Chapter 14

The colour of poultry meat: understanding, measuring and maintaining product quality

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1 Introduction

Colour is a crucial criterion that determines the consumer acceptance of meat products. Consumers can rapidly assess the visual appearance of fresh meat, and colour causes an immediate positive or negative psychological response (Nanke et al., 1998). Consumers know what fresh or processed meat colour should look like and relate the colour to the product quality, safety and storage history (Kropf, 1980; Seideman et al., 1984; Allen et al., 1997, 1998). In case of U.S. beef industry, about 15% of retail beef is discounted in price due to discolouration, which can be estimated to annual revenue losses of 1 billion dollars (Liu et al., 1995; Mancini and Hunt, 2005). Despite no available estimation of economic losses for poultry meat, the cost reduction caused by surface discolouration in poultry meat is likely to be considerable (Kuttappan et al., 2012). This chapter reviews the fundamentals of meat pigments; the colour of fresh, cooked, cured and irradiated poultry meats; the mechanism and prevention of discolouration and methods for colour measurement.

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2 Meat pigments

2.1 Overview

Meat colour, which is one of the most important organoleptic factors that determines consumers' acceptability, can be different depending upon the chemical status of haem pigments, muscle type (red or white) and observation conditions such as light sources. However, the most crucial attribute is the concentration and chemical status of meat pigments.

There are three types of representative haem pigments (myoglobin, haemoglobin and cytochrome c), which are responsible for the colour of poultry meat. In well-bled red muscle tissues, myoglobin is the main haem pigment, and it constitutes about 70 to 95% of the total pigment (Rickansrud and Henrickson, 1967; Fox, 1987; Judge et al., 1989). Some oxygen-utilizing enzyme such as catalase can also act as a pigment, but its contribution to meat colour is not considerable (Sandman, 1987; Pikul et al., 1986).

The concentration of haem pigments is also an important factor (Nocito et al., 1973). Poultry meat, especially breast meat, has very low myoglobin content compared with the red meats such as beef, pork and goat meat. The concentration of haem pigment varies with species, strain and age of the animal, and muscle types (Potthast, 1987): pigment concentration increases with the age of poultry. The meats of ducks and geese, particularly in the breast muscle, contain many times more haem pigments than those of chickens or turkeys. The leg and thigh muscles of chickens or turkeys have 5 to 10 times more haem pigments than their breast muscles (Saffle, 1973). The myoglobin content in the red muscles of poultry meat is 2 to 4 mg per g, whereas the content in white muscles is less than 0.5 mg per g of wet tissues (Romans et al., 1994; Pearson and Young, 1989). Thus, the phenomena of colour changes in poultry breast meat are different from those in thigh meat.

2.2 Chemistry of haem pigments

Haem pigments consist of two components: one is haem ring, a non-protein portion that is the key to colour changes, and globin, a protein portion. Myoglobin and

![Figure 1](https://example.com/figure1.png)

**Figure 1** Colour and the absorption maxima of myoglobin with six different ligand compounds (pigments and absorption maxima): Metmyoglobin (505 and 630 nm); oxymyoglobin (543 and 580 nm); deoxymyoglobin (540 nm, not shown); carbon monoxide myoglobin (541 and 577 nm) and nitric oxide myoglobin (547 and 578 nm).
cytochrome c molecule have a globin and a haem ring, whereas haemoglobin is made of four myoglobin subunits. The amino acid residues of globin are oriented so that their non-polar portion points inward. The only polar amino acids inside the myoglobin are two histidines, which have critical functions at the haem-binding site (Bandman, 1987). The haem portion of the pigment is of special interest because the characteristics meat colour and the formation of the sixth ligand depend on the state (valency) of the iron within the haem ring (Judge et al., 1989). The fifth ligand of haem ring is linked to proximal histidine of haem pigments.

The reflectance and absorption spectra of haem pigments differ depending on the status of haem iron and the ligand molecule attached to the sixth coordinate of the haem ring. The ability of haem iron to coordinate with a sixth ligand is changed by the chemical state of haem iron. When haem iron is in oxidized form (ferric state, Fe$^{3+}$), it cannot combine with any other molecule. Only when the haem iron is in reduced form (ferrous state, Fe$^{2+}$), it can combine with a compound to make a sixth ligand (Judge et al., 1989). A few gaseous molecules (oxygen, nitric oxide and carbon monoxide) are permitted to access the reduced haem iron (Fig. 1). Various conditions of haem iron and sixth ligand determine the colour properties of myoglobin (Table 1).

Oxymyglobin has a reduced iron bound with oxygen as a sixth ligand. This molecule imparts bright-red colour desirable for fresh meat colour. During the conversion of muscle to meat, oxygen is mainly present at the outer surface of meat. Therefore, the myoglobin in the centre of meat is usually in the reduced form and is weakly combined with a water molecule or stabilized by the postal histidine of globin (Lehninger, 1982). The colour of the reduced haem pigment is purple, and is called deoxymyglobin. The purple colour can be turned into bright-red colour by exposing the meat to air (Suman and Joseph, 2014). If oxygen partial pressure in meat is low, haem iron becomes oxidized to form brown

<table>
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<th>Table 1 The colour properties of myoglobin depending on the chemical state of iron atom and a colour-generating ligand</th>
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<td><strong>Haem protein</strong></td>
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colour, and the pigment is called metmyoglobin. Formation of high-level metmyoglobin in fresh meat is not desirable because consumers can misunderstand the meat as old or low-quality meat.

The oxymyoglobin is considerably stable and is not oxidized to metmyoglobin under reduced conditions (Judge et al., 1989). However, once the meat is oxidized by exposing the meat to the open air for long time, it is hard to revert the meat under reduced conditions. Therefore, along with the haem complex formation, the oxidation–reduction potential (ORP) of meat is also critical for colour changes because the colour intensity of ferrous haem pigment is stronger than that of the ferric state. The reduction of metmyoglobin involves an enzyme system, metmyoglobin reductase that require NADH and NADPH coenzymes (Hagler et al., 1979), and the reducing activity increases with the rise of meat pH (Walter and Taylor, 1965).

3 The colour of fresh poultry meat

3.1 Fresh meat pigment

A bright-red colour is considered as a desirable fresh meat colour except for poultry breast meat. Bluish-white is the normal colour of skinned poultry breast meat due to its low pigment concentration. Although all three common forms (deoxy-, oxy- and met-) of myoglobin exist in fresh meat, the colour of fresh meat is mainly imparted by the bright-red oxymyoglobin and purple deoxymyoglobin (Ghorpade and Cornforth, 1993). The bright-red colour of fresh meat depends on the proportion of oxymyoglobin and the rate of oxygen diffusion, oxygen consumption rate (OCR), and partial pressure of oxygen at the meat surface (Giddings, 1977). The colour of fresh poultry meat is influenced by sex (Smith et al., 2015), ante-mortem factors such as diet, bird management and preslaughter stress (Schneider et al., 2012). The stress level reflects a decrease of pH in post-mortem muscle. The ultimate pH is strongly correlated with meat quality parameters such as tenderness, water-holding capacity (Zhu et al., 2012), cooking loss, juiciness and meat colour (Guidi and Castigliego, 2010; Bianchi and Fletcher, 2002; Qiao et al., 2001). Poultry meat with lower ultimate pH has higher L-values, imparting a paler appearance with lower consumers’ acceptance (Fletcher, 1999). Heat stress and struggling during the slaughtering process are also factors influencing the pH decline of poultry meat (Ngoka and Froning, 1982).

At the beginning stage of storage, the degree of oxygen penetration in meat is low due to the decreased oxygen consumption by mitochondria (Bendall and Taylor, 1972). At a few millimetres below the meat surface, there is a region where the oxygen partial pressure is in the optimal range for the formation of a metmyoglobin layer (Ledward, 1970). Thus, packaging with high oxygen partial pressure can be beneficial to extend the fresh meat colour (Taylor and MacDougall, 1973), even though the conditions can trigger lipid oxidation during the extended storage. Vacuum-packaged meats have mainly purple deoxymyoglobin. Some approaches have utilized anoxic atmospheres in master packs for shipment to retail (Choulira et al., 2007; Petrou et al., 2012), and meat cuts are subsequently displayed in traditional oxygen-permeable packaging to bloom. The use of modified atmosphere packaging can discolor fresh meat because the inner gases such as carbon dioxide or nitrogen reduce the pH or partial pressure of oxygen, resulting in brown colour (Seideman et al., 1984).
When fresh meat is cut, the deoxymyoglobin predominated before cutting changes to bright-red colour because the reduced myoglobin contacts with the oxygen of air and forms oxymyoglobin (Renerre, 1999). However, the stability of formed oxymyoglobin can vary depending upon the continued supply of oxygen and reducing environments for pigments. The OCR of tissue is different depending on the species and muscle types. A high OCR decreases oxymyoglobin formation and maintains myoglobin in a reduced state. Because the deoxymyoglobin is less stable than oxymyoglobin, the pigment can be oxidized easily to metmyoglobin. If meat is continuously exposed to oxygen, myoglobin is gradually oxidized to metmyoglobin especially at the low oxygen partial pressure, high temperature, high ionic strength and low pH (Renerre, 1999). Since the oxygen solubility in water increases as the temperature decreases, the maintenance of low temperature is highly desirable. The activity of oxygen-utilizing enzymes will increase with increasing storage temperature, which contributes to lowering the oxygen tension at the meat surface. After long-term storage, metmyoglobin becomes visible at the surface, and the meat colour turns to complete brown.

Aerobic microbial flora in their logarithmic growth phase have a high oxygen demand and may reduce the oxygen partial pressure to increase the formation of metmyoglobin causing brown discoloration (Andersen and Skibsted, 1992). Raw meat pigment is susceptible to bacterial discoloration, in which case green colour develops on product surfaces. Hydrogen sulphide produced by microbial contamination can form a green pigment called sulphmyoglobin. This greening usually results from poor sanitation or improper storage conditions where products are contaminated.

The loss of moisture from meat surfaces concentrates pigments and reduces light reflection due to the loss of intracellular water, both of which cause dark colour. During frozen storage, an excessive loss of moisture from meat surfaces will result in dehydration and discoloration of localized areas. Upon thawing, meat colour is improved just a little (Judge et al., 1989).

### 3.2 Metmyoglobin reduction

Specific attention is given to metmyoglobin reduction and antioxidant approaches for minimizing oxymyoglobin oxidation (Faustman et al., 1996; Reddy and Carpenter, 1991). The metmyoglobin-reducing enzyme (metmyoglobin reductase) has been considered to minimize the oxidation of oxymyoglobin (Faustman et al., 1988). α-Tocopherol maintained oxymyoglobin by the enhancement of cytochrome b$_5$-mediated reduction of metmyoglobin (Lynch et al., 1998; Sheldon et al., 1997; Rey et al., 2015). Meats contain negligible amounts of ascorbic acid, and the addition of ascorbic acid to meats may be beneficial for inhibiting metmyoglobin formation (Lee et al., 1999). The reduction in meat is related with NADH as a coenzyme, which facilitates the conversion of ferrimyoglobin to its ferrous form (Andersen and Skibsted, 1992). Metmyoglobin-reducing activity increases with decreasing pH, although to a lesser extent than for oxymyoglobin autoxidation. Reducing activity can be indirectly measured using ORP. Vacuum-packaged meat has lower ORP values than aerobically packaged one, and vacuum conditions maintained haem pigments of poultry breast with strongly reduced conditions (Nam and Ahn, 2002a). Irradiation can also provide poultry meat with reduced conditions, and irradiation dose was negatively correlated with ORP values (Table 2). Once reducing equivalents in the meat are exhausted, a complete metmyoglobin formation will occur (Ledward, 1984).
Table 2 Pearson correlation coefficients between colour values, irradiation dose, storage time, carbon monoxide (CO), redox potential and TBARS of vacuum-packaged turkey breast

<table>
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<tr>
<th></th>
<th>a*-value</th>
<th>b*-value</th>
<th>IR</th>
<th>Storage</th>
<th>CO</th>
<th>ORP(^{b})</th>
<th>TBARS(^{c})</th>
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<tr>
<td>L*-value</td>
<td>0.05</td>
<td>-0.76*</td>
<td>0.20</td>
<td>-0.21</td>
<td>0.23</td>
<td>-0.09</td>
<td>-0.30</td>
</tr>
<tr>
<td>a*-value</td>
<td>-</td>
<td>0.33</td>
<td>0.88**</td>
<td>0.26</td>
<td>0.79**</td>
<td>-0.39</td>
<td>0.58</td>
</tr>
<tr>
<td>b*-value</td>
<td>-</td>
<td>0.17</td>
<td>0.03</td>
<td>0.23</td>
<td>-0.23</td>
<td>0.73*</td>
<td></td>
</tr>
<tr>
<td>Irradiation</td>
<td>-</td>
<td>0.00</td>
<td>0.89**</td>
<td>-0.44</td>
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<td>0.47</td>
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<tr>
<td>Storage</td>
<td>-</td>
<td>-0.23</td>
<td>0.37</td>
<td></td>
<td>-0.19</td>
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<tr>
<td>CO</td>
<td>-</td>
<td></td>
<td>-0.74*</td>
<td>0.63</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>ORP</td>
<td>-</td>
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<td>-</td>
<td>-0.42</td>
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\(^{a}\)Irradiation dose; \(^{b}\)Oxidation–reduction potential; \(^{c}\)2-Thiobarbituric acid-reactive substances.

\(^{*}\)Value with significant correlation (p < 0.05), n = 18.

\(^{**}\)Value with significant correlation (p < 0.01).


3.3 Discolouration

Discolouration in fresh meat is mainly caused by oxidation of haem pigment to metmyoglobin, which has an unattractive brown colour. Oxymyoglobin is more stable than deoxymyoglobin because of the hydrogen bonding between the bound oxygen and a distal histidine (Giddings, 1977; Renerre, 1999). The differences between species and muscles in their ability to form metmyoglobin can be related to the inherent differences in the concentration of mitochondria, activity of mitochondrial enzymes and content of accessory factors (Renerre, 1999). Therefore, meat has different partial oxygen pressure, pH, reducing ability and glycolytic rate (Pedrao et al., 2015).

At high oxygen tension, oxymyoglobin can persist for several days before discolouration occurs. When the oxygen partial pressure is reduced and the oxidation to metmyoglobin is favoured, brown discolouration develops (Fox, 1987). If the oxygen pressure is reduced to partially vacuum conditions, myoglobin will be oxidized to metmyoglobin. However, if the oxygen partial pressure reaches zero, deoxymyoglobin will be formed (Lawrie, 1983). The autoxidation rate was more dependent on the ligand accessibility of the myoglobin. Partial or complete loss of tertiary structure of globin results in an increased rate of oxymyoglobin oxidation (Livingston and Brown, 1981). The brown discolouration of fresh meat can be found in predominantly spoiled or after prolonged storage. However, in even fresh meat, the discolouration phenomenon can occur because of several reasons. Meat illuminated with light has relatively high rate constant of autoxidation (Kropt, 1980).

There is a strong relationship between broiler breast meat colour and muscle pH (Fletcher, 1999; Van Laack et al., 2000). The oxygen partial pressure also depends on temperature and ultimate pH of meat (Petracci et al., 2004). A high ultimate pH nearing neutral maintains respiratory activity and causes dark meat where deoxymyoglobin predominates (Livingston and Brown, 1981). An acidic ultimate pH enhances myoglobin oxidation and may lead to browning or fading of colour (Alnahhas et al., 2014). Low pH reduces the stability constant for the haem–globin linkage and increases the autoxidation.
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rate (Chan et al., 2011). At pH values below 5, protonation of bound oxygen is accelerated, and release of superoxide anion is favoured. The unfolding of the globin moiety allows much easier attack of water molecules or hydroxyl radicals (Faustman et al., 1996). Low pH will also cause myoglobin to be more readily oxidized to metmyoglobin (Seideman et al., 1984). Guardia et al. (2014) reported that short-term nutritional strategies such as changing amino acid profile before slaughter can alter the pH of breast meat with limited impact on broiler growth and carcass composition.

Unusual discolouration can be found in an unexpected pH range of meat (Li et al., 2015). The abnormal paleness of PSE (pale, soft and exudative) meat is due to the high proportion of extracellular free water (Popp et al., 2013). The high free water in tissues increases the reflecting surface and L-value, and decreases the colour intensity greatly (Judge et al., 1989; Barbut, 1996). Tissues with high pH also can have high OCR due to high enzyme activities. Zhu et al. (2011) reported that PSE is generated due to elevated temperature during early post-mortem period, resulting in rapid glycolysis, which consequently induces phosphorylase denaturation. In addition, high temperature at early post-mortem could activate AMP-activated protein kinase (AMPK) and affect protein solubility (Zhu et al., 2013; Van Laack et al., 2000). Pedrao et al. (2015) reported that refrigeration treatment was effective in retarding the post-mortem glycolytic rate and preventing PSE conditions in poultry.

3.4 Lipid and myoglobin oxidation

The presence of oxidized unsaturated fatty acids may affect the colour of fresh meat (Qiao et al., 2002b). Primary changes during lipid oxidation are the production of free radicals and peroxides such as superoxide anion, hydrogen peroxide, hydroxyl radical and ferryl myoglobin radical. The oxidation of fatty acids influences not only flavour but also colour and texture of meat (Arroyo et al., 2015). Colour deterioration is essentially dependent on the rates of myoglobin autoxidation induced by lipid oxidation (Yin et al., 1973). Consequently, the oxidation of fatty acids or pigments can accelerate the oxidation of the other, which is called co-oxidation (Faustman and Cassens, 1990; Gatellier et al., 1993).

Free metal ions such as copper, iron, zinc and aluminium can catalyse the oxidation of oxymyoglobin (Kanner, 1994). Processing of raw meat such as deboning, mechanical separation, restructuring and grinding can also increase lipid and pigment oxidation (Renerre, 1999). The disruption of muscle membrane promotes the formation of free radicals through the interaction of iron with oxygen. In frozen meat, light in conjunction with oxygen increased lipid and colour oxidation (Berthelsen and Skibsted, 1987). Superoxide anion radicals generated from membrane electron transport systems may autoxidize oxymyoglobin into metmyoglobin. Ferrous iron can be converted to ferric iron and produces free radicals by oxidative stress. Therefore, lipid and pigment oxidation was closely coupled. Lipid oxidation can promote pigment oxidation and vice versa. Lipid oxidation may be a promoter of myoglobin oxidation, but it was not always possible to deduce whether or not the pigment oxidation caused lipid oxidation (Renerre and Labadie, 1993).

3.5 Blood spots and white striping

Improper slaughtering, which generates blood spot, affects the colour of meat. In fresh meat, a bloody appearance can reduce consumers' acceptability, and the pigments in the
blood spots can be oxidized and converted to undesirable grey-brown or darker colour after cooking (Lyon et al., 1986; Schilling et al., 2015). The blood spots on breast and thigh can be minimized through optimal stunning and handling conditions (Hoen and Lankhaar, 1999). The migration of haemoglobin-rich bone marrow from the thigh femur to meat tissue in frozen meat can also result in undesirable colour changes (black colour) after cooking (Guidi and Castigliego, 2010). Bone discolouration can occur around the leg and thigh bones, knees joints and wing by freezing and thawing young chickens (Judge et al., 1989). White striping in broiler breast fillets is a defect resulting in the reduction of consumer acceptance. It is characterized grossly by the occurrence of white striations seen parallel to the direction of muscle fibres and could be associated with increased growth rate in birds (Kuttappan et al., 2013).

4 The colour of cooked poultry meat

4.1 Cooked meat pigments

The colour of cooked meat must be grey-brown and is caused by protein (globin) denaturation during heat processing under aerobic conditions. The brown pigments of cooked meat are denatured metmyoglobin due to the formation of denatured globin haemichrome (ferrihaemochrome). When meat is cooked under the anaerobic conditions such as vacuum-packaging conditions, denatured globin haemochrome (ferrohaemochrome, pink/red colour) is formed. However, it is easily oxidized to ferrihaemochrome (brown colour) (Suman and Joseph, 2014). The cooked brown pigment could be partially reversible to red colour during refrigerated storage (Froning et al., 1968). When a nitrogen compound (nicotinamide) reacted with the haem during cooking, pink colour was produced (Ahn and Maurer, 1989c). For the pink colour formation in cooked turkey breast meat, ORP of meat was an important factor (Cornforth et al., 1986). The pH was also important for the colour of cooked meat as the heat stability of the metmyoglobin increased with a rise in pH of the pigment solution (Satterlee and Zachariah, 1972; Ahn and Maurer, 1989b). In some cases, pink colour, which will be explained later, can be found in even fully cooked meat. Complete disappearance of pinkness in cooked meat does not require intensive cooking (Howe et al., 1982).

4.2 Discolouration during cooking

The brown colour of cooked meat is detectable when approximately more than 60% of the myoglobin is in metmyoglobin form. Metmyoglobin formation is accelerated by the conditions that cause denaturation of protein portion of myoglobin, and by oxidation under low oxygen tension. Denaturation increases by lowering the pH of meat (Fletcher et al., 2000). Low-pH muscles have open muscle fibre structure, allowing for greater discolouration. The addition of phosphates to the meat reduces the amount of pigment denaturation due to pH increase. The addition of NaCl increased the rate of heat-induced denaturation of myoglobin. The reverse effect of NaCl and phosphates was observed with cytochrome c (Ahn and Maurer, 1989a). Cytochrome c is very stable against heat denaturation and can resist denaturation at 105°C (Cornish and Froning, 1974).
The effect of fat contents to the discoloration of cooked meat is very low, but the surface browning is occasionally the result of fat decomposition and polymerization with carbohydrate and protein decomposition products (Judge et al., 1989).

4.3 Pink colour defect
Pink discolouration in cooked, uncured poultry meat, especially breast meat (white muscle), is considered a quality defect, which can cause consumer's complaint because consumers may perceive it as an indicator of undercooked or contaminated meat (Holownia et al., 2003). Therefore, pink discolouration is a negative factor for cooked meat colour with an economic concern to the processors. Pink defect has been generated by the undernaturally myoglobin, contamination with nitrite or nitrate (Froning et al., 1969; Ahn and Maurer, 1987), severe stress at pre-slaughtered (Ngoka and Froning, 1982), absorption of combustion gases such as nitric oxide or carbon monoxide (Froning et al., 1969) or use of non-thermal pasteurization by irradiation (Nam and Ahn, 2002). Poultry breast meat was more susceptible than highly pigmented beef to pinking in the presence of sodium nitrate in soy isolates (Heaton et al., 2000).

Although the usual concentration of nitrate and nitrite in turkey breast meat was not high enough to cause a pink colour defect, it is possible under certain conditions such as high nitrate levels in feed or water supplies, high microbial load and long storage conditions (Ahn and Maurer, 1987). While cooking in a gas oven, a small amount (ca. 0.4 ppm) of nitrogen dioxide gas causes pinking of turkey roll, but the solubility of nitrogen monoxide gas at meat surfaces was lower than nitrogen dioxide (Cornforth et al., 1998). The pink colour generated by nitrite can be identified easily by acetone-HCl extraction (Homsey, 1956; Ahn and Maurer, 1989a). Irradiation also increases the pink colour in cooked poultry breast meat (Nam and Ahn, 2002b).

The haem-complex forming ligands such as pyridine and its derivatives were suggested as possible nitrite substitutes to fix meat colour. The haem complexes have a strong effect on the redness of the cooked meat, especially under reduced conditions (Ahn and Maurer, 1990a,c). ORP measurements of cooked turkey rolls showed that haemochrome formation was promoted by reducing conditions and prevented by oxidizing conditions (Cornforth et al., 1986; Ahn and Maurer, 1989a).

Cytochrome c has been suggested as a contributing factor to pink colour development in cooked turkey breast meat. Ahn and Maurer (1990b) reported that the pink colour of turkey breast could be formed by the binding of denatured ferrocytochrome c with several ligands. The cytochrome c content of poultry meat was closely correlated with the colour of meat and with the content of total haem pigment (Pikul et al., 1987).

Proper slaughtering practices (minimizing stress conditions such as exhaust gases, prolonged transport, high temperature and carcass washing using nitrate-free water) prevent poultry pink colour defect (Ahn and Maurer, 1987; Bowker et al., 2014). The pinking in poultry meat was inhibited by addition of several ingredients such as citric acid, non-fat dry milk and whey protein concentrate (Dobson and Cornforth, 1993; Schwarz et al., 1999; Kieffer et al., 2000). Those chelating additives may have the ability to bind haem iron during heat processing and to inhibit pink pigments formation. Despite the pigments that cause pinking is known, a better understanding of how processing factors affect endogenous conditions is essential to control the pink colour defect in uncured cooked poultry breast products (Holownia et al., 2003).
5 The colour of cured poultry meat

The main objective of curing meat is not only to extend shelf life but also to develop an attractive pink colour. Nitric oxide myoglobin is a natural cured pigment before heating, and its colour is bright-red. During cooking, the nitric oxide pigment is stabilized by the denaturation of globin of myoglobin and is converted to nitrosyl haemochrome. The pigment is bright pink colour characteristic of cured meat. Nitrate or nitrite, which can be added as a curing agent to meat, cannot be directly combined to myoglobin. If nitrate is used in curing, it must be converted to nitrite by nitrate-reducing microorganisms, which is, in turn, reduced to nitric oxide. Nitrite also may be reduced to nitric oxide by natural reducing activity of post-mortem muscle tissues (Judge et al., 1989).

Since nitrite is a very efficient oxidizing agent for myoglobin, the initial reaction is probably the conversion of reduced myoglobin or oxymyoglobin into metmyoglobin. Nitric oxide then combines with the haem portion of metmyoglobin to produce nitric oxide metmyoglobin. Reduction of nitric oxide metmyoglobin must be accomplished either naturally in meat or by reductants included in the cures. Therefore, cured meat pigment formation is also absolutely dependent on reduced conditions of meat (Kim et al., 1988). Usually reducing agents such as ascorbic acid and erythorbic acid are included in curing agents. Sulphydryl groups released during heat processing are also strong reducing compounds. After further heating, denaturation of globin is complete and the other site of haem can be taken up by another nitric oxide. The pigment is called dinitrosyl haemochrome, which is more stable and brightly redder than nitrosyl haemochrome (Lee and Cassens, 1976).

Nitric oxide myoglobin and nitrosyl haemochrome are very susceptible to light fading. During long-term display of cured meat products, the fading of the cured meat colour can be brought about by either lipid oxidation or light dissociation of the nitric oxide from the ferrous porphyrin coordination complex and subsequent formation of not only metmyochromogen but also green pigments. A brownish grey colour develops on exposed meat surface during light fading because faded pigment has its haem group in the ferric state. Therefore, to protect the light fading of cured product colour, the elimination of oxygen from meat surfaces by vacuum packaging is recommended (Min and Ahn, 2012). In the absence of oxygen, the nitric oxide split from haem by light will not be oxidized, and it can then recombine with the haem.

6 The colour of irradiated poultry meat

Ionizing radiation is an excellent method to reduce microbial numbers, but can significantly influence meat quality. Ionizing radiation can affect the rate of lipid oxidation and colour of meat. Irradiated raw chicken and turkey breast muscles had increased redness, and the increased red or pink colour was stable during refrigerated storage (Millar et al., 1995; Nanke et al., 1998). The increases of redness in meat by irradiation vary depending on species, muscle type, irradiation dose and packaging environment (Luchsinger et al., 1996; Ahn et al., 1998; Nanke et al., 1999). The $a^*$ value (redness) of raw poultry breast was increased by irradiation in both aerobically and vacuum-packaging systems (Luchsinger et al., 1996), but the vacuum-packaged meat was significantly redder than aerobically packaged ones during storage (Nanke et al., 1998, 1999). Irradiation also increases the
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The pink colour in precooked poultry meat (Nam et al., 2002). The increased red colour in cooked meat by irradiation may be a problem as discussed above.

Many researchers proposed that the red colour in irradiated light meat is oxymyoglobin, oxymyoglobin (oxyMb)-like pigment (Giddings and Markakis, 1972; Nanke et al., 1998), or carboxyl-myoglobin or nitric oxide myoglobin (Millar et al., 1995). However, the red pigment cannot be an oxymyoglobin because the red colour formed by irradiation can be produced under anoxic conditions, and the carboxyl group is too big to get inside of haem pocket to form the sixth ligand with haem iron. Nam and Ahn (2002a,c) proposed the pigment responsible for the red colour in irradiated light meat as carbon monoxide myoglobin (CO-Mb). Furuta et al. (1992) first reported that carbon monoxide could be produced from organic components such as alcohols, aldehydes, ketones, carboxylic acids, amides and esters by irradiation. Subsequently, Ahn and Lee (2006) found that meat components such as glycine, asparagine, glutamine, pyruvate, glyceraldehydes, α-ketoglutarate and phospholipids were good substrates for CO production by irradiation. It is also well known that irradiation produces hydrated electrons (aqueous e−), a powerful reducing agent, and decreases the ORP of meat (Thakur and Singh, 1994). The decrease of ORP in meat can play an important role in CO-Mb formation because the CO-Mb complex can only be formed when haem pigment is in reduced form (Nam and Ahn, 2002a,c). The lower ORP in irradiated meat, however, was maintained only under vacuum-packaging conditions (Nam and Ahn, 2002b). Maintaining reducing conditions (low ORP conditions) in meat is important for CO-Mb formation because the CO-Mb complex can only be formed when the haem pigment is in reduced form (Cornforth et al., 1986). Therefore, the decrease of ORP and CO production by irradiation are major factors for CO-Mb ligand formation of irradiated light meat (Nam and Ahn, 2002a,b; Brewer, 2004). In irradiated red meat, however, ORP or the status of haem pigments is more important than CO production or CO-Mb ligand formation. The content of haem pigments in beef is about 10 times greater than that of light meat and the proportion of CO-Mb to total haem pigments in irradiated beef is small (Ahn and Lee, 2004).

Aerobic packaging was more desirable than vacuum packaging in reducing the intensity of irradiated meat colour, as exposing irradiated poultry meat to aerobic conditions decreased the formation of carbon monoxide-myoglobin due to the competition of CO with oxygen and the oxidation of haem iron under aerobic conditions (Du et al., 2002).

7 Objective colour measurement for meat products

Measurement of colour also requires three dimensions of colour (hue, saturation and lightness). Any colour can be matched exactly using a suitable mixture of the three primaries (red, blue and green) and the relative amounts required to match a given colour are known as tristimulus value. In principle, meat colour can be measured by visual appraisal or instrumental colour methodology.

Objective colour measurement is necessary to understand mechanisms leading to colour changes and to devise strategies for elimination of colour defect in poultry meat. Colorimeter is a tricolorimetric system used for measuring hue, saturation and lightness of meat. Usually, the Hunter Lab or CIE Lab values and reflectance at specific wavelengths are used to express colour data (Bianchi et al., 2006). Numerous researchers have used \( L^*, a^*, \) and \( b^- \) values to document treatment effects on colour. Ratio of \( a/b \), hue angle or
saturation index is also used for discolouration studies (MacDougall, 1982). Tapp et al. (2011) reviewed the instrumental colour measurement information in meat science research using 1068 peer-reviewed journal articles. The paper reported that most researchers used Minolta (60.0%) over Hunter (31.6%), and most of the research was done using illuminant D_65 (32.3%). Various reflectance values have been used to measure meat colour, to follow colour change and to quantitate myoglobin forms. A major advantage of reflectance is that repeated measurements can be made on individually packaged sample. However, measurement reproducibility may be less as much of the light is scattered on translucent meat surfaces (Guidi and Castigliego, 2010).

Extraction procedures can give sharper peaks and better separation than reflectance measurements. However, it is possible to overestimate oxymyoglobin and metmyoglobin, and underestimate deoxymyoglobin because of changes occurring during extraction and measurement (AMSA, 2015). Each of the haem pigments has a characteristic absorbance spectrum, which can be used to determine the proportion of each pigment at a meat surface (Krzywicki, 1979; Millar et al., 1996). Reduced myoglobin has a diffuse absorption band with a maximum at 555 nm. Oxymyoglobin has two sharp peaks at approximately 540 and 580 nm. Metmyoglobin has an absorption peak at 505 nm and second weaker peak at 630 nm (Bandman, 1987). CO-Mb responsible for the red or pink colour of irradiated poultry meats showed absorption peaks at 541 and 577 nm (Nam and Ahn, 2002a).

Equations to estimate the myoglobin forms were summarized by Hunt (1980). For cured meat colour, a reflectance ratio of wavelengths 650/570 nm (Erdman and Watts, 1957) and the amount of total haem pigment and the percentage conversion total pigment to nitrosohaemochrome are widely used (Hornsey, 1956). The brown colour of cooked meat is difficult to measure instrumentally. Therefore, lack of redness or the percentage of denatured pigments is used in the colour evaluation of cooked meat (Trout and Gutzke, 1996).

A computer vision system (CVS) has been applied to the colour measurement of foods. The CVS has been proved efficient and reliable even when the samples have nonhomogeneous colour, shapes and surfaces (Girolami et al., 2013). Wu and Sun (2013) suggested that further in-depth research is required on the development of a faster, lighter/smaller and less-expensive CVS hardware, which is necessary to increase the image resolution, reduce image acquisition and analysis time, and improve the speed and space of storage for detailed colour measurement.

8 Conclusions

Numerous research works on the colour of fresh, cooked, cured and irradiated poultry meats; the fundamental chemistry of poultry meat pigments and the mechanisms of discolouration have been conducted. However, there are still a few significant basic concepts and treatments that need to be answered. In particular, the chemistry of pink colour regeneration in oven-roasted poultry breast meat during storage, the prevention of pinking in uncured cooked poultry breast meat, the role of genetics in meat colour and the relationships between metmyoglobin reduction and oxygen consumption have been suggested for the future research to solve practical meat colour problems. Developing new methods for colour detection using advanced CVS or biomedical techniques is also necessary to apply the new technologies to practical systems. The effect of additives,
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packaging materials, processing, oxidative stress of live birds and slaughtering conditions on breast meat colour needs further attention.

9 Where to look for further information

For an overview of the fundamental basis of myoglobin's interactions with biomolecules in postmortem skeletal muscles, factors influencing meat colour and the chemistry of meat colour phenomena; current research in meat colour:


10 References


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