LWT - Food Science and Technology 73 (2016) 473–480

Contents lists available at ScienceDirect

LWT - Food Science and Technology

journal homepage: www.elsevier.com/locate/lwt

The use of computer vision system to detect pork defects

Marta Chmiel*, Mirosław Słowiński

Warsaw University of Life Sciences-SGGW, Faculty of Food Sciences, Department of Food Technology, Division of Meat Technology, 159c Nowoursynowska Street, 02-787, Warsaw, Poland

ARTICLE INFO

Article history:
Received 7 April 2016
Received in revised form
15 June 2016
Accepted 23 June 2016
Available online 24 June 2016

Keywords:
Computer vision system
Pork
PSE defect
Meat defects

ABSTRACT

The aim of this study was to determine the effectiveness of computer vision system (CVS) to detect meat defects of *m. longissimus lumborum* (*LL*) in industrial settings. The material consisted of 230 muscles. Based on pH_1 (45 min) and pH_2 (24 h post-mortem) meat classification into quality groups was conducted. To give more precise characterization of the raw material (proving the defect or not) the electrical conductivity (EC), drip loss, thermal drip and water holding capacity (WHC) were determined. The color of the meat in CIEL*a*b* and by CVS was measured and the study into how the CVS can be employed in meat defect detection was done. It was found that it is possible to employ the CVS to detect PSE (pale, soft, exudative) and DFD (dark, firm, dry) and to classify meat into quality groups. It was not possible to differentiate RSE (red, soft, exudative) from RFN (red, firm, normal) meat in this study. The highest accuracy of raw material classification using the CVS method was reported for the HSL (hue, saturation, lightness) color parameters at 81.7%. Therefore, the computer vision system can be employed for rapid analysis of the quality of pork *m. longissimus lumborum* under industrial conditions.

1. Introduction

Non-standard quality of the marketed pork causes significant problems for the meat industry (Florowski, Florowska, Kur, & Pisula, 2013). The main issue associated with pork meat quality is a high PSE (pale, soft, exudative) occurrence. This phenomenon has drawn the attention of scientists and processors for many years (Barbut et al., 2008; Van De Perre, Ceustermans, Leyten, & Geers, 2010). The PSE meat when compared to the normal meat (red, firm, normal; RFN) is characterized by a lighter, unnaturally pale color with varied saturation, deteriorated WHC, an increased meat drip loss and soft consistency (Van de Perre and Permentier, 2010). The product of such quality should not be used for the culinary meat production since an excessive meat drip loss is negatively perceived by the consumers. Moreover, the utilization of PSE meat is hampered (Florowski et al., 2013), causing, inter alia, lower yield of the finished product. The biggest disadvantage is that the PSE occurs in the biggest and the most valuable muscle groups such as *m. longissimus dorsi*, *m. semimembranosus*, *m. semitendinosus* and *m. gluteus medius*. The muscles of neck, shoulder and knuckle are less vulnerable. The fat cuts of half-carcass (belly, dewlap and groin) are not affected by PSE.

Some authors (Barbut et al., 2008; Channon, Payne, & Warner, 2000; Gajana, Nkukwana, Marume, & Muchenje, 2013; Gregory, 2010) claim that the animal breeders and meat processors should give a special attention to the defect elimination through selective breeding and control of environmental factors influencing the meat quality. However, in the foreseeable future it is rather unlikely to eradicate major meat defects, including PSE, using zootechnical methods. Thus, it is important to identify these defects, classify the raw material and determine its end-use (as a raw material for processing or culinary purposes) what, will result in its more rational utilization. Unfortunately, unambiguous identification of PSE and other meat defects is extremely difficult. In industrial practice the meat quality evaluation is performed either visually being encumbered with numerous errors or by means of apertures measuring the following attributes: pH, EC and color lightness (Brewer, Novakofski, & Freise, 2006; Warris, Brown, & Paściak, 2006). The above-mentioned instrumental analyzes are the examples of contact methods, which may result in cross-contamination of the meat and besides it is difficult to use them directly on the meat dressing and fabrication line (Papadakis, Abdul-Malek, Kamdem, & Yam, 2000).

Abbreviations: CVS, computer vision system; DFD, dark, firm, dry meat; EC, electrical conductivity; HSL, hue, saturation, lightness; HSV, hue, saturation, value; PSE, pale, soft, exudative meat; RFN, red, firm, normal meat; RGB, red, green, blue; RSE, red, soft, exudative meat; WHC, water holding capacity.

* Corresponding author.
E-mail address: marta_chmiel@sggw.pl (M. Chmiel).

http://dx.doi.org/10.1016/j.lwt.2016.06.054
0023-6438/

One of the proposed methods in rapid on-line evaluation of meat quality is the computer vision system (CVS). This method has been successfully used in industrial practice to classify and assess the meatiness of large animal carcasses and to classify the poultry carcasses (Craigie et al., 2012; Fortin et al., 2003; Pabiou et al., 2011). The research has been undertaken to check the possibility of the CVS employment to evaluate the meat quality and many works have been written on beef (Jackman, Sun, Allen, Brandon, & White, 2010; Sadkowski et al., 2014) and pork meat (Faucitano, Huff, Teuscher, Gariepy, & Wegner, 2005) marbling. Recently, the technology based on the image analysis involves tracking the elements on the meat dressing and fabrication line (Larsen, Hviid, Jørgensen, Larsen, & Dahl, 2014). According to Girolami, Napolitano, Faraone, and Braghieri (2013) it is possible to use the CVS to evaluate the meat color parameters. In addition to being rapid and objective, this method can be used on-line directly on the meat dressing and fabrication line. Moreover, this technique is non-invasive and, as a consequence, does not pose a health hazard for the consumers (Papadakis et al., 2000; Saldaña, Siche, Castro, Huamán, & Quevedo, 2014; Trinderup, Dahl, Jensen, Carstensen, & Conradsen, 2015).

The aim of this study was to determine the applicability of the CVS method to detect the *m. longissimus lumborum* defect in industrial settings. Additionally, the accuracy of raw material classification into quality groups by means of this method was determined.

2. Material and methods

2.1. Research material and organization

The sampling material comprised 230 *longissimus lumborum (LL)* muscles dissected from 230 different right swine half-carcasses.

The animal slaughtering was conducted in industrial environment using a two step-chilling process (1st ambient temperature: −10 °C, time 1–2 h, 2nd ambient temperature: 0–4 °C, time approx. 22 h, to reach an internal temperature no higher than 4 °C in the muscle). The samples were obtained in 9 batches on 9 various slaughter days. For the analysis the longest muscle was selected as it is one of the biggest and most histologically homogenous muscle of the pork carcass (it constitutes 10% of the carcass weight). Most works on the PSE meat concern this type of muscle owing to its high susceptibility to wateriness and color changeability (Karamucki, Jakubowska, Rybarczyk, & Gardzielewska, 2013).

At 45-min post-mortem the pH_1 of the raw material was determined at the area of thoracic vertebra. At the same location electric conductivity (EC_1) was determined at 90-min post-mortem. After the half-carcasses had been cooled for 24 h the pH_2 and EC_2 measurements were retaken at the same location. Then the muscle with a bone was dissected from half-carcasses between 1st and 4th lumbar vertebra (weighing 1000 g) and, then, the EC_3 was measured. Directly after that, using the CIE$L^*a^*b^*$ coordinates and the CVS method, the color of muscles on a freshly cut surface (after 20 min blooming time) dissected from the lumbar side was determined. The raw material classification into quality groups was conducted on the basis of pH_1 and pH_2 readings using the following criteria: RFN (normal meat) $pH_1 > 5.8$, pH_2 5.5–6.0; PSE (exudative meat) $pH_1 \leq 5.8$, $pH_2 \leq 5.5$; DFD $pH_1 > 6.0$, $pH_2 > 6.0$, RSE $pH_1 > 5.8$, $pH_2 \leq 5.5$ (Pospiech, Iwanowska, & Montowska, 2011).

At 48 h post-mortem, in order to give more precise characterization of the raw material, the selected parameters of its technological quality were determined proving the defect or not. To do so, from each sample a slice was cut off (weighing around 100 g, boneless) used for the determination of the drip loss. The remaining part of raw material was deboned and then comminuted in the meat mincer (Diana 886.8, Zelmer, Rzeszów, Poland) equipped with ø 3 mm plate and the water holding capacity (WHC) and thermal drip was measured. The raw material was also described in terms of total heme pigments and the content of basic chemical components (water, total protein, collagen and fat). The captured photos of the analyzed pork muscles underwent image analysis.

2.2. Methods

2.2.1. The pH measurement

The pH values were measured by inserting a spearhead electrode and a temperature sensor of pH-meter CP-411 (Elmetron, Zabrze, Poland) directly into the analyzed raw material. The device was calibrated with two buffers (pH 4 and 7). All measurements were analyzed in triplicates from which an average was calculated.

2.2.2. Electrical conductivity (EC) measurement

The electrical conductivity (EC) was measured using Pork Quality Meter (PQM MT-03, Zakład Techniki Mikroprocesorowej EXE, Poznań, Poland) by inserting its probe into the muscle crosswise to the myocytes. The device was calibrated using a 5 and 20 mS measurement standard provided by the producer (which also provided a PQM).

2.2.3. CIE$L^*a^*b^*$ measurements

The CIE$L^*a^*b^*$ coordinates were determined using a Konica Minolta CM2600d spectrophotometer (Minolta, Wrocław, Poland). The following settings were chosen: illuminant D65, observer 10°, aperture 8 mm, calibrated with a white plate (L^* 99.18, a^*−0.07, b^*−0.05). The measurements were taken on a freshly cut surface of the analyzed muscle samples of the loin after 20-min bloom time at 4–6 °C. All measurements were analyzed in quintuplicate from which an average was calculated. Using a Konica Minolta apparatus the parameters of C^* (Chroma) and h° (hue angle) were calculated based on the a^* and b^* values.

2.2.4. Image capture and analysis

The photos of the meat samples were taken in accordance with the procedure described by Chmiel, Słowiński, and Dasiewicz (2011) and Chmiel, Słowiński, Dasiewicz, and Florowski (2012). Briefly, after 20 min of blooming, the samples were placed in front of a black background at a measurement station and images were taken. Standard conditions for obtaining images were provided: halogen lighting (4 matt bulbs, 18 W each, color temperature of 2800 K, color rendering index of 90–100). Images were obtained using the following camera CANON EOS 350D with an EF-S 60-mm macro lens digital camera (Canon, USA), connected to the computer, vertical position at 500 mm distance between the lens and meat surface and an angle of 45° with the light source. Camera settings were as follow: manual mode with the f/4.0 aperture value, image exposure time 1/100 and ISO 200, zoom and flash off. Images were saved in RAW format. Then, the white balance was corrected and a color profile was selected (Adobe RGB) using Canon Utilities ZoomBrowser EX 5.6 (version 5.6.0.27; Canon).

The processed images were saved in TIFF format and analyzed using Image Analyzer software (developed for the Division of Meat Technology, Warsaw University of Life Sciences, Warsaw, Poland). The detailed operation of this software has been previously described (Chmiel et al., 2011). Information regarding the color and lightness of each particular pixel was acquired from images. The software calculated the average color components of the meat slices for RGB (red, green, blue), HSV (hue, saturation, value), and HSL (hue, saturation, lightness) models.

2.2.5. Drip loss evaluation

Each slice (weighing approx. 100 g) was weighed and sealed in a polyethylene bag. The samples were stored at 4–6 °C for 24 h. Following this, the bags were opened, the exudative moisture was decanted and the samples were reweighed. The amount of exudation was expressed as a percent of the original weight and the following formula was fitted:

drip loss = [(weight before − weight after cooling storage) ÷ weight before cooling storage] × 100%

2.2.6. Water holding capacity (WHC)

Water holding capacity was determined according to Grau and Hamm (1952) method in modification by Pohja and Niinivaara (1957). A 0.3 g sample of meat placed on a filter paper (Whatman 1) was put between two glass plates and loaded (2 kg). After 5 min, the surface areas occupied by meat and muscle juice was determined. Results were presented as the area of the pressed muscle juice reduced by the surface occupied by meat, and expressed as area size per 1 g of raw material (cm^2/g). The higher WHC value, the worse water holding capacity of meat.

2.2.7. Thermal drip

Thermal drip was determined according to Miazek and Mroczek (2013). Samples of 30 g (±0.1 g) of grinded meat were weighed into beakers (150 cm3). Meat was pressed at the bottom of the beaker and covered with foil. Heat treatment was conducted in a water bath with a temperature of 70 °C (±2 °C) for 30 min. The samples were cooled in air for 20 min to a temperature of 20 °C, the drip (liquid fraction) was decanted and the sample weight was measured again. The thermal drip was determined according to the formula: TD = (a−b)/(a−c) × 100%, where TD − thermal drip (%); a − weight of beaker with the sample before heat treatment (g); b − weight of beaker with the sample after heat treatment, after decanting the drip (g); and c − weight of empty beaker (g).

2.2.8. Total heme pigment content

The total heme pigments content was measured according to a method described by Hornsey (1956). The extraction of pigments was performed using acetone acid solution (acetone:$HCl_{concentr}$ = 40:3). Previously thermically processed 5 g sample of comminuted meat, was weighed (with 0.01 g precision) and then placed into bottles made of dark glass. Following this, 21.5 cm^3 acidified acetone solution was added in two phases: 5 cm^3 (mixed in order to achieve homogenous consistency), and then the remaining solution (16.5 cm^3). The whole mixture was stirred for 3 min and, after that, it was left to cool down for 30 min in darkness. Next, the extract was filtered through a drain and the absorbance was measured with a HITACH-U-1100 (Hitachi Corporation, Ltd., Tokyo, Japan) spectrophotometer using a wave length of 640 nm in relation to a reagent blank. This reagent blank was produced by decanting 21.5 cm^3 acetone acid solution into a laboratory flask with 25 cm^3 volume, which was refilled with distilled water up to the mark. The total pigment content was calculated using the following formula: X = A640*680, where:, X − content of total heme pigments (hemin ppm), A_{640} − value of filtrate absorbance at 640 nm wave length.

2.2.9. Basic chemical composition

The basic chemical composition was determined using a FoodScan meat analyzer (FOSS Denmark) according to PN-A-82109:2010 (PCS, 2010).

2.2.10. Statistical analysis

The obtained results were analyzed statistically by subjecting all the data to analysis of variance (One-Way ANOVA). Significant differences between features were verified by HSD Tukey's test at a significance level of $\alpha = 0.05$. The accuracy of the raw material classification was verified using discriminant analysis. The quality classification was tested by means of cross-validation using *K*-fold for $K = 1$ (i.e. using leave-one-out method, Lachenbruch & Mickey, 1968; Krzanowski, 2005). The dependencies between the analyzed parameters were calculated using Pearson (linear) correlation. Owing to numerous dependencies, their linearity was investigated using Kozak and Wnuk (2011) method. The correlation was described using, inter alia, so called correlogram, i.e., graphical display of correlation matrix developed by Friendly (2002). To make the correlation analysis easier, the order of parameters in the matrix was established using hierarchical clustering.

3. Results and discussion

3.1. Classification and characterization of raw material quality - the pH-based classification

Out of 230 pork *m. longissimus lumborum* (*LL*) samples, 104 were classified as RFN, 102 as PSE and 24 did not satisfy the classification criteria for the given two quality groups. For the above-mentioned 24 samples the pace of post-mortem changes and the pace of pH drop was characteristic neither of RFN meat nor of PSE meat. In spite of an initial high pH_1 (>5.8), the pace of pH decrease in 11 samples was slow whilst 24 h post-mortem pH_2 was still elevated (>6.0). The samples were classified as DFD. The remaining 13 samples were also characterized by pH_1 attributed to the meat of normal quality however it dropped rapidly and 24 h after slaughtering pH_2 was ≤5.5 (characteristic of PSE meat). The samples were classified as those belonging to RSE meat. As a result, the analyzed raw material was divided into 4 quality groups 1. RFN, 2. PSE, 3. DFD and 4. RSE.

3.2. The characterization of raw material quality

The *m. longissimus lumborum* classified as PSE was marked by a significantly ($P \leq 0.05$) higher electrical conductivity EC_1, EC_2 and EC_3, when compared with the remaining quality groups (Table 1). Similar relationships were observed by Van de Perre and Permentier (2010b). Only upon measuring the electrical conductivity on the muscles dissected from the carcass it was established that the EC_3 of the DFD meat was significantly lower when compared to the rest of meat quality groups (Table 1). The highest correlation coefficients were determined between pH_1, pH_2 and EC_3 of the analyzed meat (Fig. 1).

The PSE and RSE meat had considerably ($P \leq 0.05$) more profuse drip loss and thermal drip and deteriorated WHC when compared to the RFN and DFD meat. The DFD meat had significantly ($P \leq 0.05$) less drip loss and the best WHC (Table 1). Similar findings were reported by other authors (Di Luca, Mullen, Elia, Davey, & Hamill, 2011; Lee et al., 2012). Overabundant drip loss from the PSE meat limits its commercial application for culinary purposes. Excessive drip in a packaging is negatively perceived by the consumer. The worsened WHC of PSE meat in comparison with RFN and DFD meat was attributed to a low meat pH (close to isoelectric point (IP) of muscle proteins). The closer IP of muscle proteins, the worse water holding and binding capacity of meat. This dependency was confirmed in the subsequent correlation analysis. The computed correlation coefficients between pH_1/pH_2 and WHC were significantly high (Fig. 1).

The meat classified as PSE had significantly lighter color

Table 1
The selected quality characteristics of the analyzed groups of *m. longissimus lumborum*.

Characteristics		Meat quality classes			
		RFN (n = 104)	PSE (n = 102)	RSE (n = 13)	DFD (n = 11)
pH_1	x ± sd	6.2a ± 0.3	5.8b ± 0.1	6.0a ± 0.1	6.5c ± 0.2
	min÷max	5.7÷6.8	5.4÷5.9	5.8÷6.2	6.1÷6.8
pH_2	x ± sd	5.7a ± 0.1	5.5b ± 0.1	5.5b ± 0.01	6.3c ± 0.2
	min÷max	5.5÷6.1	5.2÷5.5	5.4÷5.5	6.0÷6.7
EC_1 (mS)	x ± sd	3.1a ± 1.1	4.9b ± 2.3	2.7a ± 0.9	2.9a ± 0.4
	min÷max	1.8÷6.0	2.2÷13.0	1.7÷4.9	2.4÷3.6
EC_2 (mS)	x ± sd	3.6a ± 1.2	6.0b ± 2.7	4.1a ± 1.8	3.6a ± 0.8
	min÷max	2.0÷7.0	2.0÷10.0	2.0÷7.2	2.4÷4.7
EC_3 (mS)	x ± sd	8.5a ± 2.4	10.3b ± 1.6	9.5ab ± 2.6	6.1c ± 1.2
	min÷max	2.3÷11.9	5.0÷13.8	6.3÷12.9	4.2÷8.2
Drip loss (%)	x ± sd	4.0a ± 2.4	6.3b ± 1.7	5.9b ± 2.4	0.8c ± 0.4
	min÷max	0.5÷8.9	2.0÷12.0	3.6÷8.6	0.1÷1.5
Thermal drip (%)		4.6a ± 2.4	6.3b ± 3.1	6.3b ± 3.5	1.6c ± 0.6
	min÷max	0.5÷8.9	1.8÷15.3	1.3÷13.2	0.2÷2.4
WHC (cm^2/g)	x ± sd	14.8a ± 4.6	27.5b ± 5.2	20.7b ± 4.3	3.8c ± 1.8
	min	7.2÷26.9	15.0÷36.4	13.3÷29.0	0.5÷7.1
Total heme pigment content (ppm hemin)	x ± sd	59.4a ± 9.1	59.2a ± 9.4	57.6a ± 7.3	56.9a ± 6.8
	min÷max	41.5÷86.4	40.1÷85.7	49.6÷69.4	49.6÷67.9
Water content (%)	x ± sd	72.6a ± 1.1	73.1a ± 1.1	72.6a ± 1.2	73.1a ± 1.1
	min÷max	70.3÷74.1	71.0÷74.6	70.8÷74.1	70.9÷74.1
Protein content (%)	x ± sd	22.3a ± 1.1	22.2a ± 0.8	22.1a ± 0.9	22.2a ± 0.7
	min÷max	20.1÷23.7	21.0÷23.5	20.2÷23.7	21.4÷23.4
Collagen content (%)	x ± sd	1.0a ± 0.2	1.0a ± 0.2	1.2a ± 0.1	1.2a ± 0.2
	min÷max	0.8÷1.3	0.6÷1.3	1.0÷1.4	0.8÷1.7
Fat content (%)	x ± sd	4.3a ± 1.2	4.0a ± 1.2	4.4a ± 1.5	4.0a ± 1.4
	min÷max	2.3÷5.9	2.3÷6.9	2.4÷8.0	1.9÷6.4

a, b – means in columns with the same letters referring to the same characteristic do not differ significantly ($P > 0.05$).
x ± sd - average ± standard deviation, min÷max - minimum and maximum values.

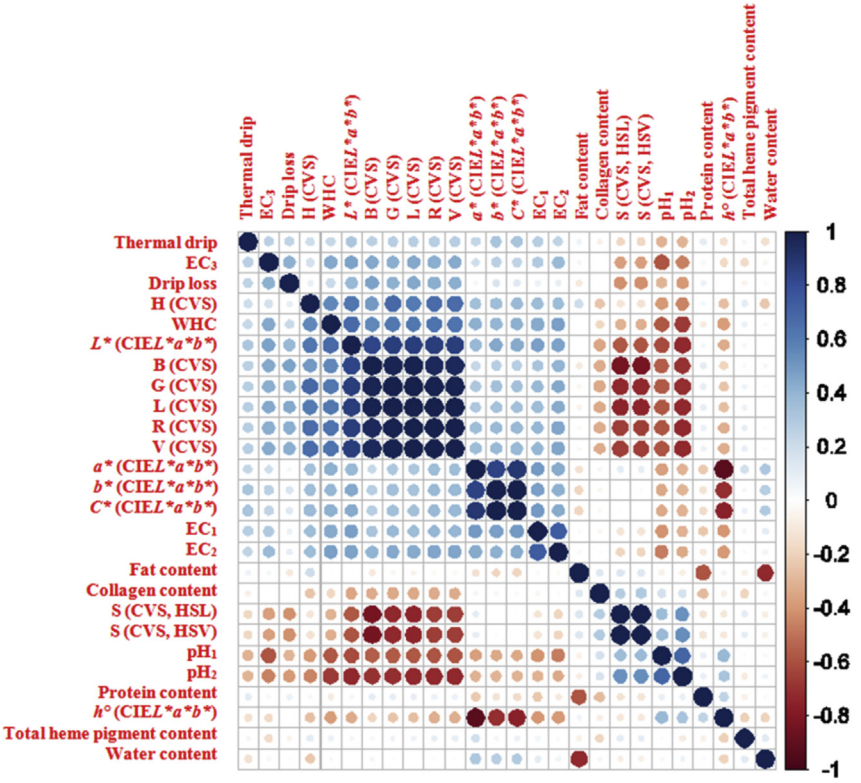

Fig. 1. Correlation corrgram between the individual characteristics.

expressed by L^* (CIE$L^*a^*b^*$) coordinate and those color parameters which directly characterize the lightness (V and L) determined by means of the CVS method when compared to the remaining meat quality groups. The DFD meat, in turn, was marked by the darkest color (Table 2). However different color of meat classified to different quality groups was not influenced by different total heme

Table 2
The color coordinates of the analyzed groups of determined in the CIE$L^*a^*b^*$ scale and by means of the CVS method.

Characteristics			Meat quality classes			
			RFN (n = 104)	PSE (n = 102)	RSE (n = 13)	DFD (n = 11)
CIE$L^*a^*b^*$	L^*	x ± sd	49.3a ± 2.9	56.0b ± 3.1	48.8a ± 1.4	39.3c ± 2.0
		min÷max	43.4÷53.6	50.2÷64.6	46.5÷50.8	36.2÷42.7
	a^*	x ± sd	2.2a ± 1.4	3.5b ± 2.0	1.9a ± 1.1	1.7a ± 0.9
		min÷max	0.1÷7.6	0.3÷12.0	0.1÷3.6	0.5÷3.3
	b^*	x ± sd	10.7a ± 1.4	12.2b ± 1.8	10.9a ± 1.2	10.4a ± 0.9
		min÷max	7.2÷14.9	9.1÷19.4	8.5÷12.9	8.3÷11.5
	C^*	x ± sd	11.0a ± 1.6	12.8b ± 2.3	11.1a ± 1.3	10.5a ± 1.0
		min÷max	7.2÷16.8	9.2÷21.8	8.8÷13.3	8.4÷11.6
	h°	x ± sd	79.5a ± 6.7	75.0b ± 6.1	80.5a ± 5.2	81.2a ± 5.8
		min÷max	63.3÷97.1	56.0÷88.4	71.7÷90.8	72.7÷93.2
CVS	R	x ± sd	79.3a ± 5.6	90.9b ± 4.7	80.7a ± 3.2	63.9c ± 5.1
		min÷max	62.7÷91.0	82.0÷103.3	76.4÷86.4	54.0÷69.2
	G	x ± sd	54.0a ± 5.7	65.7b ± 5.1	55.0a ± 3.5	39.2c ± 3.7
		min	38.0÷65.5	55.6÷79.3	49.0÷60.6	32.4÷42.9
	B	x ± sd	52.6a ± 5.1	62.0b ± 4.5	53.7a ± 2.7	39.7c ± 3.8
		min÷max	37.0÷64.8	52.6÷73.8	48.5÷58.3	33.0÷44.5
	H	x ± sd	0.1a ± 0.1	0.2b ± 0.1	0.1ac ± 0.05	−0.03c ± 0.1
		min÷max	−0.1÷0.3	0.0÷0.3	0.0÷0.1	−0.1÷0.1
	S	x ± sd	34.4a ± 2.8	31.9b ± 2.8	33.8ab ± 2.0	39.8c ± 1.7
		min÷max	28.4÷42.3	26.9÷39.0	30.4÷37.8	38.1÷43.5
	V	x ± sd	31.1a ± 2.2	35.6b ± 1.9	31.6a ± 1.3	25.0c ± 2.0
		min÷max	24.6÷35.7	32.2÷40.5	30.0÷33.9	21.2÷27.1
	H	x ± sd	0.1a ± 0.1	0.2b ± 0.1	0.1ac ± 0.05	−0.03c ± 0.1
		min÷max	−0.1÷0.3	0.0÷0.3	0.0÷0.1	−0.1÷0.1
	S	x ± sd	20.9a ± 2.1	19.1b ± 2.0	20.5ab ± 1.5	25.0c ± 1.4
		min÷max	16.6÷26.9	15.6÷24.3	17.9÷23.4	23.7÷28.1
	L	x ± sd	25.8a ± 2.1	30.0b ± 1.7	26.3a ± 1.1	20.1c ± 1.7
		min÷max	19.5÷30.3	26.5÷34.6	24.6÷28.0	16.8÷22.0

a, b – means in columns with the same letters referring to the same characteristic do not differ significantly ($P > 0.05$).
x ± sd - average ± standard deviation, min÷max - minimum and maximum values.

pigment content (Table 1). Additionally, a small amount of fat – similar in all quality groups (approx. 4%, Table 1) - should not affect the meat lightness. Additionally, the analyzed raw material from different meat quality classes was characterized by similar water, protein, and collagen content. As for the parameters of RGB model, a concurrent increase in all three R, G, B parameters of PSE meat was reported when compared with the values of these parameters in normal meat (RFN). It leads to an increase in image lightness and, the PSE meat color expressed through values of parameters determined by means of the CVS method was lighter than the normal meat. Similarly, a concurrent proportional drop in the values of all three color parameters of RGB model in the DFD meat was observed when compared with the values of the color coordinates of the normal meat (RFN) resulting in a drop of image lightness. The color of the DFD meat expressed through the RGB parameters was consequently darker than that of the RFN meat. The above-mentioned dependencies were reflected in the subsequent correlation analysis (Fig. 1). The findings obtained by many authors indicated that there exist correlations between meat pH and the lightness of its color. The PSE meat is lighter while the DFD is darker than the RFN meat (Brewer et al., 2006; Warris et al., 2006).

No significant differences in the lightness of RFN and RSE meat color were discovered (Table 2). No significant differences in means of the remaining achromatic color components a^* and b^* were found in DFD, RSE and RFN meat, whilst the PSE meat had significantly the highest values of these parameters (Table 2). The raw material classified as PSE was marked by significantly the highest Chroma values determined both by means of CIE$L^*a^*b^*$ (C^*) and the CVS method (S parameter) whereas the hue angle values were the lowest (h° or H). The reverse dependency was observed in the DFD meat (Table 2). The described dependencies were consistent with the literature (Chmiel et al., 2011; Di Luca et al., 2011; Faucitano et al., 2010).

3.3. Dependencies between quality and color parameters of meat

The next stage of the current study involved determination of the dependency between the individual quality parameters of the analyzed *m. longissimus lumborum* and, inter alia, color coordinates determined by means of two methods. In order to do so, the correlation analysis was conducted. Due to numerous dependencies, their linearity was verified using the method developed by Kozak and Wnuk (2011). The correlation was presented using correlogram (Fig. 1) i.e., a graphic presentation of correlation matrix (Friendly, 2002). The key accompanying the figure shows the colors for the size of correlation (the positive dependencies were marked blue whilst the negative ones with red). Besides, the size of the point denotes the dependency strength – no linear dependency no such a point. It was established that there is a negative linear dependency between the pH of the analyzed *LL* (taken both at 45-min and 24-h post-slaughter) and L^* color coordinate determined by means of CIE$L^*a^*b^*$ (Fig. 1, Table 3). The correlation and determination coefficients between pH and the color lightness L^* were higher for the pH measured at 24-h post-mortem than that of 45 min indicating to a closer connection between the analyzed parameters. Over 50% of cases the color lightness was determined by pH_2. These findings are in accordance with the dependencies reported by Brewer et al. (2006), Warris et al. (2006) and Van De Perre and Permentier, (2010b) .

The obtained correlation and determination coefficients between the meat pH_1 and pH_2 and the color coordinates determined by means of the CVS method (R, G, B, V and L) were similar to those ones computed for the color lightness determined in the CIE$L^*a^*b^*$ scale (Table 3, Fig. 1). As a consequence, the color measurement using reflection method might be replaced with the CVS method. Similar conclusions were made by Girolami et al. (2013). The results showed that the colorimeter did not generate coordinates

Table 3
Correlation and determination coefficients and regression equation between pH_1 and pH_2 and the color coordinates characterizing the lightness determined by means of the CVS method and in the CIE$L^*a^*b^*$ scale of the analyzed *m. longissimus lumborum*.

Independent variable (x)	Dependent variable (y)	Correlation coefficient (r)	Determination coefficient (R^2) (%)	Regression equation
pH_1	R (CVS)	−0.59*	34.8	y = −17.3267x + 187.026
	G (CVS)	−0.58*	33.6	y = −17.0696x + 160.244
	B (CVS)	−0.56*	31.4	y = −13.967x + 139.498
	V (CVS)	−0.59*	34.8	y = −6.80699x + 73.4143
	L (CVS)	−0.58*	33.6	y = −6.24605x + 64.6177
	L^*(CIE$L^*a^*b^*$)	−0.62*	38.4	y = −10.8085x + 116.187
pH_2	R (CVS)	−0.74*	54.8	y = −27.7427x + 239.407
	G (CVS)	−0.72*	51.8	y = −27.2157x + 211.2
	B (CVS)	−0.71*	50.4	y = −22.7871x + 186.5
	V (CVS)	−0.74*	54.8	y = −10.8867x + 93.9234
	L (CVS)	−0.73*	53.3	y = −10.117x + 84.1514
	L^*(CIE$L^*a^*b^*$)	−0.73*	53.3	y = −16.4136x + 143.855

*significant correlation at $P \leq 0.05$.

corresponding to the true color of meat. Instead, the CVS method gave valid measurements that reproduced a color very similar to the real one.

In our study, also in this case the correlation and determination coefficients were higher for the pH taken at 24-h post-slaughter (pH_2). As for the R, G, B, V and L coordinates in more 50% the color lightness expressed by these coordinates was determined by pH_1 or pH_2. Concerning the rest of color coordinates: a^* and b^* (CIE$L^*a^*b^*$) as well as H and S (CVS), the calculated correlation coefficients between these coordinates and the meat pH were lower (Fig. 1). Higher than those obtained in the present studies correlation and determination coefficients between the pH and the color lightness determined by means of the CVS method were achieved by Chmiel et al. (2012) in their research into the employment of color coordinates determined by means of the CVS method to detect the DFD *m. semimembranosus* beef meat. It might have been attributed to a greater difference in the color of RFN and DFD beef meat.

Summing up, the pH of the analyzed *m. longissimus lumborum* was significantly correlated with most color coordinates while the highest correlation coefficients were obtained for the color lightness L^* (CIE$L^*a^*b^*$) and color coordinates characterizing the lightness (R, G, B, V and L) determined by means of the CVS method. Like the coordinates determined in CIE$L^*a^*b^*$ scale, the color coordinates determined by means of the CVS method might be used for the detection of the PSE and DFD meat along with the pH evaluation of the pork *LL* and the classification of raw material into the quality groups (RFN, PSE and DFD).

3.4. The evaluation of classification accuracy of swine m. longissimus lumborum (LL) into quality groups using the CVS method

In order to evaluate the accuracy of the analyzed *m. longissimus lumborum* into the quality groups based on the color coordinates determined by means of the CVS method, the discrimination analysis was performed. For comparison, an analogous analysis was carried out for color coordinates determined in CIE$L^*a^*b^*$ scale. The obtained results were presented in Table 4. The color coordinates of RGB, HSV and HSL had similar discrimination strength of the analyzed *m. longissimus lumborum* into quality groups. The classification accuracy for RGB, HSV and HSL models was 80.0, 80.9 and 81.7%, respectively (Table 4). The obtained results indicate that out of 230 samples of *m. longissimus lumborum* 184–188 were correctly classified into appropriate quality groups. As a comparison, the classification accuracy based on the color coordinates determined in the CIE$L^*a^*b^*$ scale was similar and reached 82.6%.

Table 4
Total error of raw material classification based on the color coordinates determined by the CVS method and in the CIE$L^*a^*b^*$ scale and on per-quality groups basis as well as the precise results of classification into the quality groups determined during the validation model of the discrimination analysis.

Total classification error	Classification				
	Group	True rate		Error rate	
		(%)	(Item)	(%)	(Item)
RGB model					
20.0%	RFN	84	87	16	17 (14 PSE, 3 DFD)
	PSE	89	91	11	11 (11 RFN)
	RSE	0	0	100	13 (12 RFN, 1 PSE)
	DFD	82	9	18	2 (2 RFN)
HSV model					
19.1%	RFN	82	85	18	19 (14 PSE, 5 DFD)
	PSE	91	93	9	9 (9 RFN)
	RSE	0	0	100	13 (12 RFN, 1 PSE)
	DFD	82	9	18	2 (2 DFD)
HSL model					
18.3%	RFN	84	87	16	17 (13 PSE, 4 DFD)
	PSE	91	93	9	9 (9 RFN)
	RSE	0	0	100	13 (12 RFN, 1 PSE)
	DFD	73	8	27	3 (3 RFN)
CIE$L^*a^*b^*$ scale					
17.4%	RFN	88	92	12	12 (12 PSE)
	PSE	82	84	18	18 (18 RFN)
	RSE	0	0	0	13 (13 RFN)
	DFD	100	11	100	0

Using the color coordinates of RGB model, the classification accuracy of the raw material into all quality groups was 80.0%, and on per-quality groups basis: 84% samples (87 items) were correctly classified as RFN meat whereas 16% (14 items as PSE and 3 items as DFD) were misclassified (Table 4). 89% of samples (91 items) were correctly classified as PSE whilst 11% of samples were incorrectly classified as RFN meat. As for the RSE meat, no sample was classified (correctly or not) into this quality group, out of 13, almost all of them (12) were classified as the normal meat. The classification accuracy of raw material into the DFD group was 82% while 18% (2 samples) were misclassified as the RFN meat (Table 4).

Using the color coordinates of HSV model, 80.9% of *m. longissimus lumborum* was classified correctly into appropriate quality groups, and on per-quality groups basis: 18% of RFN meat samples were misclassified (14 items as PSE and 5 as DFD). Regarding the PSE meat, the classification accuracy of the raw material was 91% with 9% being misclassified as RFN meat.

The classification accuracy of the raw material into appropriate quality groups using the color coordinates of the HSL model was 81.7%. On per-quality group basis: 84% of samples (87 items) were

correctly classified as RFN meat whereas 16% was misclassified as PSE and DFD (13 and 4 samples, respectively). Like the color coordinates of HSV model, the classification accuracy for PSE meat based on the model HSL parameters was 91%, whereas 9% was incorrectly classified as RFN. Once more, no sample was classified (correctly or not) as RSE quality group and of 13 samples, 12 were classified as RFN meat and 1 as PSE meat. Out of 11 DFD samples 8 were correctly classified and 3 of them were misclassified as RFN meat (Table 4).

In comparison, the classification accuracy of the raw material based on the color coordinates determined in the CIE$L^*a^*b^*$ scale was 82.6%. Again for this color model, no sample was classified (correctly or not) as RSE meat and all the samples were incorrectly classified as RFN meat. All the DFD samples were correctly classified whilst the accuracy for RFN and PSE classification was 88 and 82%, respectively. 12 RFN meat samples were misclassified as PSE while 18 RFN samples were incorrectly classified as PSE (Table 4).

Chmiel et al. (2012) achieved higher classification accuracy of the CVS for RFN and DFD beef *m. semimembranosus*. As for the color coordinate L^* (CIE$L^*a^*b^*$), 91.8% of the analyzed samples were correctly classified into appropriate meat quality groups. And as far as the coordinates V and L (CVS) were concerned, the classification accuracy was also high and reached 90.0 and 88.4%, respectively. The obtained higher accuracy of raw material classification into individual beef meat quality groups might have been caused by bigger differences in the color of RFN and DFD meat. In the studies of Zapotoczny, Szczypiński, and Daszkiewicz (2016) a method for evaluating the quality of medium-ground and finely-ground cold meats with the use of computer-assisted image analysis was developed. Statistical model used by authors discriminated cold meats with 89–100% accuracy, subject to product type. Also in the studies undertaken by Sun et al. (2016), the accuracy of CVS method was investigated. Eighteen color features were extracted from three different color spaces (RGB, HSI and L*a*b*) and were shown to have useful information regarding pork color. L*, a*, and b* extracted from images were significantly correlated with Minolta colorimeter L*, a*, and b*, respectively. Additionally, a favorable coefficient of determination ($R^2 = 0.82$) was achieved when using the linear regression method for predicting pork color score.

4. Conclusions

It may be inferred that there exists possibility of the CVS employment in detection of PSE and DFD *m. longissimus lumborum* as well as their classification into the quality groups. The accuracy of raw material classification was 80.0% for the RGB model and 80.9% for the HSV model and 81.7% for the HSL model. This was similar to the classification accuracy based on the color coordinates in the CIE$L^*a^*b^*$ scale and reached 82.6%. Consequently, the CVS method can be used for a rapid quality evaluation of porcine *m. longissiumus lumborum*. One advantage of the CVS method is the fact that it gives the possibility to analyze the color of the whole meat surface in a non-invasive and on-line way while the area measured by means of a colorimeter or a spectrophotometer covers only the area of measurement head. In addition, this is a contact method and has to be used periodically. The implementation of the CVS into the industrial practice will allow evaluating the culinary and processing quality of the meat with a great accuracy and in this way will show an appropriate direction of its employment. The right selection of raw material and its optimal utilization will, in consequence, ensure the quality standardization and high consumer acceptability for the products. Thus, both producers and consumers will benefit. This is especially important now when meat processing plants are competing for markets.

Acknowledgements

This work was financially supported by Ministry of Science and Higher Education Republic of Poland by a grant number No. NN 312 068739 in 2010–2012.

References

Barbut, S., Sośnicki, A. A., Lonergan, S. M., Knapp, T., Ciobanu, D. C., Gatcliffe, L. J., et al. (2008). Progress in reducing the pale, soft and exudative (PSE) problem in pork and poultry meat. *Meat Science, 79*, 46–63.
Brewer, M. S., Novakofski, J., & Freise, K. (2006). Instrumental evaluation of pH effects on ability of pork chops to bloom. *Meat Science, 72*, 596–602.
Channon, H. A., Payne, A. M., & Warner, R. D. (2000). Halothane genotype, preslaughter handling and stunning method all influence pork quality. *Meat Science, 56*, 291–299.
Chmiel, M., Słowiński, M., & Dasiewicz, K. (2011). Lightness of the color measured by computer image analysis as a factor for assessing the quality of pork meat. *Meat Science, 88*, 566–570.
Chmiel, M., Słowiński, M., Dasiewicz, K., & Florowski, T. (2012). Application of a computer vision system (CVS) to classify beef as normal or DFD. *Journal of Animal Science, 90*, 4126–4130.
Craigie, C. R., Navajas, E. A., Purchas, R. W., Maltin, C. A., Bünger, L., Hoskin, S. O., et al. (2012). A review of the development and use of video image analysis (VIA) for beef carcass evaluation as an alternative to the current EUROP system and other subjective systems. *Meat Science, 92*, 307–318.
Di Luca, A., Mullen, A. M., Elia, G., Davey, G., & Hamill, R. M. (2011). Centrifugal drip is an accessible source for protein indicators of pork ageing and water-holding capacity. *Meat Science, 88*, 261–270.
Faucitano, L., Huff, P., Teuscher, F., Gariepy, C., & Wegner, J. (2005). Application of computer image analysis to measure pork marbling characteristics. *Meat Science, 69*, 537–543.
Faucitano, L., Ielo, M. C., Ster, C., Lo Fiego, D. P., Methot, S., et al. (2010). Shelf life of pork from five different quality classes. *Meat Science, 84*, 466–469.
Florowski, T., Florowska, A., Kur, A., & Pisula, A. (2013). Comparing effect of added collagen and soyabean proteins on quality of restructured cooked hams made from PSE meat. *Food Science Technology Quality, 4*(89), 90–99.
Fortin, A., Tong, A. K. W., Robertson, W. M., Zawadski, S. M., Landry, S. J., Robinson, D. J., et al. (2003). A novel approach to grading pork carcasses: Computer vision and ultrasound. *Meat Science, 63*, 451–462.
Friendly, M. (2002). Corrgrams: Exploratory displays for correlation matrices. *American Statistic, 56*, 316–324.
Gajana, C. S., Nkukwana, T. T., Marume, U., & Muchenje, V. (2013). Effects of transportation time, distance, stocking density, temperature and lairage time on incidences of pale soft exudative (PSE) and the physico-chemical characteristics of pork. *Meat Science, 95*, 520–525.
Girolami, A., Napolitano, F., Faraone, D., & Braghieri, A. (2013). Measurement of meat color using a computer vision system. *Meat Science, 93*, 111–118.
Grau, R., & Hamm, R. (1952). Eine einfache Methode zur Bestimmung der Wasserbindung Fleisch. *Fleischwirtschaft, 4*, 195–297.
Gregory, N. G. (2010). How climatic changes could affect meat quality. *Food Research International, 43*, 1866–1873.
Hornsey, H. C. (1956). The color of cooked cured pork. I. Estimation of the nitric oxide-haem 300 pigments. *Journal of the Science of Food and Agriculture, 7*, 534–540.
Jackman, P., Sun, D. W., Allen, P., Brandon, K., & White, A. M. (2010). Correlation of consumer assessment of longissimus dorsi beef palatability with image colour, marbling and surface texture features. *Meat Science, 84*, 564–568.
Karamucki, T., Jakubowska, M., Rybarczyk, A., & Gardzielewska, J. (2013). The influence of myoglobin on the colour of minced pork loin. *Meat Science, 94*, 234–238.
Kozak, M., & Wnuk, A. (2011). Inspecting associations in multivariate data sets with an interactive modified Bland-Altman plot. *Romanian Agricultural Research, 28*, 259–262.
Krzanowski, W. J. (2005). Misclassification rates. In B. S. Everitt, & D. C. Howell (Eds.), *Encyclopedia of statistics in behavioral science, 3* pp. 1229–1234). Chichester: John Wiley & Sons, Ltd.
Lachenbruch, P. A., & Mickey, M. R. (1968). Estimation of error rates in discriminant analysis. *Technometrics, 10*, 1–11.
Larsen, A. B. L., Hviid, M. S., Jørgensen, M. E., Larsen, R., & Dahl, A. L. (2014). Vision-based method for tracking meat cuts in slaughterhouses. *Meat Science, 96*, 366–372.
Lee, S. H., Choe, J. H., Choi, Y. M., Jung, K. C., Rhee, M. S., Hong, K. C., et al. (2012). The influence of pork quality traits and muscle fiber characteristics on the eating quality of pork from various breeds. *Meat Science, 90*, 284–291.
Miazek, J., & Mroczek, J. (2013). Effect of Gel-fat additive and time of sterilization on properties of mode canned product. *Food Science Technology Quality, 5*(90), 80–89.
Pabiou, T., Fikse, W. F., Cromie, A. R., Keane, M. G., Näsholm, A., & Berry, D. P. (2011). Use of digital images to predict carcass cut yields in cattle. *Livestock Science, 137*, 130–140.
Papadakis, S. E., Abdul-Malek, S., Kamdem, R. E., & Yam, K. L. (2000). A versatile and

inexpensive technique for measuring color of foods. *Food Technology, 54*, 48–51.
PCS. (2010). Polish committee for standardization. Polish standard. In *Meat and meat products. Determination of fat, protein and water content*. Warsaw, PCS: Spectrometry method in near-infrared transmission (NIT) using the calibration on artificial neural networks (ANN). PN-A-82109:2010.
Pohja, N. S., & Niinivaara, F. P. (1957). Die Bestimmung des Wasserbindung des Fleisches mittels der Konstantdrück methode. *Fleischwirtschaft, 9*, 193–195.
Pospiech, E., Iwanowska, A., & Montowska, M. (2011). Meat defects and their characteristic. In A. Pisula, & E. Pospiech (Eds.), *Meat - Science and technology base* (pp. 233–243). Warsaw, Poland: SGGW Publisher.
Sadkowski, T., Ciecierska, A., Majewska, A., Oprządek, J., Dasiewicz, K., Ollik, M., et al. (2014). Transcriptional background of beef marbling — Novel genes implicated in intramuscular fat deposition. *Meat Science, 97*, 32–41.
Saldaña, E., Siche, R., Castro, W., Huamán, R., & Quevedo, R. (2014). Measurement parameter of color on yacon (*Smallanthus sonchifolius*) slices using a computer vision system. *LWT - Food Science and Technology, 59*, 1220–1226.
Sun, X., Young, J., Liu, J. H., Bachmeier, L., Somers, R. M., Chen, K. J., et al. (2016). Prediction of pork color attributes using computer vision system. *Meat Science, 113*, 62–64.
Trinderup, C. H., Dahl, A., Jensen, K., Carstensen, J. M., & Conradsen, K. (2015). Comparison of a multispectral vision system and a colorimeter for the assessment of meat color. *Meat Science, 102*, 1–7.
Van De Perre, V., Ceustermans, A., Leyten, J., & Geers, R. (2010). The prevalence of PSE characteristics in pork loin and cooked ham – Effects of season and lairage time. *Meat Science, 86*, 391–397.
Van De Perre, V., Permentier, L., De Bie, S., Verbeke, G., & Geers, R. (2010). Effect of unloading, lairage, pig handling, stunning and season on pH of pork. *Meat Science, 86*, 931–937.
Warris, P. D., Brown, S. N., & Paściak, P. (2006). The colour of the adductor as a predictor of pork quality in the loin. *Meat Science, 73*, 565–569.
Zapotoczny, P., Szczypiński, P. M., & Daszkiewicz, T. (2016). Evaluation of the quality of cold meats by computer-assisted image analysis. *LWT - Food Science and Technology, 67*, 37–49.