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REVIEW PAPER

Determinants of broiler chicken meat quality and factors affecting them: a review

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Abstract Broiler production at mass level has already been achieved and now emphasis is being laid on increasing meat quality by altering various characteristics of broiler meat. Appearance, texture, juiciness, wateriness, firmness, tenderness, odor and flavor are the most important and perceptible meat features that influence the initial and final quality judgment by consumers before and after purchasing a meat product. The quantifiable properties of meat such as water holding capacity, shear force, drip loss, cook loss, pH, shelf life, collagen content, protein solubility, cohesiveness, and fat binding capacity are indispensable for processors involved in the manufacture of value added meat products. Nutrition of birds has a significant impact on poultry meat quality and safety. It is well known that dietary fatty acid profiles are reflected in tissue fatty acid. Management of poultry meat production is reflected mostly on consumption features (juiciness, tenderness, flavour) of meat. After slaughter, biochemical changes, causing the conversion of muscle to meat, determine final meat quality. Postmortem carcass temperature has profound effect on rigor mortis and the physicochemical changes observed in PSE muscles are attributed to postmortem glycolysis, temperature, and pH. Primary processing and further processing have become a matter of concern with respect to nutritional quality of broiler meat. Genetic variation among birds could contribute to large differences in the rate of rigor mortis completion and meat quality. Heritability estimates for meat quality traits in broilers are amazingly high (0.35–0.81), making genetic selection a best tool for improvement of broiler meat quality.

Keywords Broiler meat quality · Nutrition · Management · Processing · Genetics

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Introduction

There are many definitions of quality, but the most preferred one is; "Quality is the composite of those characteristics that differentiate individual units of a product and which have significance in determining the degree of acceptability of that unit to the user" (Groom 1990). However, for meat industry, meat quality is a term used to describe the overall meat characteristics including its physical, chemical, morphological, biochemical, microbial, sensory, technological, hygienic, nutritional and culinary properties (Ingr 1989). It is a well-known fact that broiler production at mass level has already been achieved and now emphasis is laid on increasing meat quality by altering the said characteristics of broiler meat. The appearance, texture, juiciness, wateriness, firmness, tenderness, odor and flavor are the most important and perceptible meat features that influence the initial and final quality judgment by consumers before and after purchasing a meat product (Cross et al. 1986). Furthermore, for processors, manufacturing value added meat products, quantifiable properties of meat such as water holding capacity, shear force, drip loss, cook loss, pH, shelf life, collagen content, protein solubility, cohesiveness, and fat binding capacity are indispensable to acquire excellent functional properties that will ensure a final product of exceptional quality and profitability (Allen et al. 1998). However, poultry grading system used worldwide continues to be based on aesthetic attributes such as conformation, presence or absence of carcass defects, bruises, missing parts, and skin tears without taking into account the functional properties of meat which has thwarted the rise of further processing industry. Consumers, with increasing health consciousness, are becoming more aware of the nutritional value of the foods they eat. This knowledge, together with the current emphasis on being physically fit and slim trim, has led to an increase in the emphasis on food labels such as Light, Lean, low-fat, reduced-fat, reduced calories, etc. (John et al. 2016). Poultry meat and egg products are natural candidates to meet this emerging demand because of their high nutrient content and relatively low caloric value. Whether or not a poultry product meets the consumer's expectations depends upon the conditions surrounding various stages in the bird's development from the fertilized egg through production and processing to consumption (Northcutt 2009). With these arguments the current review is set to discuss the broiler meat quality attributes and various factors affecting them.

Determinants of broiler meat quality

Appearance (colour)

It could be argued that appearance is the most important quality attribute of cooked or raw poultry meat because consumers associate it with the product's freshness, and they decide whether or not to buy the product based on their opinion of its attractiveness. Poultry meat is unique because it is sold with intact skin or without skin. There are reports of regional preferences in USA for pale to deep pigmentation, whilst consumers in the UK tend to prefer a white, non-pigmented skin (Fletcher 2002). The availability of lipid soluble pigments such as carotenoids in the feedstuff, feed sources (e.g. grain type), xanthophylls concentrates and exotic sources (e.g. broccoli, paprika extract and tomato), feed additives (e.g. fish oils, antioxidants, vitamins and trace minerals), xanthophyll stability and biological availability and management and processing parameters (e.g. breed and strain, disease and health, environment, housing type, scalding, pre-slaughter conditions, processing variables and sex) and the ability of some breeds to deposit carotenoid pigments in the skin determine the extent of pigmentation (Northcutt 2009).

A number of factors affecting poultry meat colour that include sex, age, strain, processing procedures, chemical exposure, cooking temperature, irradiation, and freezing conditions has been reported (Mugler and Cunningham 1972). Broilers have been reported to have significantly lower heme pigment concentrations than turkeys because broilers reach market ages at substantially younger ages than turkeys. Many breeds lack the genetic ability to deposit pigments in the epidermis giving a white colour, irrespective of diet. Flock health is important as certain diseases affect pigment absorption and deposition. The bleaching of epidermal layer occurs at temperatures exceeding 54 °C, so care must be taken during the scalding operation. On the other hand, principal heme pigments found in meat are myoglobin, hemoglobin, and cytochrome C (Froning 1995). However, poultry meat has significantly lower myoglobin concentration than that of other species (Millar et al. 1994). Age, intramuscular fat, meat moisture content of the birds and stress immediately before and during slaughter affects meat colour. Ante-mortem temperature stress and excitement just prior to slaughter has been shown to affect turkey meat colour more than that of chicken meat (Ngoka et al. 1982). Both the myoglobin content and the muscle pH contribute to meat colour and meat colour defects.

The main factors affecting poultry meat colour are the state of the haem pigments, pre-slaughter factors (genetics, feed, handling, stress, heat and cold stress, gaseous environment), slaughter, chilling and processing conditions (stunning techniques, presence of nitrates, additives and pH, final cook temperature, reducing conditions, irradiation) (Froning 1995). The degree of protein denaturation and physical appearance of meat, dependent on post-mortem temperature and pH, influence the amount of light that is reflected from the interior and exterior of the meat surface because light scattering is directly proportional to the extent of protein denaturation (Lawrie 1991). Light scattering affect meat lightness (L*) in a fashion inverse to that caused by heme pigment concentration, having a minimal effect on meat redness (a*) and yellowness (b*). Muscles at pH $\geq$ 6.0 are characterized by minimal protein denaturation, low light scattering and hence translucent appearance. However, muscles at pH $\leq$ 6.0 undergo greater protein denaturation, causing increased light scattering and opaqueness (Anadon 2002).

The main issues with broiler meat colour are muscle type (dark or light meat), colour variation and colour defects. In addition, it is the only species known to have muscles that are dramatic extremes in colour (white and dark meat) (Northcutt 2009). Raw breast meat exhibits a pale pink colour, while raw thigh and leg meat appears dark red. Mottling, extreme paleness (PSE-like condition) or darkness and appearance defects such as bruises, poor bleeding, haemorrhages, bone darkening and other blood related problems of meat have reflected badly on poultry industry.

Texture

Texture is probably the most important quality factor associated with consumer satisfaction in the eating quality of poultry. The texture and degree of firmness of the meat is a function of the amount of water held intramuscularly. Water tightly bound to the muscular proteins has a swelling effect on muscle proteins, occupying the spaces between myofibrils and giving the meat a more firm structure (Anadon 2002). While conversion into meat, the rate and extent of the chemical and physical changes occurring in the muscle also determines its tenderness. Slaughtering of a bird stops blood circulation which in turn blocks supply of oxygen or nutrients to the muscles. Thus, muscles run out of energy, contract and become stiff. This stiffening, called rigor mortis, is followed by softening again making meat tender when cooked (Northcutt 2009). Any breach in this normal conversion of muscle to meat will affect its tenderness.

The major factors affecting meat tenderness are maturity of the connective tissues and contractile state of the myofibrillar proteins along with environmental stress, scalding temperature, age of birds, rate of rigor development, rate of chilling and filleting time. The maturity of connective tissue is a function of chemical cross bonding of the collagen in the muscle which increases with age, hence the tough meat is found in older birds. Whereas, the contractile state of the myofibrillar proteins depend on the rate and severity of rigor mortis development. Though, it is not clear whether the total amount of muscle collagen is affected by age or not, its heat resistance increases and salt solubility decreases with age (Zanusso 2002), making the meat less suitable for further processing where salt solubility is important e.g. brining and marinating. However, there is no age related differences in the tenderness of breast and thigh meat (5, 8 weeks of age) of broilers with more juiciness in the breast meat of older birds (Sonayia et al. 1990).

Flavour

Flavour is another quality attribute that consumers use to determine the acceptability of poultry meat. Though, it is difficult to distinguish between taste and odour while consumption, both of them contribute to the flavour of poultry. Flavour development occurs while cooking of poultry meat due to sugar and amino acid interactions, lipid and thermal oxidation and thiamin degradation. These chemical changes are not unique to poultry but the lipids and fats in poultry are unique and combine with odour to account for the characteristic 'poultry' flavour (Northcutt 2009).

Generally, it is not only difficult to produce a flavour defect but also to enhance flavour during production and processing. Breed/strain variation in palatability of the meat is well documented. For instance, Hinai-jidori chickens of Japan (Kiyohara et al. 2011), Korean native/-farm chickens (Jung et al. 2011) and kadaknath of India have significantly higher flavour scores compared to that of broilers. The reason for breed variation may be due to variations in content of Inosine-5′-monophosphate (IMP) (Tang et al. 2009), arachidonic acid and docosahexaenoic acid (DHA) (Lee et al. 2012), amino acids, including aspartic acid, threonine, serine, glycine, alanine, tyrosine, lysine, and arginine. The lipid derived compounds, the 2-alkenals such as hexenal, heptenal, octenal, nonenal, undecenal, and dodecenal as well as aldehydes, including octanal, nonanal, decanal, and decadienal are related to both chicken-specific aroma and flavour (Ramarathnam et al. 1993). Also, cooking for prolonged periods caused flavour enhancement of chicken meat through sugar-amine reaction (Millard reaction). In contrast to boiling, the cooking methods under high temperature and low moisture conditions such as roasting, grilling, frying, and pressure cooking, involving heat treatments in which the temperature exceeds 100 °C, cause the formation of a vast number of heterocyclic compounds found in the aroma of cooked meats (Melton 1999). The pH of food is important in the development of flavours in the Maillard reaction (Calkins and Hodgen 2007). The pH ranging between 4.5 and 6.5 favours the formation of nitrogen-containing compounds which contribute to food flavours. The post-mortem ageing cause the generation of many chemical flavour compounds including sugars, organic acids, peptides, free amino acids, and metabolites of adenine nucleotide metabolism which determine the final flavour of meat (Liu et al. 2012). These components serve either directly as flavour components or as a pool of reactive flavour intermediates that form many of the characteristic meat flavours after cooking (Spanier et al. 1997). Irradiation affects meat quality including flavour and aroma primarily through the production of free radicals (Perez-Alvarez et al. 2010). The dimethyl trisulphide has been reported as the most potent off-odour compound in irradiated raw chicken followed by cis-3 and trans-6-nonenal, oct-1-en-3-one and bis (methyl thio) methane (Patterson and Stevenson 1995). It is imperative that increase in irradiation-induced sulphur-containing volatiles, due to high concentration of sulphur containing amino acids in poultry meat, appear to be the result of radiolytic degradation of sulphur-containing amino acids (Ahn 2002) and lipid oxidation (Jo and Ahn 2000), which produces cabbage-like or rotten vegetable putrid odours. Age of the bird at slaughter (young or mature birds) affect the flavour of the meat. The maximum flavour development occurs during the sexual maturation of broilers due to changes in the lipid fraction or fatty acid composition (Zanusso 2002).

Nutritional quality

The major components of raw poultry meat are proteins, lipids and minerals at proportions between 18.4 and 23.4%, 1.3 and 6.0%, 0.8 and 1.2% respectively (Culioli et al. 2003). Breast meat contains less than 3 g fat/100 g and corresponding average value for dark meat (skin off) is 5–7 g/100 g. Unlike beef and dairy fat, chicken meat contains no trans fat (Greger 2014) which contributes to coronary heart disease and about half of the fat is made up of the desirable monounsaturated fats, and only one-third of the less healthy saturated fats. The World Cancer Research Fund and others (Bingham 2006) have suggested that the consumption of large amounts (more than 500 g/week) of red meat, particularly processed meat, but not chicken meat, may be unhealthy. Poultry meat, particularly from scavenging birds due to their varied diet, is an important provider of the essential polyunsaturated fatty acids (PUFAs), especially the ω-3 fatty acids (Farrell 2013). The amounts of these important fatty acids, particularly long-chain polyunsaturated fatty acids (LC-PUFA), can be increased more easily in chicken meat than in other livestock meats, although negative effects on the oxidative stability may erupt.

Water holding capacity

Water holding capacity (WHC), having direct bearing on the colour and tenderness of meat, is among the most important functional properties of raw meat. For categorization of WHC of meat samples the terms water binding potential (WBP), expressible moisture and free drip has been proposed (Jauregui et al. 1981). The WBP represents the maximum amount of water that muscle proteins can retain under the conditions prevailing at measurement. Expressible moisture refers to the quantity of water that can be expelled from the meat by the use of force and free drip refers to the amount of water that is lost by the meat without the use of force other than capillary forces (gravity). About 88–95% of the water in the muscle is held intracellularly within the space between actin and myosin filaments and rest is located between the myofibrils (Offer and Knight 1988). Increase in the water content of muscles, enhancing tenderness, juiciness, firmness, and appearance, improve the quality and economical value of meat. WHC is the function of factors such as pH, sarcomere length, ionic strength, osmotic pressure, and development of rigor mortis which act by altering the cellular and extracellular components (Offer and Knight 1988).

After death, due to lack of oxygen supply lactic acid production occurs resulting into decline of pH which causes protein denaturation, loss of protein solubility and in an overall reduction of reactive groups available for water binding on muscle proteins. The reduction of reactive groups occurs because the pH of the muscle reaches the isoelectric point at which positive and negative charges on the reactive groups of the proteins are equal which attract each other leaving almost nothing to react with the charged groups of water and thus impairing the ability of the proteins to bind water (Wismer-Perdersen 1986). The lack of energy supply results in accumulation of actinomyosin complexes which causes loss of space between the myofibrillar proteins and the consequent decrease in WHC. As rigor mortis progresses, divalent cations such as Mg^{2+} and Ca^{2+} in the sarcoplasm neutralize the negatively charged reactive groups on adjacent protein chains, reducing the electrostatic repulsion between them (Wismer-Perdersen 1986) which further reduces the space available for water to be retained intramuscularly and increases the amount of water expelled to the extracellular space.

pH

pH has a direct bearing on the meat quality attributes such as tenderness, water-holding capacity, colour, juiciness and shelf life. The broiler breast meat with high pH has a higher water binding capacity than meat with lower pH. The pH of broiler meat is the function of amount of glycogen in the muscle prior to slaughter and the rate of glycogen conversion into lactic acid after slaughter. Identification of colour is an easy way to determine the pH of meat. If the meat is very dark, it will have a high pH and if it is very light, it will have a low pH (Anadon 2002).

A direct correlation between the color of the breast fillets and the pH of the meat has been reported (Fletcher 1995). In vitro studies show that a pH reduction of 1 unit increases the rate of protein denaturation by 12 times (Offer 1991). It is believed that low pH causes the proteins in the muscle to spread out, causing the light to reflect differently from the surface, resulting in the light color. The variations in breast meat colour, mainly due to pH effects, were shown to affect shelf life, odour development, moisture pick up in marination, drip loss, water holding capacity and cooking loss (Allen et al. 1998). Lighter than normal fillets had an initial pH of 5.8, marination pick-up of 6%, drip loss of 5.88%, and 34.4% cook loss. Darker than normal fillets had an initial pH of 6.02, 7.67% marination pickup, 3.34% drip loss, and 32.9% cook loss which shows a significant impact on drip loss. Poultry meat with low pH has been associated with low water-holding capacity (WHC), which results in increased cook-loss, drip loss, shelf-life and decreased tenderness (Barbut 1993).

Factors affecting the determinants of broiler meat quality

Broiler nutrition and meat quality

Nutrition of birds has a significant impact on poultry meat quality and safety. The response of a bird to its feed is closely related to the changes in the growth of the skeleton, muscle and fat depot. Feeding of Low-fat and carbohydrate-rich diets to birds do not influence sensory characteristics (Moran 2001), but decrease carcass fat, carcass yield and breast meat yield (Smith et al. 2002). As the dietary energy needed exceeds the optimum level of protein necessary to attain its delivery, body fatness increases and muscle mass decreases with the reverse occurring when protein is in excess of energy and mainly affecting the yield of breast meat. However, feeding of high nutrient density (high energy, high protein) diets result in an improved carcass yield and decreased fatness, with more distinct responses in males (Hess and Bilgili 2004). An increase of protein and amino acid content of carcasses has been reported by reducing dietary fat and increasing crude protein or single amino acids (Waldroup et al. 2001). However, contrary to this, Aletor et al. (2003) reported an acceleration of de novo fat synthesis, causing higher levels of saturated fatty acids (SFA) and mono-unsaturated fatty acids (MUFA) in liver and higher levels of triglycerides and cholesterol in blood plasma, while feeding low protein diets.

Poultry meat has been discovered as an interesting basis for functional foods. It is well known that dietary fatty acid profiles are reflected in tissue fatty acid. For improvement of nutritive value of poultry meat lot of experimentation has been done with ω-3 fatty acids (Crespo and Esteve-Garcia 2001). A lower abdominal fat pad was reported in birds fed PUFA-rich diets (Crespo and Esteve-Garcia 2001). They argued that fatty acids could cause an inhibition of lipogenesis, redistribution of lipids in the body, or higher energy expenditure despite their higher digestibility with respect to saturated fatty acids (SFA). Carcass quality changes associated with unsaturated fatty acids may be tearing of skin during plucking and increased cooking loss. Though, a general problem with enriching poultry meat with LC-PUFA may be the more liquid fat, there appears to be minimal effect on breast tenderness with improved flavour but reduced perceived juiciness. Conjugated Linoleic acid (CLA) is another fatty acid which is anti-carcinogenic, prohibits atherosclerosis, improves immune function, reduces body fat and improves meat yield (Du and Ahn 2002). CLA causes increase in SFA content by the inhibition of Δ9-desaturase. Du and Ahn (2002) observed an increase in protein content and a decrease in the fat content of tissue, by increasing CLA supplements in diets to 3%, causing higher texture values along with a paler and less intensive meat colour (a*, b*).

Antioxidants (mainly α-tocopherol) play a significant role in preventing oxidation of LC-PUFA while enriching poultry meat with ω-3 fatty acids. Huang et al. (1990) argued that DHA content in thigh muscles can be increased without causing fishy flavour by feeding menhaden fish oil up to 3% along with 0.1% ethoxyquin (antioxidant). Dietary supplementation of α-tocopherol (Guo et al. 2003) and selenium (Yaroshenko et al. 2004) significantly reduce thiobarbituric reactive substances (TABRS) in tissues and significantly improve meat functional properties under heat stress. Recently, consumers have become cautious of using GMO (genetically modified organisms) feed components in animal nutrition, although no dangerous transfer of plant DNA or recombinant DNA to tissues has been proven yet. Though, no significant differences were observed in broilers fed transgenic corn compared to non-modified corn variety in terms of fattening performance, slaughter performance and nutrient contents in broiler tissues (Taylor et al. 2003), the potentially dangerous effects of GMO in animal diets on human health by consumption of animal products cannot be fully ignored.

Broiler management and meat quality

In addition to strong impact of genotype on meat quality, particularly texture, management does play an important role in meat quality, particularly in consumption features (juiciness, tenderness, flavour). However, Grashorn and Clostermann (2002) have reported that differences in meat quality between poultry meat from intensive and extensive production systems are mainly genetic in nature, whereas production environment (except temperature) is less important. Stocking density is one of the most important husbandry practices in poultry production. Though, improving the economic returns of production, high stocking density does not affect slaughter performance or meat quality significantly (Feddes et al. 2002), except for a higher proportion of downgraded carcasses. Standard feed withdrawal period prior to slaughter reduces stress with positive effects on slaughter yield and tenderness of meat

(Bilgili 2002). In poultry production loading, transport, unloading, slaughtering and processing of birds are unavoidable steps which have impact on meat quality, particularly consumption characteristics. All these actions induce stress and may result in PSE-like (pale, soft, exudative) conditions recognized as tough meat by the consumer. Brightness (L*a*b*) and pH of the meat can be easily used to determine the PSE condition (Swatland 2004). Although, the reasons not fully clarified, Wilkinson and Scott (2005) investigated the impact of satellite cells in the muscle fibre, stimulated by nutritional, environmental or physiological factors, in the development of PSE meat. Further, Guarnieri et al. (2004) reported the reduced incidence of PSE and improved meat quality in broilers by treating birds with a water shower spray directly before slaughter.

Transportation, especially in combination with high environmental temperature, will increase the incidence of PSE. The most critical stress inducing stages in the slaughtering of poultry are unloading, shackling and stunning of birds. In order to improve and make this process less stressful, automatic on farm crating systems, automatic unloading of crates in the slaughter house combined with controlled atmosphere stunning (CAS) instead of electrical stunning have been introduced (Raj et al. 1997). In particular, CAS has been very instrumental with respect to carcass quality, decrease in proportion of down grading due to bruises and broken bones, along with improved meat colour (less bright) and tenderness of breast meat (Fletcher 2002). Slaughtering meat type poultry is a very rapid process due to the high degree of mechanization. Time between shackling of live birds and carcasses entering the cooler will normally not exceed 15 min. According to Contreras and Beraquet (2001) the dissection of warm carcasses (hot boning) results in meat quality aberrations. Alternatives to overcome this problem may be muscle tensioning or electrical stimulation of the muscles. Further, low voltage, high frequency electrical stunning has been found to overcome meat quality aberrations (Contreras and Beraquet 2001). Groom (1990) argues that fresh bloom and the absence of strong odours, essential carcasses quality attributes, requires large volumes of potable water for washing purpose. However, controversial point is that inevitably chicken carcasses pick up some water during the washing and cooling processes. So a very close supervision and control of the washing, evisceration and chilling processes are necessary. Though, most poultry chilling is accomplished by immersing the carcasses in ice water for 30–60 min, an alternative method is air chilling, where carcasses are not immersed but chilled by refrigerated air.

Biochemical changes and meat quality

After slaughter, biochemical changes, causing the conversion of muscle to meat, will determine final meat quality. Even after death due to asphyxia resulting from bleeding, muscle cells continue to consume and produce ATP as long as glycogen sources are available and pH conditions are optimal. According to Greaser (1986) this anaerobic metabolism results in the depletion of glycogen and accumulation of lactic acid in the muscle which cannot be removed due to the lack of blood circulation, thus, causes a decrease in sarcoplasmic pH to a point that inhibits further glycolysis and ATP production. Though, ATP production ceases, ATP consumption continues to cause the dissociation of the actomyosin complexes preventing rigor mortis. However, when the ATP concentration falls below 1 μM/g of tissue, the dissociation between actin and myosin is arrested and the onset of rigor mortis, a vital process for desirable meat quality, begins and 0.1 μM ATP/g of tissue marks the completion of rigor (Offer 1991). However, Greaser (1986) further argued that the time taken for completion of rigor varies with species, muscle, fiber type, holding temperature, rate of glycolysis and the extent of struggling at the time of death. Barring the faster rate of glycolysis and rigor development in poultry, biochemical postmortem changes involved in the conversion of muscle to meat are similar to mammalian species. Dransfield and Sosnicki (1999) have reported 1 h time period for completion of rigor in broiler chicken. A more rapid postmortem pH decline in turkey breast muscles was observed by Ma and Addis (1973) than in the more severe case of PSE in pork muscle, which may be partially attributed to the high white fiber content of poultry breast muscles adapted to anaerobic metabolism (Dransfield and Sosnicki 1999).

Carcass temperature and meat quality

The postmortem carcass temperature has a marked impact on rigor mortis and overall meat quality. Broiler carcasses exposed to higher temperatures during processing exhibit rapid rates of glycolysis and a premature onset of rigor mortis. Dransfield and Sosnicki (1999) reported 20 times increase in protein denaturation with a temperature increase of 10 °C. Further, the carcass at elevated temperatures show accelerated glycolysis and toughened breast meat and vice versa. It is shown that carcass temperature increases due to the generation of heat resulting from the conversion of glycogen to lactic acid and the hydrolysis of ATP and creatinine phosphate in muscles along with the scalding temperatures as high as 55 °C. Genetic improvements in poultry have also been correlated with carcass temperatures during processing. Intense selection for heavier carcasses and thicker muscles have led to increase in time required to reduce the internal musculature temperature, thus decreasing chilling rates and consequently increasing the exposure time of carcasses to elevated temperatures (Rathgeber et al. 1999). However, Dransfield and Sosnicki (1999) suggest increased rate of carcass cooling to ward off the potential detrimental PSE-like effects of rapid growth and heavy muscled lines.

Pre slaughter factors and meat quality

The interaction between the genotype and the environment has a profound effect on meat quality of poultry (Debut et al. 2003). The birds subjected to heat stress prior to slaughter generally have higher body temperature and result into rapid pH decline and onset of rigor in muscles. Such pre-slaughter conditions usually lead to pale, soft, and exudative (PSE) meat, which in turn results lower possessing yields, increased cooking losses, and reduced juiciness (Aberley et al. 2001). This PSE condition described first time by Ludvigsen (1954) in swine as muscle degeneration. Since 1970s, such meat quality problems have been reported in turkeys and broilers with a prevalence ranging between 5 and 40% (Owens et al. 2000). The PSE condition in poultry has been associated with factors such as stress, genetic strain, gender, season of the year, geographical region, pre-slaughter handling, and processing practices. Any stress shortly before or at slaughter has been reported to cause PSE due to an increased rate of post-mortem metabolism, accelerated glycolysis, and pre-mature on set of rigor mortis. The correlation of corticosterone to colour of meat has been reported by Kannan et al. (1998), as prolonged and short-term elevation of plasma corticosterone levels produce changes in color of the breast and thigh muscles, respectively and they concluded that higher plasma corticosterone levels in broilers were undoubtedly associated with PSE-like meat.

According to Offer (1991) and Solomon et al. (1998) postmortem glycolysis, temperature, and pH are the three most important factors contributing to the physicochemical changes observed in PSE. However, other factors such as genetics, muscle type, processing practices, and pre slaughter stressors have also been recognized to impact the biochemical processes during the conversion of muscle to meat (Solomon et al. 1998). PSE meat results due to protein denaturation and loss of protein functionality when carcasses are exposed to high temperatures and low pH early after slaughter (Offer 1991; McKee and Sams 1998). Offer (1991) reported that PSE meat can also develop, especially in the deep musculature, if carcasses are cooled slowly such that postmortem pH will decline at a normal rate but carcass temperature will remain high for prolonged periods of time, exposing carcasses to pH values near ultimate pH while carcasses are still hot. Muscles that show PSE have a postmortem pH decline of 1.04 units/h while normal muscles have a pH decline of 0.65 units/h (Offer 1991). However, Berri et al. (2001) reported that ultimate pH is determined by the glycogen level in the muscle at slaughter, while the rate of pH decline is determined by enzyme activity involved in postmortem glycolysis. Development of PSE condition is also dependent on the type of muscle fiber involved. Red meat is less susceptible than white meat to the development of PSE because of higher amounts of myoglobin and hemoglobin, lower glycolytic potential, higher oxidative metabolism and lower glycogen content compared to white fibers (Solomon et al. 1998).

A lower initial and final postmortem pH and higher rates of postmortem pH decline was exhibited by breast meat of heat stressed turkey, resulting in pale meat and increased cooking losses, compared to non-stressed turkeys (McKee and Sams 1998). Thus, the seasonal heat stress might be a factor in the development of PSE by accelerating postmortem metabolism and biochemical processes in the muscle. The effects of fasting on meat quality of poultry are particularly important, so feed withdrawal period of 8–12 h before slaughtering is a common practice. It significantly reduces muscle energy stores used during postmortem metabolism, thus, accelerates onset of rigor. Ngoka et al. (1982) reported that a feed withdrawal period of 15 h in turkeys resulted in meat with significantly higher ultimate pH without affecting color.

The low colour intensity and greater exudation of water in PSE meat occurs due to loss of protein functionality and the inability of the muscle proteins to retain water. This high proportion of extracellular water has many surfaces causing greater reflection of light with limited capability to absorb it (Forrest et al. 1975). Therefore, this light scattering along with loss of myoglobin, hemoglobin and other exudates greatly reduces the color intensity of PSE meat. As discussed earlier the denaturation of proteins occur as a result of exposure to low pH and high temperatures early during rigor mortis causing less water to be retained by the meat due to loss of reactive groups and space between actin and myosin filaments to hold water, thus increasing drip loss or decreasing water holding capacity. According to Wismer-Perdersen (1986) approximately two-thirds of the reduction in water retention is due to the rigor bonds, while postmortem pH accounts for the remaining third. The actomyosin complex formation causes shortening and compactness of the muscles which significantly reduces the WHC of PSE meat and increases rate and extent of drip formation and loss of water (Offer 1991). Offer (1991) reported that histological studies of the filament lattice revealed that the reduction of length of myosin heads by just 2 nm (from normal 19 nm to 17 nm) in PSE muscles is enough to cause a closer relationship between the myosin and actin filaments that increases the amount of water expelled from the meat.

Primary processing of poultry meat and its quality

Processing and its effects on the nutritional value of poultry have become more of a concern during the past few years. Processing can be divided into primary processing (stunning, scalding, plucking, chilling, postmortem aging, freezing and cold storage) and further processing (heating, storage, freeze–drying, irradiation, and creation of restructured or ready-to-eat products). In general primary processing, except wet chilling, has very little impact on nutritional value of poultry.

Chilling: According to Sams (2001) the chief objectives of poultry chilling are to increase food safety for consumers and extend product shelf-life for marketing. The poultry carcass temperature should be reduced to 4.4 °C or less within 4–8 h in relation to the weight of the carcass after slaughter (USDA 2009). It is obvious that immersion chilling may directly affect the water-soluble nutrients in poultry meat with no significant impact on proteins or lipids. Though, fresh poultry, if chilled and stored under ideal conditions, can have a shelf-life of 2–3 weeks, during immersion chilling Pippen and Klose (1955) reported increases in calcium, sodium, phosphorus, potassium, chlorine, and nitrogen in chill water and recorded losses of solids from the poultry meat (4.8 and 4.0 g/Kg respectively) after 24 h of immersion in water. Ang and Hamm (1983) argued that hot-deboned birds (without chilling) had significantly less moisture (0.9%), more ash (12%), more phosphorus (5.2%), more potassium (5.8%), and less sodium (10%) than water-chilled broilers. Immersion chilling also causes water uptake, leading to a dilution effect on other components, increase in drip loss and further leaching of solids (Pippen and Klose 1955). Ang et al. (1982) indicate that deep chilling is the best method tested for retaining mineral content of the meat, whereas, vitamin and protein retention does not vary with chilling methods. Under the proper conditions, tenderness is well maintained throughout the chilled/frozen storage life, but improper chilling/freezing, can produce severe toughening and meat of poor eating quality (James 2002). James et al. (2006) argued that chilling methods can influence the quality and visual appearance of carcasses which in turn affect their overall acceptability and carcasses can absorb water (4–6%) through the skin and surrounding fat in contrast to air chilling. Though, challenged by the factors like cross-contamination, wastewater management, reshackling, and post-chill purge loss (Sams 2001), immersion chilling is most popular method of chilling as compared to air chilling. However, it has been reported that color, pH, shear force, or water holding capacity (Zhuang and Savage 2009), marination properties, sensory quality and tenderness (Perumalla et al. 2011) of broiler breast meat were not affected by different chilling method.

Postmortem aging: Postmortem aging is the next primary processing step in which the biochemical changes, discussed earlier, take place. Postmortem changes in protein denaturation and degradation play a key role in determining final meat quality. Time of aging has a marked impact on the nutritional quality of poultry meat. Khan and Lentz (1965) reported that freezing during rigor caused the most drip loss upon thawing, the lowest protein solubility, larger losses of nitrogen constituents and ribose, and the greatest cooking loss. Broiler meat in post rigor period has maximum extractable nitrogen. LC-PUFA are produced in aged muscle, but not in un-aged muscle along with the lipid changes causing an increase in free fatty acids and decrease in phosphatidyl choline and phosphatidyl ethanolamine (Hay et al. 1973). Zhuang and Savage (2012) have hypothesized that aging broiler breast fillets for a longer period of time before marination would result in enhanced marination performance, including marinade uptake and marinade retention of a salt/phosphate-based marinade and overall product yield, cook loss, and overall cooked product yield.

Freezing: Leygonie et al. (2012) describe freezing as a commonly accepted method of food preservation to ensure the safety of meat products in the global meat export market. During frozen storage, a series of physical and biochemical changes do happen, such as water loss, color change, lipid and protein oxidation, which influence the quality of frozen chicken meat (Soyer et al. 2010). The effects of freezing arise out of differences in standing time, rate of freezing and rate of thawing. Freezing arrests almost all kinds of biochemical reactions by inhabiting the available enzyme systems due to which vitamin retention is excellent in frozen foods if proper temperature (−20 °C) is maintained. The rate of freezing has a strong bearing on drip losses resulting in losses of B vitamins during thawing and subsequent cooking (Bender 1978). It may be because freezing and thawing of meat disrupts the cell membranes and changes the internal structure of biological materials. However, Bowers and Fryer (1972) reported no significant loss of riboflavin or thiamine in a cooked product after 5 weeks of storage at −17.5 °C. Further, West et al. (1959) found that after 2 and 4 months of frozen storage (−29 °C), pre-cooked frozen chicken breasts had the same thiamine content as those of raw frozen, thawed, and then cooked chicken breasts. According to Lee and Dawson (1973) Linoleic acid levels in the raw frozen chicken dropped to 20% after 3 months and 16% after 6 months. However, in general no impact of freezing on the nutritional value of protein has been depicted.

Further processing of poultry meat and its quality

In poultry industry the term ''further processed'' is used in a similar fashion as the term "processed meats" in red meat industry. As mentioned earlier methods used for further-processed products are size reduction, deboning, restructuring, emulsifying, batter/breading, heating, and freezing. Further processed product can be either "ready to eat" or "ready to cook" product. Since, further processing reduces the time of preparation and efforts of the consumer; they are also termed as "convenience foods". However, critics have implied that further processing reduce the nutritional value of poultry meat. A brief review of few methods used for preparing "Further processed" products and their impact on nutritional value of poultry meat is as follows.

Heat Processing: The cooking of meat results in a number of quality changes viz. flavor and taste enhancement, inhibition of microorganism, increase of shelf life and digestibility (Broncano et al. 2009). However, cooking also mainly contributes to the deterioration of the cooked meat giving undesirable odours, rancidity, texture modification, nutritional losses and toxic compound production. Each cooking method has its own advantages and disadvantages depending upon the product processed (Cholan et al. 2011). Among all the processing methods heat is the most destructive one. Lysine and threonine and thiamine are most affected amino acids and vitamin, respectively, depending on time of exposure and the degree of heat. In oven heating Hall and Lin (1981) found significantly ($P < 0.01$) higher thiamine retention in breast meat at high temperature short cooking time (204 °C, 46 min) than low temperature long cooking time (121 °C, 131 min) and probably due to a lower end temperature of the breast meat (82 °C) significantly ($P < 0.01$) higher thiamine content was also retained in breast meat compared to the thigh meat because of thicker and larger size of breast meat. Thus time of exposure to heat has more impact than temperature on nutritional quality of "further processed" meat product. Generally, riboflavin and niacin are less susceptible to heat than thiamine. Though, niacin is stable to air and light at all pH levels, riboflavin can be destroyed under alkaline conditions (Bender 1978). The effects of heating on protein appear to be minimal and there occurs minor losses of all amino acids except tryptophan. No significant effect was found on fatty acids upon heat treatment of meat samples (Myers and Harris 1975). Thomas and Calloway (1961) reported no changes in riboflavin, niacin and total amino acid levels due to canning. However, in vitro pepsin digestion revealed the availability of lysine, cystine, methionine, and tryptophan reduced to less than 50% after canning. Ascorbic acid and thiamine, both present in only minimal quantities in poultry meat, are susceptible to loss during prolonged storage of conventionally canned foods. Significant losses in thiamine and niacin of cured, smoked, and cured canned chicken versus canned chicken were observed by Millares and Fellers (1949). Higher pH (6.1 vs 5.6) and longer heat exposure increased the losses. Microwave cooking can alleviate two major destructive components of conventional heating: external heat and time of heating.

Frying is a common process, often utilized in the food industry due to significant sales of vast quantity of fried products. Frying modifies food properties by inducing water loss, by stimulating thermo-oxidation reactions, changing the color of the product to brown and by modifying the lipid profile (Ramirez et al. 2004). Frying induces no significant loss of riboflavin and thiamine in meat. Though, Warner et al. (1962) reported no change in the biological value of the fats in skillet-fried chicken, Nakai and Chen (1984) found that only fatty acid composition changes, but not the total amount of fat in chicken meat, upon frying. They observed decrease in palmitic, palmitoleic, and linoleic acids and an increase in oleic acid. Contrary Lee and Dawson (1973) observed that raw chicken had linoleic acid levels of 20% of the total lipid which increased to 34% upon cooking (frying). On the other hand, boiling is most detrimental to B vitamins than any other heat treatment. The leaching out of thiamine, riboflavin, and niacin into water during boiling depends on the cooking time and the surface area involved. Bender (1978) observed that meat cut up into small pieces and boiled for 15 min caused the loss of 80% of water-soluble vitamins, muscle extractives and proteins, though, denatured by boiling, had no effect on nutritional value.

Dehydration and freeze–drying: Freeze–drying (lyophilization) is a drying process in which the solvent and/or the suspension medium is crystallized at a low temperature and thereafter sublimated from the solid state directly into the vapor phase (Liu et al. 2008). Changes in nutritional value of poultry meat, while low-temperature dehydration and freeze–drying, are meager, since no heat is used. Freeze–drying has no destructive effects on thiamine, niacin, or riboflavin in chicken muscle. Thomas and Calloway (1961) concluded that thiamine retention was most favored by freeze–drying raw poultry and least favored by irradiation. Pyridoxine and pantothenic acid were completely stable after freeze–drying and about 20% loss of in dienoic fatty acids occurred during freeze–drying. No changes in digestibility of the freeze–dried chicken were observed, by both pepsin (in vitro) and humans. However, Caparino (2000) has reported that the final product obtained may differ in physico-chemical, nutritional, sensory and rehydration properties and microstructures.

Irradiation: Irradiation, generally not approved in poultry, causes minimal nutritional losses (Thomas and Josephson 1970). Two forms of radiation processing, radurization and radicidation, are used on chilled poultry in a few countries to prolong shelf life with almost insignificant effect on protein, fat and vitamin levels. Radurization, designed to kill or inactivate food spoilage organisms, and radicidation, designed to kill or inactivate all disease-causing organisms, are accomplished at processing levels below 10 kGy, followed by refrigerated storage. However, Froning (1978) argues that these processes have only of pasteurizing value, and extend shelf-life by 2 weeks at most. A third form of irradiation processing with sterilizing property is radappertization. Precooked foods in vacuum-sealed containers are exposed to ionizing radiation while frozen (−20 to −40 °C) at doses high enough to achieve commercial sterility (25 to a maximum of 70 kGy, otherwise, palatability may be affected). When radappertization is done at room or chilled temperatures it results in the formation of off flavors and odors. Unsaturated fats are most affected by Radappertization causing oxidation, degradation, and decarboxylation of the lipid fraction (Thomas and Josephson, 1970). Lewis et al. (2002) and Nam and Ahn (2003) reported that as the dose of irradiation increased the thiobarbituric acid reactive substances (TBARS) increased in chicken and turkey breasts respectively. Further, they have reported proportional increase of colour values of irradiated meat with increasing dose of radiation. However, on the other hand, Lewis et al. (2002) observed no significant difference in the appearance and overall acceptability of irradiated meat from that of non-irradiated one. Irradiation also causes a decrease in protein solubility, water-holding capacity, while drip loss increases (Josephson and Peterson 1983). DeGroot et al. (1972) reported that lysine availability and protein efficiency ratios of irradiated chicken were unaffected by irradiation (6 kGy) after 6 days of refrigeration followed by conventional cooking. Thiamine is the most radiation-sensitive B vitamin. Riboflavin and niacin were usually found to be stable to all forms of radiation processing, with a maximum loss of 20% (DeGroot et al. 1972).

Genetics and meat quality

During last few decades the primary breeding companies constantly developed new lines through selection with unprecedented improvement in performance and carcass traits along with increased breast meat yield to cater the rising demands for white meat and further processed products (Anadon 2002). The heritability estimates of various parameters like meat quality traits (0.35–0.81), postmortem pH decline (0.35–0.49), lightness (0.50–0.75), redness (0.57–0.81), yellowness (0.55–0.64), drip loss (0.39), etc. suggest that genetic selection is a best tool for improvement of broiler meat quality. Although, the improvements have been possible due to moderately high heritabilities and favorable genetic correlations among these performance and carcass traits, a higher incidence of PSE meat in the broiler and turkey industries has been reported, suggesting a negative impact of selection on meat quality traits. Wang et al. (1999) argued that genetic improvements through intense selection for rapid growth and heavy muscling are the possible contributors to the increased incidence of PSE in poultry. Sante et al. (1995) reported that high performance turkey breeds have a higher rate of meat pH decline (2 times higher) compared to slow growing breeds and similar trend were also observed in commercial broiler lines. Berri et al. (2001) reported altered breast muscle metabolism due to intense selection for growth and body composition traits in broilers. McKee et al. (1998) studied the use of succinyl-choline to induce a condition similar to porcine stress syndrome (PSS) in turkeys. A higher incidence of PSE was observed in birds treated with succinylcholine compared to non-treated control birds suggesting that the PSE problem in poultry meat could have the same origin as in pork meat. Symptomatic similarities in the etiology of PSE in turkeys and pigs suggests that genetic selection for growth performance could have increased the susceptibility of turkeys to stress, especially to those stressors that induce PSE meat in pork (McKee et al. 1998). Although, Wang et al. (1999) has hypothesized that a certain population of commercial turkeys may have an altered sarcoplasmic reticulum Ca^{2+} channel protein resulting in abnormal activity of the protein and leading to the development of PSE meat, a genetic basis for differences in postmortem glycolysis in turkeys and broilers has not been established yet.

Le Bihan-Duval et al. (1999) argued that after 13 generations of selection for body weight, breast meat and breast meat yield an increase by 18, 29 and 9% respectively was observed and selection for abdominal fat weight and percentage reduced them by 6 and 20%, respectively. Further, in this experiment selection resulted in higher ultimate pH with no differences in meat lightness (L*). However, meat redness (a*), yellowness (b*) and breast meat drip loss were significantly reduced and WHC improved in the selected line when compared to the control line. Interestingly, a strong negative genetic correlation of −0.76 was found between pH at 24 h postmortem and abdominal fat percentage. So Anadon (2002) argues that the traditional selection for increased white meat yield could result in detrimental effects on meat quality while selection against abdominal fat could improve meat attributes due to its high negative correlation with the ultimate pH of meat. However, the impact of genetic selection on meat quality is not still clear as a result of contrasting reports obtained under experimental conditions and commercial farms. But the identification of factors related to meat quality and the PSE condition in poultry will be of extraordinary achievement of breeding companies to improve meat quality. At molecular level there is a need for the discovery of a gene directly associated with the PSE condition in poultry which would facilitate the identification and removal of the said gene from the flock through the use of molecular techniques and marker assisted selection (Anadon 2002).

Conclusion

In conclusion it can be argued that improvement of broiler chicken meat quality is dependent on multiple factors, thus a very complex process. Faulty disposition of any of these factors will reflect badly on meat quality. These factors will help us develop designer and value added meat products making broiler meat production even more economical and beneficial for human health. Desired meat composition, product type and quality can be achieved through the above discussed factors.

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Compliance with ethical standards

Conflict of interest The authors contributing to the compilation of this review do not have any conflict of interests.

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