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Review Article

Pale soft exudative (PSE) and dark firm dry (DFD) meats: causes and measures to reduce these incidences - a mini review

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Abstract: Pale Soft Exudative (PSE) and Dark Firm Dry (DFD) meats are two of the major quality defects facing the meat industry. These defects reduce consumer acceptability, shelf life and yield of meat thus affecting profits tremendously. Breed, sex, species, pre-slaughter and post-slaughter handling of animals are among the main predisposing factors contributing to PSE and DFD in meats. Nowadays, strenuous efforts are being made by farmers, researchers and all stakeholders in the meat industry to reduce the incidence of PSE and DFD meats. Modern technologies to reduce these incidences in meats have included careful design of vehicles for transporting live animals to the abattoir, the design of abattoirs, stunning methods, and chilling processes. Various additives and/or ingredients have also been introduced to improve upon the processing qualities of PSE and DFD in processed meat products. In this review, PSE and DFD meats, the causes and measures to reduce these incidences are described.

Keywords: pale soft exudative, dry firm dark, meat, meat industry

Introduction

Profitability in any venture has model the meat industry to aim towards producing animals that are efficient feed converters, fast growing and have high lean meat content with minimum production cost. These have been achieved through manipulation of genetic made up of animals and careful selection of breeds. These have also resulted in the production of animals that are much more susceptible to stress and consequently the development of meat quality defects such as Pale Soft Exudative (PSE) and Dark Firm Dry (DFD) meats. Other quality defects such as bloodspalsh bruising, skin blemish, poultry cyanosis, two-toning, spoilage of meat, broken bones and death (Calkins et al., 1980; Forrest, 2010) have been identified. Earlier on, PSE was associated with pigs and DFD in all species. However, PSE characteristic meat has been reported in turkey (Owens et al., 2000), chickens (Swatland, 2008), ostriches (Van Schalkwyk et al., 2000) and cattle (Aalhus et al., 1998) in recent times. This explains the degree to which PSE and DFD in meats are evolving.

Quantity and quality determine the price consumers are prepared to pay for meat and meat products. As the live animal is converted to meat, and the meat moves along the line of distribution (from slaughter, processors, retailers and finally to the consumer), quality becomes increasingly important and the quality characteristics change (O'Neill et al., 2003). PSE and DFD meats look unattractive and discriminated against by consumers (Viljoena et al., 2002). They have poor processing characteristics, reduce yield and high potential of spoilage (Newton and Gill, 1981) compared to normal meat. There can also be the danger that consumers will begin to associate poor quality meat to food safety issues (Cassens, 2000).

The conditions of PSE and DFD meats are significant causes of financial loss. Cassell et al. (1991) showed that PSE and DFD meat cost the Australian food industry $20 million. In UK, Guise (1987) reported that, an annual cost of $20 million was incurred by the pig industry due to PSE and DFD meats. The normal rate of incidence for PSE and DFD meats is reported to range from 10 to 30 % but in some isolated cases may be up to 60 % (McKeith et al., 1994, Santos et al., 1994). In the USA, the estimated percentage of PSE and DFD in meat was reported to be 16 % and 10 %, respectively (Cassens et al., 1992). In Canada, Fortin (1989) reported an estimated prevalence of PSE to be between 20 – 90 %. Santos

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et al. (1994) showed an estimated prevalence of 30 % and 10 % for PSE and DFD respectively, in Portugal. Surveys have suggested that there is an increasing incidence of PSE and DFD in meat (Warriss, 2000). This work aimed at explaining PSE and DFD meats, the phenomenon that leads to PSE and DFD, and possible suggestions to reduce these incidences.

What is PSE and DFD meat?

PSE and DFD meat conditions are described in relation to the characteristics of normal meat. Nowadays, it can be suggested that both conditions occur in all species depending on how animals are handled pre-slaughter. They are defined in connection with the pH of meat at a specific time after slaughter. PSE is said to have occurred when the pH of meat is < 6 at 45 minutes after slaughter. DFD (also known as dark cutting in beef) is when the ultimate pH post mortem measured after 12 – 48 hours is ≥ 6. Table 1 shows typical PSE, normal and DFD meats. Table 2 summarizes typical pH value limits for PSE, normal and DFD. In practice, allowances can be allowed for these pH ranges. For example in countries where the incidence of PSE is high a stricter pH value of < 5.8 post mortem at 45 minutes can be used (Warriss, 2000). Similarly, an ultimate pH value of 6.2 can be allowed for DFD meat depending on the species. The above definitions do not also take into account the variation in different muscles of the carcass, therefore minor considerations have to be made in judging meat as being PSE or DFD. Warriss (2000) said that for redder muscles especially those found around the neck and shoulder regions, a much higher pH value of < 6.3 can be considered normal. Red, oxidative muscle fibres have relatively low concentration of glycogen which can easily be depleted post mortem. This makes them prone to DFD. Example is the muscles in the ham region. Conversely, white muscle fibres have relatively high glycogen and are prone to PSE. Example is the muscles in the loin region.

The determination of PSE, normal or DFD is also achieved subjectively or objectively by measuring meat color, pH and drip loss. Table 3 shows the color and drip loss values for various categories of PSE and DFD meats.

Causes of PSE and DFD

The most common factor leading to both PSE and DFD in meat is stress ante-mortem. Exposing animals to acute stress just before slaughtering leads to PSE. Acute or short term stress that can lead to PSE include the use of electric goads, fighting among animal just before sticking, beating of animals prior to slaughter and overcrowding in the lairage. Acidification occurs in muscles post-mortem due to the breakdown of glycogen to lactic acid. In PSE meats, the rate of acidification after slaughter is stimulated faster than normal and lower pH values are reached in the muscle when the temperature of the carcass is still high. The combination of low pH and high temperature in PSE meat causes the denaturation of some muscle proteins leading to reduction in their water holding capacity. This happens because the myofibrillar components (the myofilament lattice) expel the resulting fluid into the extracellular space which increases in volume (Warriss 2000). When such meat is cut the fluid is released resulting in the exudates. A large amount of exudates reflects poor water holding capacity as found in PSE meats. Warriss (2000) explained that, light scattering from meat surface is probably due to differences in refractive indices of the sarcoplasm and myofibrils. The larger the difference, the higher the scattering and the paler the meat appears. The shrinkage of the myofilament lattice increases the amount of light reflected from the meat. At high scattering the amount of absorbed light is low and the haem pigments selectively absorbed green light, thus reducing the normal red color. This makes PSE meat less red and more yellow. The low pH in PSE also promotes the oxidation of haem pigments from purple or red myoglobin (Mb) and oxymyoglobin (MbO_2) to brown metmyoglobin (met Mb).

When animals are exposed to chronic or long term stress before slaughtering DFD meats can occur. Examples of chronic stress are transportation animals over long distances, long hours of food deprivation, and overcrowding of animals in the lairage over a long period of time. Chronic stress prior to slaughter leads to the depletion of stored glycogen, thus less glycogen is available post-mortem affecting the normal process of acidification and leaving the pH of meat high. A condition referred to as DFD. In DFD, Warriss (2000) explained that, the high pH results in relatively little denaturation of proteins, water is tightly bound and little or no exudates is formed. This is because there is little or no shrinkage of the myofilament lattice and the differences in refractive index of the myofibrils and sarcoplasm are reduced. The muscles absorbed light making the meat appear darker. Oxygen penetration is reduced by the closed structure and any oxygen reaching the interior is used up by the high cytochrome activity encouraged by the high pH. This results in a thin surface layer of bright red oxygenated myoglobin (MbO_2) allowing the purple color of the underlying reduced myoglobin (Mb) to show through. Table 4 and 5 summarize the events leading to PSE and DFD in meats.

Table 1. Actual condition of different typical meats

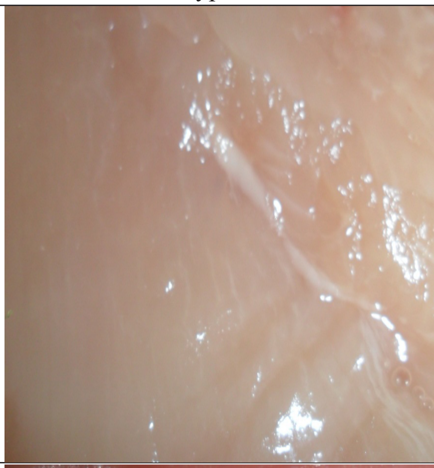
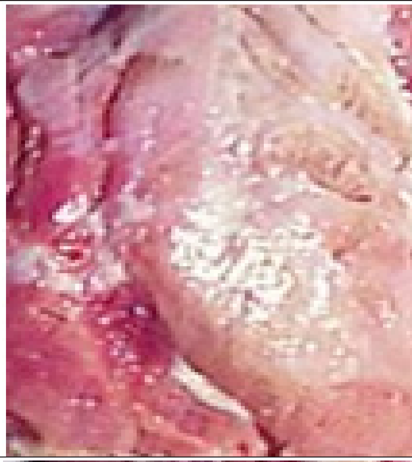
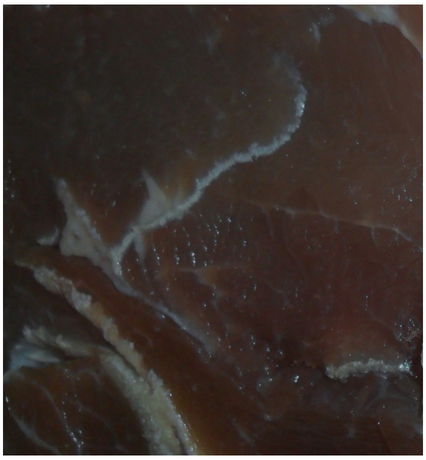
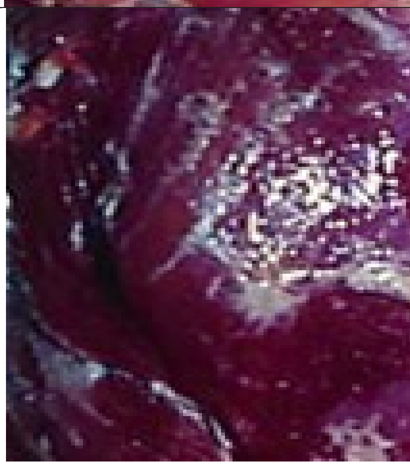
	Typical	Actual Condition
PSE meats		
Normal meats		
DFD meats		

Table 2. Typical limits of pH values for PSE, normal and DFD meat.

No.	Condition	Main conditions describing them	References
1.	PSE	Meats with pH at 45 minutes being lower than 6.0	Warriss (2000), Barbut *et al.* (2005), Swatland (2008)
		Meats with pH ultimate value of 5.3	Warriss (2000), Barbut *et al.* (2005) Swatland (2008)
2.	Normal	Meats with pH at 45 min being 6.4	Warriss (2000), Viljoena *et al.* (2002)
		Meats with pH ultimate value of 5.5	Warriss (2000), O'Neill *et al.* (2003), Gua`rdia *et al.* (2005)
3.	DFD	Meats with pH at 45 minutes being 6.4	Warriss (2000), Viljoena *et al.* (2002)
		Meats with pH ultimate value higher than 6.0	Bartos *et al.* (1993), Kreikemeier *et al.* (1998), Mounier *et al.* (2006)

Table 3. Color and drip loss values in meat of different quality

No.		Meat type	DFD	Normal	PSE	Reference
1.	Lightness (L*)	Pork	42 - 48	54	60 - 66	Warriss and Brown (1993)
		Beef	37 - 40.4	-	-	Muchenje *et al.* (2009)
		Turkey	-	47.31-48.99	54.72 -56.85	Owens *et al.* (2000)
		Pork	45.6	-	-	O'Neill *et al.* (2003)
2.	Hue (°)	Pork	1-22	38	48 -53	Warriss and Brown (1993)
		Pork	7.8	-	-	O'Neill *et al.* (2003)
3.	Saturation (chroma)	Pork	3 - 5	7	9 - 12	Warriss and Brown (1993)
		Pork	6	-	-	O'Neill *et al.* (2003)
4.	Reflectance (EEL)	Pork	20 - 32	44	56 - 67	Warriss and Brown (1993)
5.	Drip loss (%)	Pork	0 - 5	10	13 - 15	Warriss and Brown (1993)
		Turkey	-	0.72	2.52	Owens *et al.* (2000)
6.	Colour	Beef	4.8 ±1.6	6.1 ±1.9	-	Viljoena *et al.* (2002)

Table 4. Summary of events leading to PSE in meats

No.	PSE-Meat	References
1.	Short term stress prior to slaughter	Warriss (2000)
2.	Accelerated rate of post-mortem glyclolysis resulting in low pH while carcass is still high	Bowker *et al.* (2000)
3.	Pale, lean and soft texture	Santos *et al.* (1994), Bowker *et al.* (2000)
4.	Elevated muscle glycogen content and an extended duration of post-mortem glycolysis	Bowker *et al.* (2000)
5.	Protein denatures	Santos *et al.* (1994), Bowker *et al.* (2000)
6.	Large extracellular space	Warriss (2000)
7.	Low water binding capacity	Santos *et al.* (1994), Bowker et al. (2000)
8.	It scatters more light back to the observer	Swatland (1993), Swatland (2008)
9.	Reduction in absorption of green light by Mb	Warriss (2000)
10.	Meat looks less red	Warriss (2000)

Table 5. Summary of events leading to DFD in meats

No.	DFD-Meat	Reference
1.	Long term stress prior to slaughter	Warriss (2000)
2.	Pre-slaughter glycogen depletion in muscle resulting in meat with a higher ultimate pH	Viljoen *et al.* (2002), Kannan *et al.* (2002)
3.	Small extracellular space	Warriss (2000)
4.	High water holding capacity	Zhang *et al.* (2005), Apple *et al.* (2006)
5.	Amino acids are utilised due to glucose depletion and spoilage becomes evident at lower cell densities than in normal meat	Newton and Gill (1981), Gardner *et al.* (2000)
6.	Spoilage odour is produced at an early age	Newton and Gill (1981), Gallo *et al.* (2003)
7.	High variation in tenderness	Silva *et al.* (1999)
8.	Meats transmit more light into its depth	Swatland (2008)
9.	Dark in colour	Mounier *et al.* (2006)
10.	O_2 used up by high cytochrome activity	Warriss (2000)
11.	Meat looks less red	Warriss (2000)

Preventive measures to reduce the incidence of PSE and DFD in meats

The prevention of PSE and DFD in meats will rely mainly on measures to avoid stress in animals prior to slaughter. These stresses include removal from their home environment, loading and unloading onto vehicles, feed and water deprivation during transportation, holding in unfamiliar surroundings, mixing with strange animals, lousy odour, high temperature and noise produced by moving vehicles (Warriss, 2000).

First of all there is the need to develop breeds that are resistance to stress. This is because the incidence of PSE and DFD has been found to be high in stress susceptible animals by many authors (Warriss, 2000). Barton-Gade (1988) reported that the occurrence of PSE meat is undoubtedly related to certain genotypes that are stress susceptible (Halothane positive) and have lean meat. Muchenje et al. (2009) found that Bonsmara steers suffered the most pre-slaughter stress compared to Angus and Nguni breeds when they were all exposed to the same condition of pre-slaughter handling. Inversely, Koch (2004) found that Bonsmara breeds had the lowest levels of stress hormones in a study comparing several *Bos taurus* and *Bos indicus* breeds. Animals' reactions to stress are governed by a complex interaction of genetic factors and previous experiences (Mormède et al., 2002; Mounier et al., 2006). Nevertheless, tropical breeds in particular are resistance to stress but have poor growth rate. Temperate breeds on the other hand are more susceptible to stress but have good growth rate. A combination of genotypes from both temperate and tropical regions could be useful in reducing the incidence of PSE and DFD meats.

It has also been showed that females and castrates have higher probability of producing DFD compared to entire males (Gua`rdia et al., 2005). On the contrarily (Warriss, 1996) reported that entire males are more aggressive than castrates or gilts and this behavior in boars cause a high level of hostile confrontations and fights among them, and subsequently prone to producing PSE and DFD meats. Van der Wal et al. (1999) observed that in the absence of additional stress there were no differences between sexes but as soon as stress stimuli were introduced males were more resistant. Entire males show a faster rate of recuperation from stress due to their more aggressive sexual behaviour, making them more used to chronic stress. This probably suggests that if males are handled well prior to slaughter they will produce less DFD and PSE meats, and therefore more males could be bred for meat purposes.

Loading of animals onto trucks for transportation to the abattoir has to be done with minimum stress. As much as possible loading should be done in a quiet atmosphere, avoiding the use of sticks and other forms of force. Avoid chasing and running after animals to direct them into their transporting vehicles. Climbing ramps that slope gently should be used for loading animals unto trucks for transport. In chickens, the use of mechanical harvesters (instead of manual harvesting by a team of farm hands) equipped with rotating rubber fingers have been suggested by Berry et al. (1990). The rotating rubber fingers collects and encourage the birds to move onto a moving conveyer thus reducing stress. When manual harvesting is being practiced, the team should be trained on proper ways of handling animals. Animals should be unloaded immediately when they arrive at the slaughter house. Unloading of animals at the abattoir should also be done in a quiet and gentle manner. Unloading platforms should be lowered to the ground level to facilitate descending. Wide gaps should not be created between the vehicle and the landing ground to prevent the animals from jumping. The use of hydraulic lifts in some vehicles for some animals is helpful to reduce stress.

Animals are transported to the market for sale or directly from the farm to the abattoir. In either cases stress must be reduced to the minimum. Keep transportation and marketing times short. This implies that farms, markets and abattoirs should be situated close to each other. Vehicles for transporting animals must provide them with enough ventilation and should be well maintained. Provide shade, water and feed for the animals (especially if the animals will keep long in the market). In general it is accepted that on farm feed withdrawal from 12 to 18 h before transport is a good practice for preparing pigs for transportation (Guise, 1990). To avoid long marketing times, Warriss (2000) suggested a computer auction marketing system where the characteristics of the animals are display on the internet for interested buyers to make orders. Such a system will reduce marketing time and the stress involved in holding animals for long hours in the market. Keep animals in their rearing group as mixing of unfamiliar animals will trigger fight. Overcrowding should be avoided as it increases the incidence of PSE and DFD in meats due to stress (Gua`rdia et al., 2005).

Animals waiting for slaughter can be stressed by factors such as restraint, handling, novelty of the pre-slaughter environment, adverse weather conditions, hunger, thirst and fatigue (Muchenje et al., 2009). At the abattoir animals should be rested enough to recover from stress before slaughtering. Sugar or molassed feeding has been shown to replenish muscle glycogen levels thus helping to prevent DFD (Warriss, 2000). Provide animals with food and water if they will spend more time in the lairage although this must be avoided. Provide beddings or straw on the floor if the animals will keep longer than expected in the lairage. Animals can be sprayed with mist water to cool them down especially when the weather is hot. Lairage time should also be kept short. Malmfors (1982) showed that both long journeys and long lairage periods cause a significant increase in the risk of PSE and DFD meats. Nanni Costa et al. (2002) also found that lairage time was the most important pre-slaughter factor contributing to DFD meats among the factors they investigated. Grandin (1998) recommended a resting period of between 2 – 4 hour in the lairage prior to stunning and/or sticking.

The slaughtering process is a critical point that can lead to PSE meat if any stress is introduce at this level. Abattoirs must be well designed to ensure that the animals are exposed to the least stress prior to slaughter. Stunning methods such as the use of mechanical instruments (captive bolt pistol, percussion stunner or free bullet), electrical stunning and anesthetic gas (CO2) render animals unconscious prior to sticking. This has the potential of reducing pain, distress and struggling after sticking if well done and thus can help reduce the incidence of PSE. Animals must be well restrained before stunning and/or sticking to reduce distress. Schaefer et al. (1992) showed that pre-slaughter administration of electrolytes in cattle and the use of sodium bicarbononate in pigs partially alleviate metabolic acidosis and reduce the rate of post-mortem glycolysis in muscles.

Carcasses are normally chilled after dressing. Different cooling rates can affect the rate of pH fall through lactic acid production, and the onset of rigor mortis. This can have negative effect on the carcass and meat quality. Modern chilling practice has focus on speeding up the process of chilling by utilizing refrigerated air in order to reduce microbial growth and evaporative weight loss. There is evidence that rapid chilling can reduce weight loss, the manifestation of PSE, improve the water holding and lean meat color (Warriss, 2000). Rapid chilling can be achieved by reducing the size of carcasses, covering of fats and effective circulation of cold air over the meat surface.

Conclusion

PSE and DFD meats are discriminated against by consumers. They have poor processing qualities and cause huge financial loss to the meat industry. Stress is a major contributing factor to PSE and DFD in meats. Stress arises from poor pre-slaughter handling such as striking animals with sticks, kicking them with the feet, forcing animals to move into the transporting vehicle, starving, overstocking during transport, and pushing animals to move in races at the lairage. When handling animals prior to slaughter, consideration should be made in terms of the kind of species, breed, and age. In addition slaughtering procedures and processing techniques should be closely monitored to help reduce the incidence of PSE and DFD in meats.

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References

Aalhus, J. L., Best, D. R., Murray, A. C. and Jones, S. D. M. 1998. A comparison of the quality characteristics of pale, soft and exudative beef and pork. Journal of Muscle Foods 9: 267-280.

Apple, J. K., Kegley, E. B., Galloway, D. L., Wistuba, T. J. and Rakes, L. K. 2005. Duration of restraint and isolation stress as a model to study the dark-cutting condition in cattle. Journal of Animal Science 83: 1202-1214.

Barbut, S., Zhang, L. and Marcone, M. 2005. Effects of pale, normal and dark chicken breast meat on microstructure, extractable proteins, and cooking of marinated fillets. Poultry Science 84: 797-802.

Barton-Gade, P. A. 1988. The effect of breed on meat quality characteristics in pigs. Proceedings 34th International Congress Meat Science Technology, p 568-570. Australia: Brisbane.

Bartos, L., Franc, C., Rehák, D. and Stípková, L. 1993. A practical method to prevent dark-cutting (DFD) in beef. Meat Science 34: 275-282.

Berry, P. S., Kettlewell, P. J. and Moran, P. 1990. The AFRC Mark 1 Experimental Broiler Harvester. Journal of Agricultural Engineering Research 47: 153-163.

Bowker, B. C., Grant, A. L., Forrest, J. C. and Gerrard, D. E. 2000. Muscle metabolism and PSE pork. Journal of Animal Science 79:1-8.

Calkins, G. R., Davis, G. W., Cole, A. and Hutshell, D. A. 1980. Incidence of blood splashed hams from hogs subjected to certain ante-mortem handling methods. Journal of Animal Science 50: S15.

Cassell, J. F., Dyson, S., Reiser, P. D. and Trout, J. R. 1991. Unlocking the secrets for pork quality. CSIRO Report on Research p 79.

Cassens, R. G. 2000. Historical perspectives and current aspects of pork meat quality in the USA. Food Chemistry 69: 357-363.

Cassens, R. G., Kauffman, R. G., Scherer, A. and Meeker, D. L. 1992. Variations in pork quality: a 1991 USA survey. Preceedings of the 38th International Congress of Meat Science and Technology, p 237-240. France: Clermont-Ferrand.

Forrest, J. 2010. Meat Quality Problems. Download from http://ag.ansc.purdue.edu/meat_quality/meat_quality_problems.html on 11/06/2010.

Fortin, A. 1989. Preslaughter management of pigs and its influence on the quality (PSE/DFD) of pork. Preceedings of the 35th International Congress of Meat Science and Technology, p 981-986. Roskilde: Danish Meat Science Research Institute.

Gallo, C., Lizondo, G. and Knowles, T. G. 2003. Effects of journey and lairage time on steers transported to slaughter in Chile. Veterinary Record 152: 361-364.

Gardner, G. E., McIntyre, B. L., Tudor, G. D. and Pethick, D. W. 2001. The impact of nutrition on bovine muscle glycogen metabolism following exercise. Australian Journal of Agricultural Research 52: 461-470.

Grandin, T. 1998. Dealing with excitable pigs. Temple Grenadine'swebpage. Downloaded from www.grandin.com/meat/pigs/excite.pig-1.html on 15/06/2009.

Gua`rdia, M. D., Estany, J., Balasch, S., Oliver, M. A., Gispert, M. and Diestre, A. 2005. Risk assessment of DFD meat due to pre-slaughter conditions in pigs. Meat Science 70: 709-716.

Guise, H. J. 1987. Transport review; moving pigs from farm to factory. Pig International 12: 8-16.

Guise, H. J. 1990. Problems of pig meat production and processing with particular reference to pre-slaughter handling. UK: University of London, PhD thesis.

Kannan, G., Chawan, C. B., Kouakou, B. and Gelaye, B. 2002. Influence of packaging method and storage time on shear value and mechanical strength of intramuscular connective tissue of chevon. Journal of Animal Science 80: 2383-2389.

Koch, J. W. 2004. The influence of tropical adaptation and breed type on adrenal and testicular function in beef bulls. USA: Texas A&M University, PhD Thesis.

Kreikemeier, K. K., Unruh, J. A. and Eck, T. P. 1998. Factors affecting the occurrence of dark-cutting beef and selected carcass traits in finished beef cattle. Journal of Animal Science 76: 388-395.

McKeith, F., Meeker, D. and Buege, D. 1994. Pork chain quality audit. Proceedings Reciprocal Meat Conference 47: 73-74.

Mormède, P., Courvoisier, H., Ramos, A., Marissal-Arvy, N., Ousova, O. and De´saute´ S, C. 2002. Molecular genetics approaches to investigate individual variations in behavioral and neuroendocrine stress responses. Psychoneuroendocrinology 27: 563-583.

Mounier, L., Dubroeucq, H., Andanson, S. and Veissier, I. 2006. Variations in meat pH of beef bulls in relation to conditions of transfer to slaughter and previous history of the animals. Journal of Animal Science 84: 1567-1576.

Muchenje, V., Dzama, K., Chimonyo, M., Strydom, P. E. and Raats, J. G. 2009. Relationship between pre-slaughter stress responsiveness and beef quality in three cattle breeds. Meat Science 81: 653-657.

Nanni Costa, L., Lo Fiego, D. P., Dall, O. S., Davoli, R., and Russo, V. 2002. Combined effects of pre-slaughter treatments and lairage time on carcass and meat quality in pigs of different halothane genotype. Meat Science 61: 41-47.

Newton, K. G. and Gill, C. O. 1981. The microbiology of DFD fresh meats: a review. Meat Science 5: 223-232.

O'Neill, D. J., Lynch, P. B., Troy, D. J., Buckley, D. J., Kerry, J. P. 2003. Influence of the time of year on the incidence of PSE and DFD in Irish pigmeat. Meat Science 64: 105-111.

Owens, C. M., Hirschler, E. M., McKee, S. R., Martinez-Dawson, R. and. Sams, A. R. 2000. The Characterization and incidence of Pale, Soft, Exudative Turkey meat in a commercial plant. Poultry Science 79:553-558.

Santos, C., Roseiro, L. C., Goncalves, H. and Melo, R. S. 1994. Incidence of different pork quality categories in a Portuguese slaughterhouse: a survey. Meat Science 38: 279-287.

Schaefer, A. L., Jones, S. D. M., Tong, A. K. W., Young, B. A., Murray, N. L. and Lepage, P. 1992. Effects of post-transport electrolyte supplementation on tissue electrolytes, haemotology, urine osmolarity and weight loss in beef bulls. Livestock Production Science 30: 333-346.

Silva, J. A., Patarata, L. and Martins, C. 1999. Influence of ultimate pH on bovine meat tenderness during ageing. Meat Science 53: 453-459.

Swatland, H. J. 1993. Paleness, softness, and exudation in pork - Review. In: Poulanne E. and Demeyer, D. I. (Eds). Pork Quality: Genetic and Metabolic Factors, p 273-286. UK: Wallingford.

Swatland, H. J. 2008. How pH causes paleness or darkness in chicken breast meat. Meat Science 80: 396-400.

Van der Wal, P. G., Engel, B. and Reimert, H. G. M. 1999. The effect of stress, applied immediately before stunning, on pork quality. Meat Science 53: 101-106.

Van Schalkwyk, S. J., Cloete, S. W. P., Hoffman, L. C., Brand, Z., Pfister, A. P. and Punt, K. 2000. The effect of pre-slaughter stress resulting from feed withdrawal on meat quality characteristics in ostriches. South African Journal of Animal Science 30: 147-148.

Viljoena, H. F., de Kocka, H.L. and Webbb, E.C. 2002. Consumer acceptability of dark, firm and dry (DFD) and normal pH beef steaks. Meat Science 61: 181-185.

Warriss, P. D. 1996. The consequences of fighting between mixed groups of unfamiliar pigs before slaughter. Meat Focus International 4: 89-92.

Warriss, P. D. 2000. Meat science: An introductory text. CAB-International: Wallingford.

Warriss, P. D. and Brown, S. N. 1993. Relationships between the subjective assessments of pork quality and objective measures of colour. In Wood, J. D. and Lawrence, T. L. J. (Eds). Safety and Quality of Food from Animals. Occasional Publication of the British Society of Animal Production no. 17, p 98-101. UK: Edinburgh.

Zhang, S. X., Farouk, M. M., Young, O. A., Wieliezko, K. J. and Podmore, C. 2005. Functional stability of frozen normal and high pH beef. Meat Science 69: 346-765.