira, Paraíba, Brazil

⁶ IPROCAR Research Institute, TECAL Research Group, University of Extremadura, Cáceres, Spain

spongiform encephalopathy (BSE) particularly in Europe (Conesa et al. 2003). In addition, TGA provides precise measurement of temperature, time and mass (Zhang and Chen 2016) and hence, it can be valuable to assess the thermal stability and water distribution in foods. Spectroscopic analytical techniques such as atomic emission spectrometry with inductively coupled plasma (ICP-OES) have been used in the determination of minerals in fish and crustaceans (Bilandžić et al. 2014) as well as in beef and pork under different thermal treatments (Goran et al. 2016) and in several cases, it showed to be reliable and precise methodology (Brenner and Zander 2000). According to our hypothesis, these innovative techniques may provide scientists with accurate and valuable information to establish further evidence of the role Ca^{2+} in the onset of PSE condition and explain some of the undesirable consequences of such defect on meat quality such as the WHC.

This work attempted to explore the behavior of moisture of broiler breast PSE meat by TGA and muscle strong cation elements contents determined by ICP-OES during the abnormality biological onset of PSE.

Materials and methods

Meat samples

This study was conducted in a commercial plant in Paraíba State, Brazil. Birds were of the Cobb lineage, mixed genders, 42 days old, with an average live weight of 3.03 ± 0.23 kg. The animals were slaughtered according to standard industry practice, which consisted of electrical stunning, bleeding, defeathering, evisceration, water chilling, deboning and refrigeration at 4 °C for 24 h. Samples of breast fillets (*pectoralis major*) were separated randomly for further analysis. Meat samples were classified according to pH and L^* values as in Freitas et al. (2017) as PSE meat with $\text{pH} < 5.8$ and $L^* < 51.0$ and Normal meat with $5.9 < \text{pH} < 6.2$ and $45.0 < L^* < 51.0$. pH was measured (in duplicate) by inserting electrodes into the *pectoralis major* muscle. Color was evaluated using a Minolta CR-400 colorimeter, taking five different reading points per sample for color determination (L^* , a^* and b^*).

Proximate chemical composition

Moisture, ash, protein and lipid were determined according to Association of Official Agricultural Chemists (2005) methods.

Water-holding capacity (WHC)

The WHC was determined based on the technique reported originally by Hamm (1961) and described in Wilhelm et al. (2010). A total of 80 samples divided into two treatments ($n = 40$) were collected from the cranial side of the breast fillets, cut into 2.0 ± 0.10 g cubes, and analyzed in triplicate. They were firstly carefully placed between two filter papers placed in acrylic plates and then left under a 10 kg weight for 5 min. The samples were weighed, and the WHC was determined by the exudate water weight through the following formula: $100 - [(W_i - W_f/W_i) \times 100]$, where W_i and W_f are the initial and final sample weights, respectively.

Thermal gravimetric analysis (TGA)

The TGA was performed in *pectoralis major* PSE ($n = 3$) and Normal ($n = 3$) meat samples. Thermal gravimetric (TG) curves were obtained in the temperature ranged between 9° and 750 °C, using TGA Thermobalance-50 of Shimadzu under a dynamic atmosphere of argon (50 mL min^{-1}) at 10 °C min-heating rate using alumina containing sample mass of around 10–22 mg. Calibration of the instrument was checked prior to testing and employing a standard calcium oxalate monohydrate, according to American Society for Testing of Materials (ASTM 1994). The TG moisture curves were obtained by use of the TA-60 WS Collection Monitor application. The percentages were determined from three separate tests for each sample by evaluating the mean value of the curves.

Strong cation elements determination by ICP-OES

Normal chicken breasts (*pectoralis major* m.) ($n = 20$) and PSE ($n = 20$), were freeze dried in LIOTOP model L101 (São Paulo, Brazil) and 160–190 mg sample were used (triplicate). Concentrated nitric acid (Merck) (4 mL) and hydrogen peroxide (Merck) at 30% (1 mL) subsequently submitted to heat (90 °C) in the digester block for quantitative analysis as described in AOAC (2005). The final cation measurement was carried out with a Varian 720 ES Series inductively coupled plasma optical emission spectrometry (ICP-OES), equipped with a solid state charge-coupled device detector (CCD), a peristaltic pump and a “Seaspray” nebulizer coupled to a cyclonic nebulization chamber. For the detection and quantification of calcium (Ca^{2+}), potassium (K^+), sodium (Na^+) and magnesium (Mg^{2+}), calibration curves were prepared in ultrapure water (Milli-Q) and nitric acid (Merck, Brazil), analytical grade in the concentration range of 10 a 100 $\mu\text{g.L}^{-1}$ using pure standard compounds (Merck, Brazil).

Statistical analysis

The Student *t* test ($p < 0.05$) was applied to analyse the differences between PSE and normal meat samples for their physico-chemical properties (pH, L^* , a^* , b^* and WHC), weight loss, TGA results and data of cation elements Ca^{2+} , Mg^{2+} , Na^+ , K^+ . The comparison tests ($p < 0.05$) were performed using the Statistica 7.0 software program (StatSoft, Tulsa, OK, USA).

Results and discussion

Proximate chemical composition and breast meat colour classification

As expected and shown in Table 1, PSE meat samples displayed the typical physicochemical features of this breast abnormality: lower values for pH, redness (a^*) and WHC and higher for L^* and yellowness (b^*) compared to normal breasts (Barbut 1997; Olivo et al. 2001). Moreover, they had lower amounts of moisture and lipid fraction and there was no significant difference in protein content.

Thermal gravimetric analysis

Figure 1 shows the results obtained using TGA and it is clear that there were generally three key transition temperatures: curve A, from the starting point (9 °C) to 160 °C, curve B, from 160 to 400 °C, and curve C, from 400 to 750 °C. The Figure shows the underlying relationship between WHC and the state of myofibrillar proteins.

Table 1 Proximate chemical analysis and average of L^* , a^* , b^* , pH and WHC 24 h *post-mortem* values of the chicken breast meat samples (*pectoralis major*) PSE and normal meat

	PSE	Normal
Moisture (%)	73.70 ± 0.78b	75.12 ± 0.60a
Protein (%)	22.51 ± 2.49a	23.19 ± 2.10a
Lipid (%)	0.33 ± 0.18b	0.89 ± 0.27a
Ash (%)	1.62 ± 0.18a	1.34 ± 0.17b
L^*	52.50 ± 1.15a	48.64 ± 1.24b
a^*	1.87 ± 0.60b	2.12 ± 0.70a
b^*	7.07 ± 1.94a	5.30 ± 1.64b
pH	5.83 ± 0.10b	6.04 ± 0.18a
WHC (%)	67.16 ± 3.08b	73.25 ± 2.24a

Different letters in the same column are significantly different (Student test, $p < 0.05$). Results are expressed as mean ± SD

Different letters in the same row denote significant differences between means (Student test, $p < 0.05$). Results are expressed as mean ± SD

Fig. 1 TGA analysis of broiler normal breast and PSE breast samples showing weight loss at different temperature intervals: curve A (09–160 °C); curve B (161–400 °C) and curve C (401–750 °C)

The most remarkable weight loss occurs in the curve identified as A. It is known that meat contains three different types of water namely, free, immobilized, and bound water (Huff-Lonergan and Lonergan 2005). Since bound water is trapped within the protein moieties and immobilized water is attached to the proteins, free water is usually lost during cooking as observed in curve A. That occurs up to ~ 100 °C, which happens to be the boiling temperature of water. By the time the PSE meat samples reached a temperature of 160 °C, the sample had lost about 61.17% of its original weight whilst normal samples lost 64.74% (Table 2). These results confirm that normal meat contains a higher percentage of free and immobilized water, thus a higher WHC (Table 1). In fact, PSE meat samples contain about 1.5–2.0% less moisture than normal meat, determined by regular method (Table 1) and 3.0–4.0% by TGA (Table 2), assuming that the weight lost in curve A is exclusively water.

It is in this range of temperatures that the majority of myofibrillar and sarcoplasmic proteins and collagen are denatured (Skipnes et al. 2008). The thermal denaturation of myosin which usually occurs between 54 and 58 °C is more pronounced in PSE meat samples as determined by differential scanning calorimeter (DSC) (Li et al. 2014). Actin denaturation take place around 80–83 °C (Li et al.

Table 2 Weight loss results (%) measured by TGA of PSE and Normal meat at respective temperature intervals

Temp. (°C)	PSE	Normal
9–160	61.16b	64.74a
161–400	13.08a	12.71a
401–750	11.51a	11.33a

a,b—Different letters in the same row differ by Student *t*-test ($p < 0.05$)

2014; Wright et al. 1977), denaturation of bovine titin occurs at 78.4 °C (Pospiech et al. 2002) and collagen fractions at 63–65 °C (Zhao and Chi 2009). The denaturation temperature of collagen fraction would depend on several conditions and in particular on bird age. As the broiler was slaughtered at commercial age of 42 days old, the mature collagen crosslinking, pyridinoline is not quantitatively at high level as reported previously (Coró et al. 2002) thus it is denatured at temperatures of 63–65 °C (Zhao and Chi 2009). According to the TG curves shown in Fig. 1b, c, the weight loss of protein and lipid fractions may represent approximately 10.0% each, as above 180 °C and under this condition the total lipids suffered the combustion. This was probably caused by oxygen bonding to specific unsaturated bonds, resulting in peroxide formation even at temperature below 180 °C. At temperatures higher than 180 °C, there was mass loss by thermal degradation and the decomposition of previously formed peroxides.

Strong cation elements evaluation

The concentration values (mg 100 g⁻¹) of mineral determined from the ashes from PSE and normal meat samples are shown in Table 3. Significant differences were found for Mg²⁺ and Ca²⁺ ($p < 0.05$), with Ca²⁺ being the only cation with higher concentration in PSE meat samples. Na⁺ and Mg²⁺ concentrations were 12.02 and 16.74% lower in PSE meat compared to normal samples, respectively. In addition, K⁺ concentration was 52.63% lower in PSE meat compared to the normal samples. On the other hand, Ca²⁺ was 13.98% higher in PSE meat compared to normal samples. The sum of all strong cations ($\sum[\text{Ca}^{2+}] + [-\text{Mg}^{2+}] + [\text{Na}^{+}] + [\text{K}^{+}]$) was significantly higher in normal (746.25 mg 100 g⁻¹) than in PSE (645.75 mg 100 g⁻¹) meat samples indicating the connection between PSE condition and post-mortem muscle [H⁺] with ante-mortem conditions affecting the total concentration of these strong cations, including heat stress. Greater sequestration of strong base cations in normal birds indicates that they possessed a greater capacity to defend against post-mortem acidification. It is plausible that the greater $\sum[\text{Ca}^{2+}] + [-\text{Mg}^{2+}] + [\text{Na}^{+}] + [\text{K}^{+}]$ observed probably resulted from increased animal activity expressed on a daily routine

basis. This is supported by previous reports showing that activity increased the expression of Ca²⁺-binding proteins (Ohlendieck et al. 1999) Ca²⁺ storage volume (Fryer and Stephenson 1996; Murphy et al. 2009), and Mg²⁺-ATP content and K⁺ uptake (Green et al. 2000).

Figure 2a depicts the mechanisms implicated in the onset of Rigor Mortis in normal postmortem changes of avian muscles and a controlled release of intracellular Ca²⁺. Tubules T depolarization induces the structural alteration of dihydropyridine receptor (DHPR), which is connected to the α -RyR and finally resulting in the Ca²⁺ release by the calcium channel (Fig. 2a). On the other hand, under heat stress, such as that occurred during onset of PSE meat, there is an excess of Ca²⁺ at myoplasm with the sarcoplasm reticulum triggering the excitation/contraction coupling mechanism and a subsequent fast glycolysis rate which leads to reach final pH (pHu) within 15 min (Olivo et al. 2001) to 200 min (Carvalho et al. 2017). The activation of the channel and the efflux of Ca²⁺ by the β -RyRs are caused by the local increase in the concentration of Ca²⁺ (Strasburg and Chiang 2009) resulting in PSE meat (Fig. 2b). The consequences of Ca²⁺ excess involves activation of Ca-factor enzymes such as the membrane associated age related phospholipase A₂ which has been linked as the triggering factor for the initiation of PSE symptoms in pigs (Cheah and Cheah 1981) and broiler (Soares et al. 2003). This explains why PSE meat is more sensible to lipid and protein oxidation (Carvalho et al. 2017). Another key enzyme is calpain and as shown in Fig. 3B1 and B2, firstly there is a depolymerization of myofilaments concomitantly to the sarcomere shrinkage thereafter intense calpain activity takes place on the substrates among others titin (thick myofilament), troponin (thin myofilament) and desmin (Z-line) and the entire muscle system would collapse (Wilhelm et al. 2010).

Despite of higher muscle contraction around 10% (Fig. 3B3) in relation to normal (Fig. 3A3) (Soares et al. 2003), the tenderness was shown to be higher within the PSE meat samples because of the abnormally higher protease activity (Carvalho et al. 2017; Wilhelm et al. 2010). Protease activities have been shown to affect tenderness during meat maturation and the calpain system is known to initiate enzymatic digestion of the myofibrillar structure. In fact, that calpain enzymatic activities in broilers and

Table 3 Concentration of cation elements (Na⁺, Mg²⁺, K⁺, Ca²⁺) in PSE and Normal chicken breast meat samples (*pectoralis major*)

	Cations (mg 100 g ⁻¹)			
	Na ⁺	Mg ²⁺	K ⁺	Ca ²⁺
PSE	94.82 ± 21.28a	60.99 ± 11.25b	472.77 ± 76.82b	17.17 ± 1.24a
Normal	107.78 ± 10.13a	73.26 ± 5.68a	550.44 ± 18.60a	14.77 ± 0.57b

Different letters in the same column are significantly different Student's test ($p < 0.05$). Results are expressed as mean ± SD

Fig. 2 Action potential at cell membrane to initiate glycolysis leading to *rigor mortis*. **a** Under normal quantitative conditions of Ca²⁺. **b** Under excessive Ca²⁺

Fig. 3 Longitudinal micrographs of *Pectoralis major* from normal meat samples: 1.5 h (A1) and 72 h (A2) *post-mortem* and 1.5 h (B1) and 72 h (B2) *post-mortem*. This PSE meat installation was described in detail by the author of such pictures (Wilhelm et al. 2010). A3 and

B3: Sarcomere structure of normal and PSE meat illustration, respectively. Note the longitudinal and transversal sarcomere contraction in PSE condition (B3) under excessive Ca²⁺

mammals are somehow different since, in the former, it takes 6 h for calpain activity to start developing tender meat (Lee et al. 2008).

Figure 3A1 shows micrographs from the first post-mortem hours of the normal samples. No modification in

the structure of myofilaments is visualized. It is also observed in Fig. 3A2 that after 72 h the changes occurred in the meat were minimal, apparently the sarcomere myofibrils are depolymerized and some protein fragmentation events are observed. The opposite is noticeable in

Fig. 3B1, where the PSE samples show disorganized sarcomere, in which the Z lines appear more prominent. The myosin filaments predominate within the sarcomeres reaching the Z lines. This is likely due to an increase in Ca^{2+} concentration prior to slaughter in PSE meat. This hypothesis is supported by consistently lower pH values relative to normal meat (Soares et al. 2003).

Conclusion

The Ca^{2+} determination by ICP-OES proven a 10–15% higher amount of this cation in PSE meat compared to the normal counterpart. The present results confirm that Ca^{2+} in excess in PSE is the key factor for all the onset of the symptoms of this muscle abnormality hence impairing the meat functional properties particularly the WHC. Consistently, TGA results showed that there was approx. 4.0% less moisture in PSE meat samples in relation to normal. The present results contribute to support the already well-known involvement of Ca^{2+} -factor enzymes (such as PLA_2) activities as the trigger factor to initiate the PSE symptoms and the impairment of the quality in such muscles.

Acknowledgements The authors are thankful to the CNPq for the support through the projects 483047/2013-9 and PVE 401167/2014-3. ASF holds a CAPES scholarship at the Maranhão Federal Institute for Education, Science and Technology (IFMA)/Londrina State University (UEL)-DINTER/CAPES graduate program. RHC holds a post doctor scholarship from CNPq Proc 150408/2016-1. The MSM and EII are CNPq Research Fellows.

References

- American Society for Testing of Materials (ASTM) (1994) Annual book of ASTM Standards. American Society for Testing and Materials, Philadelphia, pp 1042–1046
- Association of Official Agricultural Chemists (AOAC) (2005) Official methods of analysis of the Association of Official Agriculture Chemists. AOAC International, Gaithersburg, USA
- Barbut S (1997) Problem of pale soft exudative meat in broiler chickens. *Br Poult Sci* 38:355–358
- Bilandžić N, Sedak M, Đokić M, Varenina I, Solomun Kolanović B, Božić Đ, Šimić B (2014) Determination of zinc concentrations in foods of animal origin, fish and shellfish from Croatia and assessment of their contribution to dietary intake. *J Food Compos Anal* 35(2):61–66
- Brenner I, Zander A (2000) Axially and radially viewed inductively coupled plasmas—a critical review. *Spectrochim Acta Part B At Spectrosc* 55(8):1195–1240
- Cai J, Liu R (2007) Research on water evaporation in the process of biomass pyrolysis. *Energy Fuels* 26:3695–3697
- Carvalho RH, Ida EI, Madruga MS, Martínez SL, Shimokomaki M, Estévez M (2017) Underlying connections between the redox system imbalance, protein oxidation and impaired quality traits in pale, soft and exudative (PSE) poultry meat. *Food Chem* 215:129–137
- Cheah KS, Cheah AM (1981) Mitochondrial calcium transport and calcium-activated phospholipase in porcine malignant hyperthermia. *Biochim Biophys* 634:70–84
- Conesa JA, Fullana A, Font R (2003) Thermal decomposition of meat and bone meal. *J Anal Appl Pyrolysis* 70:619–630
- Coró FAG, Youssef EY, Shimokomaki M (2002) Age related changes in poultry breast meat collagen pyridinoline and texture. *J Food Biochem* 26:533–541
- Feng J, Zhang M, Zheng S, Xie P, Ma A (2008) Effects of high temperature on multiple parameters of broilers in vitro and in vivo. *Poult Sci* 87:2133–2139
- Freitas AS, Carvalho LM, Soares AL, Oliveira MES, Madruga MS, Neto ACS, Carvalho RH, Ida EI, Shimokomaki M (2017) Pale, soft and exudative (PSE) and dark, firm and dry (DFD) meat determination in broiler chicken raised under tropical climate management conditions. *Int J Poult Sci* 16:81–87
- Fryer MW, Stephenson DG (1996) Total and sarcoplasmic reticulum calcium contents of skinned fibres from rat skeletal muscle. *J Physiol* 493:357–370
- Goran GV, Tudoreanu L, Rotaru E, Crivineanu V (2016) Comparative study of mineral composition of beef steak and pork chops depending on the thermal preparation method. *Meat Sci* 118:117–121
- Green S, Langberg H, Skovgaard D, Bülow J, Kjær M (2000) Interstitial and arterial -venous $[\text{K}^+]$ in human calf muscle during dynamic exercise: effect of ischaemia and relation to muscle pain. *J Physiol* 529:849–861
- Hamm R (1961) Biochemistry of meat hydration. *Adv Food Res* 10:355–463
- Hardie DG (2003) Minireview: the AMP-activated protein kinase cascade: the key sensor of cellular energy status. *Endocrinology* 144:5179
- Huff-Loneragan E, Lonergan SM (2005) Mechanisms of water-holding capacity of meat: the role of postmortem biochemical and structural changes. *Meat Sci* 71:194–204
- Hughes JM, Oiseth SK, Purslow PP, Warner RD (2014) A structural approach to understanding the interactions between colour, water-holding capacity and tenderness. *Meat Sci* 98:520–532
- Jiang N, Xing T, Han M, Deng S, Xu X (2016) Effects of water-misting sprays with forced ventilation on post mortem glycolysis, AMP-activated protein kinase and meat quality of broilers after transport during summer. *Anim Sci J* 87:718–728
- Lee HL, Santé-Lhoutellier V, Vigouroux S, Briand Y, Briand M (2008) Role of calpains in postmortem proteolysis in chicken muscle. *Poult Sci* 87:2126–2132
- Li K, Chen L, Zhao YY, Li YP, Wu N, Sun H, Xu XL, Zhou FG (2014) A comparative study of chemical composition, color, and thermal gelling properties of normal and PSE-like chicken breast meat. *CyTA J Food* 13:213–219
- Mitchell MA, Kettlewell PJ (1998) Physiological stress and welfare of broiler chickens in transit: solutions not problems! *Poult Sci* 77:1803–1814
- Murphy RM, Larkins NT, Mollica JP, Beard NA, Lamb GD (2009) Calsequestrin content and SERCA determine normal and maximal Ca^{2+} storage levels in sarcoplasmic reticulum of fast- and slow-twitch fibres of rat. *J Physiol* 587:443–460
- Ohlendieck K, Frömming GR, Murray BE, Maguire PB, Leisner E, Traub I, Pette D (1999) Effects of chronic low-frequency stimulation on Ca^{2+} -regulatory membrane proteins in rabbit fast muscle. *Pflugers Arch* 438:700–708
- Olivo R, Soares AL, Ida EI, Shimokomaki M (2001) Dietary vitamin E inhibits poultry PSE and improves meat functional properties. *J Food Biochem* 25:271–283
- Pospiech E, Greaser ML, Mikołajczak B, Chiang W, Krzywdziska M (2002) Thermal properties of titin from porcine and bovine muscles. *Meat Sci* 62:187–192

- Skipnes D, Van der Plancken I, Van Loey A, Hendrickx ME (2008) Kinetics of heat denaturation of proteins from farmed Atlantic cod (*Gadus morhua*). J Food Eng 85:51–58
- Soares AL, Ida EI, Miyamoto S, Hernández-Blazquez FJ, Olivo R, Pinheiro JW, Shimokomaki M (2003) Phospholipase A₂ activity in poultry PSE, pale, soft, exudative, meat. J Food Biochem 27:309–320
- Strasburg GM, Chiang W (2009) Pale, soft, exudative Turkey—the role of ryanodine receptor variation in meat quality. Poult Sci 88:1497–1505
- Werner C, Opalka JR, Gellerich FN, Wicke M (2005) The influence of mitochondrial function on meat quality in turkey and swine. Arch Tierz Dummerstorf 48:106–114
- Wilhelm AE, Maganhini MB, Hernández-Blazquez FJ, Ida EI, Shimokomaki M (2010) Protease activity and the ultrastructure of broiler chicken PSE (pale, soft, exudative) meat. Food Chem 119:1201–1204
- Wright DJ, Leach IB, Wilding P (1977) Differential scanning calorimetric studies of muscle and its constituent proteins. J Sci Food Agric 28:557–564
- Zhang XY, Chen MQ (2016) A comparison of isothermal with nonisothermal drying kinetics of municipal sewage sludge. J Therm Anal Calorim 123:665–673
- Zhao YH, Chi YJ (2009) Characterization of collagen from eggshell membrane. Biotechnology 8:254–258