

## A COMPARISON OF TWO METHODS OF DETERMINING COLOUR CHANGE IN THE ASSESSMENT OF THE QUALITY OF PORK

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### ABSTRACT

**Background.** The colour of pork is one of the most important measures of meat quality. For the consumer, it is a sign of freshness, crucial for the decision to buy a product. The storage of meat results in constant colour changes. Differences can be found in all colour parameters, especially chromatic ones, such as redness ( $a^*$ ) and hue angle ( $h^\circ$ ), as these changes are significantly correlated with a number of quality traits. Colour change can be determined not only by evaluating changes in colour parameters, but also by establishing the change in absorbance of specific wavelengths of light. The aim of this study was to compare the usefulness of these two methods of determining colour change: parameters measured on the CIELAB and CIELCh scales and colour change (%CC) determined based on the absorbance of selected wavelengths of light, i.e. 505, 540, 560, 580 and 630 nm. In this paper, we analysed two methods of measuring colour change in terms of their relevance for meat quality assessment.

**Material and methods.** The study involved 150 samples of the *longissimus lumborum* muscle collected from 150 carcasses of pigs slaughtered on an industrial line, weighing 65–107 kg, with an average carcass weight of 86.1 kg. Meat sensory analysis (colour, wateriness, firmness), physicochemical assessment (colour, WHC, pH<sub>48</sub>) and proximate analysis (moisture, total protein, fat, ash) were carried out. The methods included the determination of (I) changes in colour parameters measured on the CIELAB and CIELCh scales, and (II) colour change (%CC) based on the absorbance of selected wavelengths: 505, 540, 560, 580 and 630 nm. Chromatic absorbance values of a wavelength of 525 nm ( $A_{525p}$ ) and the relative content of Mb, MbO<sub>2</sub> and MetMb were calculated according to the method proposed by Krzywicki (1979).

**Results.** Basic chemical composition – with few exceptions – was not significantly correlated with differences in the values of colour parameters ( $\Delta L^*$ ,  $\Delta a^*$ ,  $\Delta b^*$ ,  $\Delta C^*$ ,  $\Delta h^\circ$ ) and colour change (%CC). With an increase in scores in the sensory evaluation of colour, wateriness, and firmness, and an increase in WHC and pH<sub>48</sub>, the differences in lightness ( $\Delta L^*$ ) significantly increased and differences in chromatic value ( $\Delta a^*$ ,  $\Delta b^*$ ,  $\Delta C^*$ ,  $\Delta h^\circ$ ) and %CC decreased, for all tested combinations of wavelengths. The highest correlation coefficients were observed for  $\Delta a^*$  and  $\Delta h^\circ$  and %CC<sub>540/630</sub> and %CC<sub>580/630</sub>, with colour change (%CC<sub>540/630</sub> and %CC<sub>580/630</sub>) showing a stronger correlation with the tested meat quality traits than the differences in redness ( $\Delta a^*$ ) and hue angle ( $\Delta h^\circ$ ). We found a very strong correlation between changes in the relative levels of MetMb ( $\Delta$ MetMb) and colour change (%CC) based on the absorbance of wavelengths of 540 and 505 nm, and 580 and 505 nm ( $r = 0.950^{***}$  and  $r = 0.967^{***}$ , respectively).

**Conclusion.** The determination of colour change based on the absorbance of two combinations of wavelengths, i.e. (I) 540 and 630, and (II) 580 nm and 630 nm, is more useful in the assessment of pork quality than changes in two most relevant parameters of the CIELAB and CIELCh scales, i.e. redness ( $\Delta a^*$ ) and hue angle ( $\Delta h^\circ$ ). Moreover, the determination of absorbance of a wavelength of 630 nm was more useful for determining colour change (%CC) than 505 nm. Colour change (%CC) based on the absorbance of wavelengths of 540 and 505 nm and 580 and 505 nm reflect the changes in the relative amounts of MetMb very well.

**Keywords:** colour, CIELAB, myoglobin, meat quality, pork

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## INTRODUCTION

The colour of pork is one of the most important markers of meat quality (Lindahl, 2005). For the consumer, it is a measure of freshness, crucial for the decision to buy a product (Mancini and Hunt, 2005; Risvik, 1994). Pork colour is usually presented in the form of three parameters: lightness ( $L^*$ ), redness ( $a^*$ ) and yellowness ( $b^*$ ) – CIELAB scale (CIE, 1976), or lightness ( $L^*$ ), chroma ( $C^*$ ) and hue angle ( $h^\circ$ ) – CIELCh scale (CIE, 1976). Their measurements are usually performed with the use of various spectrophotometers and illuminants (Brewer et al., 2001; Tapp et al., 2011).

The storage of meat results in constant colour change. Unfavourable changes are associated with the oxidation of muscle pigment and thus the formation of undesirable chemicals. Changes in the structure of the meat also occur, increasing the depth of penetration of its surface layer by light and oxygen. Differences can be found in all colour parameters, especially chromatic ones, such as redness ( $\Delta a^*$ ) and hue angle ( $\Delta h^\circ$ ). As these changes are significantly correlated with a number of quality traits (Karamucki et al., 2011), colour change is an important factor in assessing meat quality. For example, colour changes in PSE (pale, soft, exudative) meat occur faster and are greater than in normal or DFD (dark, firm, dry) meat.

Colour change can be determined not only by evaluating changes in colour parameters, but also by establishing the change in absorbance of specific wavelengths of light. Methods of measuring meat colour based on reflectance/absorbance show how colour is influenced by pigment quantity and the relative content of the chemical forms of myoglobin, taking into account the physical characteristics of the tissue and differences in its structure (Lindahl, 2005).

The maxima and minima of reflectance/absorbance in the 400–700 nm spectrum of raw meat depend, amongst other things, on the amount of pigment in the layer penetrated by light and the proportions of three chemical forms of myoglobin, oxymyoglobin ( $\text{MbO}_2$ ), metmyoglobin (MetMb) and deoxymyoglobin (Mb), in that layer. The chromatic absorbance at the isobestic point of these three forms, i.e. at a wavelength of 525 nm, is directly proportional to the amount of pigment reached by light during colour measurement,

and is used to determine the amount of pigment influencing the colour. Absorbance peaks for the individual chemical forms of myoglobin are also important; i.e. at 540 and 580 nm (absorbance peaks for oxymyoglobin), 560 nm (deoxymyoglobin), 505 and 630 nm (metmyoglobin) – Hunt (1980).

Studies on the quality of pork are primarily focused on meat obtained from porkers, i.e. young animals with low amounts of muscle pigment. In particular, this applies to glycolytic muscle, such as *m. longissimus* – the most frequently tested muscle of the pig carcass (Warner et al., 1993). A small amount of pigment in these muscles results in a relatively flat spectrum. To avoid excessive flattening of the spectrum, the use of a spectrophotometer with large aperture is recommended (Yancey and Kropf, 2008). Glycolytic muscles are also very susceptible to defects in quality (for example PSE), producing wide variations in the structure of the meat, and influencing colour parameters and extremes of reflectance/absorbance.

The aim of this study was to compare the usefulness of two methods for the determination of colour change: parameters measured on the CIELAB and CIELCh scales and colour change (%CC) determined based on the absorbance of selected wavelengths, i.e. 505, 540, 560, 580 and 630 nm.

## MATERIAL AND METHODS

### Materials

The study used 150 samples of *longissimus lumborum* muscle taken from 150 carcasses (75 gilts and 75 castrates) weighing 65–107 kg, with an average carcass weight of ( $86.1 \pm 9.0$ ) kg, obtained from pigs which were crosses of Polish Large White  $\times$  Polish Landrace sows with Duroc  $\times$  Pietrain boars, slaughtered on an industrial production line. The pigs were slaughtered at about 6 months of age. Meat samples weighing about 1 kg (meat and bone) were collected after a two-step cooling of the half-carcasses (cooled for 60 min at  $-20^\circ\text{C}$  and cold stored for 24 h at  $4^\circ\text{C}$ ), during cutting, from the segment between 1st and 4th lumbar vertebra on the right half-carcass. Samples were wrapped in foil and transported in a thermos bottle to the laboratory and stored until the following day at  $4^\circ\text{C}$ .

About 48 hours after slaughter, the meat was separated from the bone and external fat and epimysium

were removed. Sensory, physico-chemical and chemical analyses were then performed. Sensory evaluation was performed on meat slices with a thickness of 10 mm. Meat used in physico-chemical and chemical analyses was minced using a meat mincer with a 4 mm mesh.

## Methods

**Sensory analysis of the meat.** Sensory analysis was carried out around 48 h after slaughter on raw meat slices with a thickness of around 10 mm, by team of 5 trained individuals. The analysis was performed in 10 sessions and conducted in daylight, and at temperature of 20°C. The team rated the colour, firmness, and wateriness of the meat on a 5-point scale: 1 point – extreme PSE (pale, soft, exudative), 2 points – slight PSE, 3 points – normal meat, 4 points – slight DFD (dark, firm, dry), 5 points – extreme DFD. The samples were assigned symbols, and then rated on a 5-point scale extended with half-points (PN-ISO 4121, 1998).

**Physicochemical assessment of the meat.** A physicochemical assessment of the meat was carried out around 48 h after slaughter. It involved colour measurements and the determination of WHC and pH<sub>48</sub>. All the assessments were performed on freshly minced meat.

**Colour measurements.** Colour measurements were made after keeping ground meat samples in measurement cells in a household refrigerator at 4°C for 20 min to allow myoglobin to oxygenate in the surface layer of meat (Brewer et al., 2001; Krzywicki, 1979). Colour was measured using a HunterLab MiniScan XE Plus 45/0 apparatus with a measuring port diameter of 31.8 mm, adapted for measuring the colour of ground meat, applying the CIELAB and CIELCh scales (CIE, 1976; 1978) and illuminant D65 and 10° standard observer recommended for meat colour measurements (Honikel, 1998). Standardisation of the apparatus was carried out relative to black and white colour standard references, with the following coordinates:  $X = 78.5$ ,  $Y = 83.3$  and  $Z = 87.8$  (for D65 illuminant and 10° observer).

Chromatic absorbance values at a wavelength of 525 nm ( $A_{525p}$ ) and the relative content of Mb, MbO<sub>2</sub> and MetMb were calculated from the reflectance curve according to Krzywicki's method (1979), using

700 nm (the highest wavelength of the instrument) instead of 730 nm (according to AMSA, 2012) as follows:

$$A_{525p} = A_{525} - A_{700}$$
$$x = 1,395 - \frac{A_{572} - A_{700}}{A_{525} - A_{700}}$$
$$y = 2,375 \times \left( 1 - \frac{A_{473} - A_{700}}{A_{525} - A_{700}} \right)$$
$$z = 1 - (x + y)$$

where:

$A_{525p}$  – chromatic absorbance values at a wavelength of 525 nm,

$A_{525}$  – absorbance values at a wavelength of 525 nm,

$A_{700}$  – absorbance values at a wavelength of 700 nm,

$A_{572}$  – absorbance values at a wavelength of 572 nm,

$A_{473}$  – absorbance values at a wavelength of 473 nm,

$x$  – relative content of MetMb,

$y$  – relative content of Mb,

$z$  – relative content of MbO<sub>2</sub>.

The instrument measures the reflectance between 400 and 700 nm at 10 nm intervals. Reflectance values at wavelengths not given by the instrument (473, 525 and 572 and 505 nm) were calculated using linear interpolation. Reflectance values were converted into absorbance values according to the formula:  $A = 2 - \log_{10}R$ , where  $A$  is absorbance and  $R$  is reflectance.

Changes in colour were induced according to the Kortz (1966) method, by 4-h illumination of samples with a fluorescent tube light at an intensity of 1250 lx in an atmosphere saturated with water vapour, at room temperature (22–24°C). After illumination, colour measurements were performed again using CIELAB and CIELCh scales, illuminant D65 and standard observer 10°. Based on the results of the measurements obtained before and after illumination, differences in the values of the colour parameters were calculated:  $\Delta L^*$ ,  $\Delta a^*$ ,  $\Delta b^*$ ,  $\Delta C^*$ ,  $\Delta h^\circ$  and colour stability (CS), according to a modified version of the Kortz (1966) method. The colour stability (CS) was expressed as % colour change – %CC (Różycka and Michalski, 1978). The colour change (%CC) and colour stability were calculated according to the following formulas:

$$\%CC_{n/z} = 50 \cdot (2 - CS_{n/z})$$

where:

$\%CC_{n/z}$  – colour change calculated based the absorbance of wavelength  $n$  (540, 560 or 580 nm) and  $z$  (505 or 630 nm)

$$CS_{n/z} = 2 - \left( \frac{A_n}{A_z} - \frac{A'_n}{A'_z} \right)$$

where:

$CS_{n/z}$  – colour stability calculated based on the absorbance of wavelength  $n$  (540, 560 or 580 nm) and  $z$  (505 or 630 nm),

$A_n, A_z$  – values of absorbance of wavelengths  $n$  and  $z$  nm before the illumination of samples,

$A'_n, A'_z$  – values of absorbance of wavelengths  $n$  and  $z$  nm after the illumination of samples.

Colour measurements using the CIELAB and CIELCh scales and reflectance measurements were performed using “duplicate standards”, which permitted the values of all the colour parameters of a given sample and its reflectance values to be obtained from a single measurement.

**WHC.** Water holding capacity (WHC) of the meat was determined according to a method by Grau and Hamm (1953), as modified by Pohja and Niinivaara (1957), where WHC is expressed as a percentage of bound water in relation to the total water content in the meat. A sample of meat weighing approximately 0.3 g (precise to the nearest 0.0001 g) was placed on a Whatman 1 blotting paper between two glass plates and subjected to a load of 2 kg for 5 minutes. Then, the surface areas of infiltration and the meat sample were drawn onto the glass plates. After drying the filter paper, both surfaces were planimetered [cm<sup>2</sup>], and then the difference in the surface areas was divided by the sample weight, thus calculating the percentage of free water in the meat. The resulting value was divided by the percentage of total water content in the meat, and after deducting this value from 100 the percentage water retention of the meat was obtained.

**pH measurement.** The pH<sub>48</sub> value was measured using a combined glass electrode (ESAgP-306W type) of a CyberScan 10 pH-meter (Eutech Cybernetics Pte

Ltd., Singapore) in a water extract (distilled water) with a 1:1 meat to water ratio, after 1 h of extraction. Buffers with pH = 7.0 and pH = 4.0 were used for calibration.

**Proximate analysis.** The following chemical constituents were determined on thawed, ground samples of meat according to the official methods of analysis of the AOAC (2003): moisture content by oven drying a *ca.* 2-g test sample at 102°C to a constant weight (950.46B, see p. 39.1.02); crude protein content by the classical macro-Kjeldahl method (981.10 see p. 39.1.19); lipid (crude) content by petroleum ether extraction using a Soxhlet apparatus (960.39 (a), see p. 39.1.05). and ash content (920.153 see p. 39.1.09).

**Statistical analysis.** Results were analysed using procedures in the software Statistica (data analysis software system), version 10; Statsoft, Tulsa, OK. Means and standard deviations were calculated for the studied traits.  $\Delta L^*$ ,  $\Delta a^*$ ,  $\Delta b^*$ , and  $\Delta C^*$  were calculated by subtracting the value of the parameter after illumination from the initial value. Conversely,  $\Delta h^\circ$  was calculated by subtracting the initial  $h^\circ$  value from the  $h^\circ$  value after illumination.

In addition, simple correlation coefficients (Pearson's  $r$ ) were calculated between the studied quality traits and the differences in colour parameters ( $\Delta L^*$ ,  $\Delta a^*$ ,  $\Delta b^*$ ,  $\Delta C^*$ ,  $\Delta h^\circ$ ) and colour change ( $\%CC$ ) for all tested combinations of wavelengths (Tables 2 and 3). Simple correlation coefficients were also determined between colour parameters ( $\Delta L^*$ ,  $\Delta a^*$ ,  $\Delta b^*$ ,  $\Delta C^*$ ,  $\Delta h^\circ$ ) and colour change ( $\%CC$ ) for the tested combinations of wavelengths (Table 4). In the case of continuous random variables, we calculated simple correlation coefficients (Pearson's  $r$ ) – Tables 2, 3, and 4, while in the case of discrete random variables (colour, wateriness and firmness) – Spearman's rank correlation coefficient (Table 3). Their significance was estimated at probability levels of  $P \leq 0.05$ ,  $P \leq 0.01$ , and  $P \leq 0.001$ .

## RESULTS AND DISCUSSION

Table 1 shows means and standard deviations for the colour parameters, chromatic absorbance of

**Table 1.** Means ( $\bar{x}$ ) and standard deviations (SD) of pork quality traits ( $n = 150$ )

Trait	$\bar{x} \pm \text{SD}$	Trait	$\bar{x} \pm \text{SD}$
$L^*$ – lightness	54.72 $\pm$ 2.56	MbO <sub>2</sub> ' – oxymyoglobin after illumination	0.344 $\pm$ 0.056
$L^{*}$ ' – lightness after illumination	54.31 $\pm$ 2.73	MetMb' – metmyoglobin after illumination	0.304 $\pm$ 0.058
$a^*$ – redness	8.33 $\pm$ 1.21	Mb' – deoxymyoglobin after illumination	0.352 $\pm$ 0.093
$a^{*}$ ' – redness after illumination	7.29 $\pm$ 0.98	$\Delta \text{MbO}_2$	0.184 $\pm$ 0.060
$b^*$ – yellowness	16.46 $\pm$ 1.04	$\Delta \text{MetMb}$	-0.100 $\pm$ 0.044
$b^{*}$ ' – yellowness after illumination	15.12 $\pm$ 0.86	$\Delta \text{Mb}$	-0.085 $\pm$ 0.066
$C^*$ – chroma	18.47 $\pm$ 1.28	%CC <sub>540/505</sub>	5.25 $\pm$ 1.62
$C^{*}$ ' – chroma after illumination	16.81 $\pm$ 0.96	%CC <sub>540/630</sub>	11.33 $\pm$ 4.27
$h^\circ$ – hue angle	63.22 $\pm$ 2.99	%CC <sub>560/505</sub>	3.53 $\pm$ 1.74
$h^\circ$ ' – hue angle after illumination	64.31 $\pm$ 3.05	%CC <sub>560/630</sub>	8.66 $\pm$ 3.70
$\Delta L^*$	0.41 $\pm$ 0.50	%CC <sub>580/505</sub>	6.10 $\pm$ 1.98
$\Delta a^*$	1.04 $\pm$ 0.66	%CC <sub>580/630</sub>	12.53 $\pm$ 4.76
$\Delta b^*$	1.33 $\pm$ 0.52	moisture content, %	74.25 $\pm$ 0.84
$\Delta C^*$	1.65 $\pm$ 0.73	total protein, %	22.07 $\pm$ 0.69
$\Delta h^\circ$	-1.09 $\pm$ 1.24	fat, %	2.55 $\pm$ 0.89
$A_{525p}$ – chromatic absorbance at 525 nm	0.361 $\pm$ 0.029	ash, %	1.12 $\pm$ 0.07
$A_{525}$ ' – chromatic absorbance at 525 nm after illumination	0.359 $\pm$ 0.030	colour, points	3.15 $\pm$ 0.74
$\Delta A_{525p}$	0.002 $\pm$ 0.008	wateriness, points	3.17 $\pm$ 0.74
MbO <sub>2</sub> – oxymyoglobin	0.529 $\pm$ 0.075	firmness, points	3.18 $\pm$ 0.74
MetMb – metmyoglobin	0.198 $\pm$ 0.037	WHC, %	76.49 $\pm$ 5.55
Mb – deoxymyoglobin	0.273 $\pm$ 0.112	pH <sub>48</sub>	5.58 $\pm$ 0.17

a wavelength of 525 nm ( $A_{525p}$ ), and the relative quantities of the chemical forms of myoglobin before and after irradiation.

Table 1 also shows differences in these parameters, colour change (%CC) during exposure, basic chemical composition, the results of sensory evaluation of colour, wateriness and firmness of meat and WHC and pH<sub>48</sub>. After irradiation,  $a^*$ ,  $b^*$  and  $C^*$  decreased,  $h^\circ$  increased, MbO<sub>2</sub> decreased, and MetMb and Mb increased. Colour change (%CC) was the highest for the combinations of wavelengths 580 and 630 nm (%CC<sub>580/630</sub>) and 540 and 630 nm (%CC<sub>540/630</sub>).

Table 2 shows simple correlation coefficients between colour parameters  $L^*$ ,  $a^*$ ,  $b^*$ ,  $C^*$ ,  $h^\circ$  and chromatic absorbance of a wavelength of 525 nm ( $A_{525p}$ ), and the relative amounts of the chemical forms of myoglobin before exposure to light, and the differences in colour parameters ( $\Delta L^*$ ,  $\Delta a^*$ ,  $\Delta b^*$ ,  $\Delta C^*$ ,  $\Delta h^\circ$ ) and colour change (%CC).

The correlation coefficients indicate that the higher initial values of  $L^*$ ,  $a^*$ ,  $b^*$ ,  $C^*$ , and the higher the amount of MbO<sub>2</sub> and MetMb, the lower the changes in lightness ( $\Delta L^*$ ) during illumination. At the same time, an increase in  $L^*$ ,  $a^*$ ,  $b^*$ ,  $C^*$ , in chromatic absorbance

**Table 2.** Coefficients of simple correlation between the differences in parameters of meat colour, the percentage of colour change (%CC), and the parameters of colour,  $A_{525p}$ , MbO<sub>2</sub>, MetMb and Mb ( $n = 150$ )

Trait	$L^*$	$a^*$	$b^*$	$C^*$	$h^\circ$	$A_{525p}$	MbO <sub>2</sub>	MetMb	Mb
$\Delta L^*$	-0.234**	-0.240**	-0.343***	-0.348***	0.109	-0.108	-0.434***	-0.324***	0.442***
$\Delta a^*$	0.351***	0.593***	0.637***	0.715***	-0.343***	0.309***	0.731***	0.538***	-0.742***
$\Delta b^*$	0.211*	0.438***	0.557***	0.592***	-0.211*	0.317***	0.602***	0.630***	-0.674***
$\Delta C^*$	0.261***	0.536***	0.610***	0.673***	-0.289***	0.347***	0.675***	0.623***	-0.728***
$\Delta h^\circ$	0.491***	0.371***	0.553***	0.559***	-0.180*	0.031	0.681***	0.326***	-0.634***
%CC <sub>540/505</sub>	0.433***	0.271***	0.386***	0.394***	-0.117	0.073	0.385***	0.292***	-0.394***
%CC <sub>540/630</sub>	0.543***	0.491***	0.630***	0.665***	-0.240**	0.183*	0.658***	0.458***	-0.660***
%CC <sub>560/505</sub>	0.221**	0.045	0.029	0.039	-0.040	-0.031	-0.007	-0.030	0.015
%CC <sub>560/630</sub>	0.459***	0.373***	0.440***	0.478***	-0.202*	0.121	0.448***	0.275***	-0.437***
%CC <sub>580/505</sub>	0.469***	0.297***	0.442***	0.445***	-0.118	0.077	0.446***	0.346***	-0.459***
%CC <sub>580/630</sub>	0.550***	0.482***	0.634***	0.664***	-0.228**	0.175*	0.661***	0.468***	-0.666***

\* $P \leq 0.05$ , \*\* $P \leq 0.01$ , \*\*\* $P \leq 0.001$ .

of a wavelength of 525 nm ( $A_{525p}$ ) and in the relative amount of MbO<sub>2</sub> and MetMb, and a decrease in the relative amount of Mb, were accompanied by a statistically significant increase in differences in redness ( $\Delta a^*$ ), yellowness ( $\Delta b^*$ ), chroma ( $\Delta C^*$ ), and colour change (%CC<sub>540/505</sub>, %CC<sub>540/630</sub>, %CC<sub>560/630</sub>, %CC<sub>580/505</sub>, %CC<sub>580/630</sub>). An increase in  $h^\circ$  was accompanied by a significant reduction in the differences in chromatic parameters ( $\Delta a^*$ ,  $\Delta b^*$ ,  $\Delta C^*$  and  $\Delta h^\circ$ ), and a reduction in colour change (%CC<sub>540/630</sub>, %CC<sub>560/630</sub>, %CC<sub>580/630</sub>). The most useful colour parameter in evaluating pork quality, i.e. lightness ( $L^*$ ), was the most correlated with changes in redness ( $\Delta a^*$ ), hue angle ( $\Delta h^\circ$ ), and colour change (%CC) calculated on the basis of the absorbance of wavelengths of 540 and 630 nm (%CC<sub>540/630</sub>) and 580 and 630 nm (%CC<sub>580/630</sub>). This confirms the results of previous studies (Karamucki et al., 2011) and indicates that these combinations are most useful for estimating changes in the colour of pork. Except in one case, we did not find statistically significant simple correlation coefficients between the parameters of colour and %CC<sub>560/505</sub>.

In the case of pork, the highest values for lightness ( $L^*$ ) are usually observed at low pH<sub>48</sub>, which is conducive to both oxygenation and oxidation of pigments.

Fresh pork with high lightness ( $L^*$ ) usually has the highest redness ( $a^*$ ), yellowness ( $b^*$ ), and chroma ( $C^*$ ) primarily due to the more oxygenated form of myoglobin (MbO<sub>2</sub>) on its surface (Chmiel et al., 2014; Gašperlin et al., 2000; Lindahl et al., 2001; 2006). However, oxymyoglobin is an unstable chemical form of myoglobin and is easily de-oxygenated and converted into an oxidised form – metmyoglobin (MetMb), reducing  $a^*$ ,  $b^*$  and  $C^*$  and increasing  $h^\circ$  (deterioration of hue angle); these changes mainly concern redness ( $\Delta a^*$ ) and hue angle ( $\Delta h^\circ$ ) (Karamucki et al., 2011). The biggest changes caused by the oxidation of pigments can be observed in PSE pork, and the smallest in DFD pork, in which the structure protects the tissues from oxygen to a greater extent (Sobina and Kondratowicz, 1999).

Table 3 presents the correlation coefficients between basic chemical composition, the results of sensory evaluation of colour, wateriness and firmness, WHC and pH<sub>48</sub>, and  $\Delta L^*$ ,  $\Delta a^*$ ,  $\Delta b^*$ ,  $\Delta C^*$ ,  $\Delta h^\circ$  and colour change (%CC), defined on the basis of change in absorbance at all tested combinations of wavelengths of light. Basic chemical composition – with few exceptions – was not significantly correlated with differences in the values of colour parameters ( $\Delta L^*$ ,

**Table 3.** Coefficients of simple correlation between the differences in parameters of meat colour, the percentage of colour change (%CC), and the meat quality traits ( $n = 150$ )

Trait	Moisture content %	Total protein %	Fat, %	Ash, %	Colour points	Wateriness points	Firmness points	WHC, %	pH <sub>48</sub>
$\Delta L^*$	-0.005	0.116	-0.054	-0.165*	0.326***	0.426***	0.435***	0.504***	0.527***
$\Delta a^*$	-0.136	0.019	0.098	-0.033	-0.368***	-0.478***	-0.483***	-0.570***	-0.582***
$\Delta b^*$	-0.049	-0.047	0.072	-0.005	-0.262**	-0.327***	-0.330***	-0.463***	-0.451***
$\Delta C^*$	-0.086	-0.026	0.087	0.002	-0.313***	-0.396***	-0.404***	-0.550***	-0.519***
$\Delta h^\circ$	-0.099	0.067	0.037	-0.193*	-0.438***	-0.523***	-0.529***	-0.574***	-0.581***
%CC <sub>540/505</sub>	-0.024	-0.041	0.063	0.018	-0.406**	-0.483***	-0.477***	-0.422***	-0.599***
%CC <sub>540/630</sub>	-0.155	-0.026	0.170*	-0.067	-0.459***	-0.531***	-0.524***	-0.630***	-0.671***
%CC <sub>560/505</sub>	0.053	-0.069	0.017	0.059	-0.191*	-0.235**	-0.228**	-0.115	-0.287***
%CC <sub>560/630</sub>	-0.108	-0.050	0.148	-0.040	-0.361***	-0.420***	-0.413***	-0.415***	-0.541***
%CC <sub>580/505</sub>	-0.033	-0.019	0.051	0.010	-0.442***	-0.521***	-0.515***	-0.473***	-0.636***
%CC <sub>580/630</sub>	-0.147	-0.015	0.153	-0.061	-0.479***	-0.554***	-0.548***	-0.579***	-0.687***

\* $P \leq 0.05$ , \*\* $P \leq 0.01$ , \*\*\* $P \leq 0.001$ .

$\Delta a^*$ ,  $\Delta b^*$ ,  $\Delta C^*$ ,  $\Delta h^\circ$ ) and colour change (%CC), which indicates that the basic chemical composition had no significant effect on those characteristics. The basic chemical composition of the *longissimus* muscle of porkers often does not show correlation with either absolute values of colour parameters or changes in these parameters, which is also due to the low variation in the basic chemical composition in the muscle.

With an increase in scores in the sensory evaluations of colour, wateriness, and firmness, and an increase in WHC and pH<sub>48</sub>, the differences in lightness ( $\Delta L^*$ ) significantly increased, and differences in chromatic value ( $\Delta a^*$ ,  $\Delta b^*$ ,  $\Delta C^*$ ,  $\Delta h^\circ$ ) and %CC decreased, for all tested combinations of wavelengths. The highest correlation coefficients were observed for  $\Delta a^*$  and  $\Delta h^\circ$  and %CC<sub>540/630</sub> and %CC<sub>580/630</sub>, with colour change (%CC<sub>540/630</sub> and %CC<sub>580/630</sub>) showing higher correlation with the tested meat quality traits than the differences in redness ( $\Delta a^*$ ) and hue angle ( $\Delta h^\circ$ ).

To summarise, of the various colour parameters, colour changes in pork were most influenced by changes in  $a^*$  and  $h^\circ$  ( $\Delta a^*$  and  $\Delta h^\circ$ ). These are also the same chromatic parameters of pork that play a less

important role in the assessment of meat quality than  $b^*$  and  $C^*$ , and above all, less significant than  $L^*$ , the most important in assessing the quality of pork. Pork meat with high lightness ( $L^*$ ) (e.g. PSE) is characterised by the lowest colour stability (the greatest colour change), while lower lightness ( $L^*$ ), e.g. in normal meat, clearly results in higher colour stability. At the same time, lightness ( $L^*$ ) is usually significantly negatively correlated with the pH of meat, and the pace and range of its decrease *post mortem* have a significant influence on other meat quality traits, such as WHC or chromatic parameters of meat ( $a^*$ ,  $b^*$ ,  $C^*$ ,  $h^\circ$ ) (Lindahl et al., 2006; Rosenvold and Andersen, 2003). Brewer et al. (2001) reported that the intensity of the pink colour in the visual evaluation of several major pig muscles (*gluteus medius*, *longissimus lumborum et thoracis*, *semimembranosus*, *biceps femoris* and *triceps brachii*) mainly depends on the lightness of colour; greater lightness is accompanied by lower visual pink colour.

Table 4 shows the simple correlation coefficients between the colour change (%CC) and:  $\Delta L^*$ ,  $\Delta a^*$ ,  $\Delta b^*$ ,  $\Delta C^*$ ,  $\Delta h^\circ$ , and  $\Delta A_{525p}$  and  $\Delta MbO_2$ , and  $\Delta MetMb$   $\Delta Mb$ .

**Table 4.** Coefficients of simple correlation between the differences in parameters of meat colour,  $\Delta A_{525p}$ ,  $\Delta MbO_2$ ,  $\Delta MetMb$ ,  $\Delta Mb$  and the percentage of colour change (%CC;  $n = 150$ )

Trait	%CC <sub>540/505</sub>	%CC <sub>540/630</sub>	%CC <sub>560/505</sub>	%CC <sub>560/630</sub>	%CC <sub>580/505</sub>	%CC <sub>580/630</sub>
$\Delta L^*$	-0.478***	-0.489***	-0.221**	-0.387***	-0.489***	-0.493***
$\Delta a^*$	0.459***	0.779***	0.037	0.567***	0.506***	0.764***
$\Delta b^*$	0.296***	0.542***	-0.133	0.304***	0.319***	0.521***
$\Delta C^*$	0.374***	0.663***	-0.071	0.424***	0.407***	0.643***
$\Delta h^\circ$	0.460***	0.735***	0.114	0.574***	0.510***	0.727***
$\Delta A_{525p}$	0.289***	0.526***	0.055	0.347***	0.299***	0.498***
$\Delta MbO_2$	0.287***	0.544***	0.182*	0.275***	0.341***	0.541***
$\Delta MetMb$	0.950***	0.858***	0.802***	0.892***	0.967***	0.877***
$\Delta Mb$	0.284***	-0.042	0.682***	0.261***	0.237**	-0.027

\* $P \leq 0.05$ , \*\* $P \leq 0.01$ , \*\*\* $P \leq 0.001$ .

In the case of colour parameters the highest correlation was found between  $\Delta a^*$  and  $\Delta h^\circ$  and %CC<sub>540/630</sub> and %CC<sub>580/630</sub> ( $r = 0.779***$  and  $r = 0.764***$  for  $\Delta a^*$ ; and  $r = 0.735***$  and  $r = 0.727***$  for  $\Delta h^\circ$ ).

In the case of the chemical forms of myoglobin, the strongest correlation was observed between  $\Delta MetMb$  and %CC<sub>540/505</sub> and %CC<sub>580/505</sub> ( $r = 0.950***$ , and  $r = 0.967***$ ). At the same time the differences in the amount of MbO<sub>2</sub> ( $\Delta MbO_2$ ) showed the highest correlation with %CC<sub>540/630</sub> and %CC<sub>580/630</sub> ( $r = 0.544***$  and  $r = 0.541***$ ), and the differences in the amount of Mb ( $\Delta Mb$ ) with %CC<sub>560/505</sub> ( $r = 0.682***$ ). Therefore, colour change was most influenced by changes in the relative amount of MetMb. As already mentioned, the increase in the chemical form of the myoglobin be mainly due to a reduction in redness ( $a^*$ ) and a deterioration in hue angle ( $h^\circ$ ) – by moving it in the direction of shorter wavelengths (Brewer, 2004; Brewer et al., 2001; Karamucki et al., 2013; Lindahl et al., 2001).

## CONCLUSIONS

The most useful in the determination of colour change in the assessment of pork quality was the determination of colour change (%CC) on the basis of the absorbance of two combinations of wavelengths; 540 and 630 nm, and 580 and 630 nm. Colour change (%CC) was more correlated with meat quality traits

than changes in the CIELAB and CIELCh parameters most useful for this purpose, i.e. redness ( $\Delta a^*$ ) and hue angle ( $\Delta h^\circ$ ). It was also found that the measurement of absorbance of a wavelength of 630 was more useful for the determination of colour change (%CC) than of 505 nm. We also found a very strong correlation between changes in the relative amounts of MetMb ( $\Delta MetMb$ ) and colour change (%CC) estimated on the basis of absorbance of a wavelength combination of 540 and 505, and 580 and 505 nm ( $r = 0.950***$  and  $r = 0.967***$ ), which demonstrates that %CC<sub>540/505</sub> and %CC<sub>580/505</sub> reflect changes in the relative amounts of MetMb.

## REFERENCES

- AMSA (2012). Meat colour measurement guidelines. American Meat Science Association.
- AOAC (2003). Official Methods of Analysis of AOAC International (17th ed.). Gaithersburg, MD, USA: Association of the Official Analytical Chemists (AOAC) International.
- Brewer, S. (2004). Review: Irradiation effects on meat colour. *Meat Sci.*, 68, 1–17. <http://dx.doi.org/10.1016/j.meatsci.2004.02.007>
- Brewer, M. S., Zhu, L. G., Bidner, B., Meisinger, D. J., McKeith, F. K. (2001). Measuring pork colour: Effect of bloom time, muscle, pH, and relationship to

- instrumental parameters. *Meat Sci.*, 57, 169–176. [http://dx.doi.org/10.1016/S0309-1740\(00\)00089-9](http://dx.doi.org/10.1016/S0309-1740(00)00089-9)
- Chmiel, M., Słowiński, M., Janakowski, S. (2014). The quality evaluation of RFN and PSE pork *longissimus lumborum* muscle considering its microstructure. *Ann. Anim. Sci.*, 14 (3), 737–747. <http://dx.doi.org/10.2478/aoas-2014-0035>
- CIE (1976). Colorimetry: Official Recommendations of the International Commission on Illumination. Publication CIE No. 15 (E–1.3.1). Bureau Central de la CIE, Paris, France.
- CIE (1978). Recommendation on uniform colour spaces, colour difference equations, psychometric colour terms. Supplement No. 2 to publication CIE no. 15 (e-1.3.1). Commission Internationale De L'Eclairage, Paris.
- Gašperlin, L., Žlender, B., Abram, V. (2000). Colour of normal and high pH beef heated to different temperatures as related to oxygenation. *Meat Sci.*, 54, 391–398. [http://dx.doi.org/10.1016/S0309-1740\(99\)00115-1](http://dx.doi.org/10.1016/S0309-1740(99)00115-1)
- Grau, R., Hamm, R. (1953). Eine einfache Methode zur Bestimmung der Wasserbindung im Muskel. *Naturwissenschaften*, 40, 29–40.
- Honikel, K. O. (1998). Reference methods for the assessment of physical characteristics of meat. *Meat Sci.*, 49, 447–457. [http://dx.doi.org/10.1016/S0309-1740\(98\)00034-5](http://dx.doi.org/10.1016/S0309-1740(98)00034-5)
- Hunt, C. M. (1980). Meat colour measurements. In Proceedings 33rd Annual Reciprocal Meat Conference of the American Meat Science Association. Purdue University West Lafayette, Indiana June 22–25, 1980, National Live Stock and Meat Board, Chicago, 41–46.
- Kortz, J. (1966). The effect of free sulfhydryl groups on the colour stability of raw meat (pork). [PhD. Thesis]. Technical University of Gdańsk, Gdańsk, Poland [in Polish].
- Karamucki, T., Gardzielewska, J., Rybarczyk, A., Jakubowska, M., Natalczyk-Szymkowska, W. (2011). Usefulness of selected methods of colour change measurement for pork quality assessment. *Czech J. Food Sci.*, 3, 212–218. <http://dx.doi.org/10.1016/j.meatsci.2013.01.014>
- Karamucki, T., Jakubowska, M., Rybarczyk, A., Gardzielewska, J. (2013). The influence of myoglobin on the colour of minced pork loin. *Meat Sci.*, 94, 234–238. <https://doi.org/10.1016/j.meatsci.2013.01.014>
- Krzywicki, K. (1979). Assessment of relative content of myoglobin, oxymyoglobin and metmyoglobin at the surface of beef. *Meat Sci.*, 3, 1–10. [http://dx.doi.org/10.1016/0309-1740\(79\)90019-6](http://dx.doi.org/10.1016/0309-1740(79)90019-6)
- Lindahl, G. (2005). Colour characteristics of fresh pork. [Ph.D. Thesis]. Swedish University of Agricultural Sciences, Uppsala.
- Lindahl, G., Henckel, P., Karlsson, A.H., Andersen, H. J. (2006). Significance of early *postmortem* temperature and pH decline on colour characteristics of pork loin from different crossbreeds. *Meat Sci.*, 72, 613–623. <http://dx.doi.org/10.1016/j.meatsci.2005.09.014>
- Lindahl, G., Lundström, K., Tornberg, E. (2001). Contribution of pigment content, mioglobin forms and internal reflectance to the colour of pork loin and ham from pure breed pigs. *Meat Sci.*, 59, 141–151. [http://dx.doi.org/10.1016/S0309-1740\(01\)00064-x](http://dx.doi.org/10.1016/S0309-1740(01)00064-x)
- Mancini, R. A., Hunt, M. C. (2005). Review: Current research in meat colour. *Meat Sci.*, 71, 100–121. <http://dx.doi.org/10.1016/j.meatsci.2005.03.003>
- PN-ISO 4121 (1998). Analiza sensoryczna – Metodologia – Ocena produktów żywnościowych przy użyciu metod skalowania [Sensory analysis – Methodology – Evaluation of food products by methods using scales; in Polish].
- Pohja, N. S., Niinivaara, F. P. (1957). Die Bestimmung der Wasserbindung des Fleisches mittels der Konstantdrückmethode. *Fleischwirtschaft*, 9, 193–193.
- Risvik, E. (1994). Sensory properties and preferences. *Meat Sci.*, 36, 67–77. [http://dx.doi.org/10.1016/0309-1740\(94\)90034-5](http://dx.doi.org/10.1016/0309-1740(94)90034-5)
- Rosenvold, K., Andersen, H. J. (2003). The significance of pre-slaughter stress and diet on colour and colour stability of pork. *Meat Sci.*, 63, 199–209. [http://dx.doi.org/10.1016/S0309-1740\(02\)00071-2](http://dx.doi.org/10.1016/S0309-1740(02)00071-2)
- Różycka, J., Michalski, Z. (1978). Relationship between fattening performance and meat quality in pigs. *Rocz. Nauk Roln.*, 98-B-4, 93–102.
- Sobina, I., Kondratowicz, J. (1999). Różnice w budowie ultrastrukturalnej normalnych mięśni świń oraz z wadami PSE i DFD [Differences in the ultra-structure of pigs' normal, PSE and DFD muscles]. *Med. Weter.*, 55(8), 542–545 [in Polish; English abstract].
- Tapp III, W. N., Yencey, J. W. S., Apple, J. K. (2011). How is the instrumental colour of meat measured? *Meat Sci.*, 89, 1–5. <http://dx.doi.org/10.1016/j.meatsci.2010.11.021>
- Warner, R. D., Kauffman, R. G., Russel, R. L. (1993). Quality attributes of major porcine muscles: A comparison with the *longissimus lumborum*. *Meat Sci.*, 33, 359–372. [http://dx.doi.org/10.1016/0309-1740\(93\)90007-5](http://dx.doi.org/10.1016/0309-1740(93)90007-5)
- Yancey, J. W. S., Kropf, D. H. (2008). Instrumental reflectance values of fresh pork are dependent on aperture size. *Meat Sci.*, 79, 734–739. <http://dx.doi.org/10.1016/j.meatsci.2007.11.006>