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The Use of Chosen Physicochemical Indicators for Estimation of Pork Meat Quality

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Abstract: The present work aimed to estimate the usefulness and effectiveness of selected physicochemical indicators in the evaluation of meat quality as well as culinary and processing value using a simple and canonical phenotypic correlation method. Studies were carried out in 495 porkers. The most relationships were obtained for the adenosine triphosphate (ATP) breakdown indicator (R_1), electrical conductivity (EC) and glycolytic potential (GP) with meat quality traits that are non-diagnostic criteria, i.e., lipids and protein content, water holding capacity (WHC), technological yield (TY), drip loss (DL) and meat tenderness (MT). The results of this study indicate that about 62% of the variability in meat quality is the result of the initial level of glycogen in muscle tissue. The strong relationship between EC_2 and pH_{24} (acidity of the muscle tissue at 24 h after slaughter) parameters and a wide spectrum of traits of meat quality (sets covering the parameters of the culinary and processing quality of meat and indicating the volume of drip loss), as well as with the pH_1 and R_1 criteria confirms the possibility to perform a quick and cheap 'on line' classification of qualitative meat properties in meat processing plants.

Keywords: quality of pork meat; phenotypic and canonical correlations; culinary and technological usefulness

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1. Introduction

Providing quality meat products is one of the elements that meet the competition in the meat market. High-quality products help attract the interest of new customers and retain that of the others [1–4]. Despite the intensive development of knowledge on the biochemical processes that determine the formation of characteristics of meat quality traits, there is a lack of objective models using the biochemical characteristics of muscles to predict future meat quality [5]. Consequently, this would allow its proper management in the meat industry.

The determination of meat quality and its culinary and technological traits follows various types of measurement which can be objective or subjective [6–12]. For example, according to Mason et al. [13] "the options for monitoring the loss of water from meat, or determining its drip loss, are limited to destructive tests which take 24–72 h to complete" The necessity of a precise, fast and economical evaluation of differences in pork quality leads to the search and developing methods used to determine such qualitative variations [14–22]. The pH value of the meat, its color, and the indicator R_1, expressed by the inosine-5′-monophosphate to adenosine triphosphate (IMP/ATP) ratio and the determination of the intensity of ATP degradation are among the most frequent measurements performed immediately after slaughter and, afterward, during the chilling storage of carcasses or meat [23,24]. Animal muscles show certain electrical properties, such as capacitance, resistance, or conductivity, which also change with the passing of time *post mortem* [25].

Increasing consumer interest in the quality and healthiness of meat and meat products has led to increased quality assurance efforts in the meat industry. Among other consequences, there has been an increase in interest in near-infrared (NIR) spectroscopy because of its ability to predict meat quality quickly, environmentally friendly and non-invasively to predict the composition (moisture, fat, and protein) of raw meat and pork products [26–29]. A wide application in the meat industry has been found using the computer vision system (CVS). It is used for the evaluation of meatiness and the classification of carcasses of pork and for the estimation of the color and marbling of pork [30–33]. Further alternative methods that can be used to assess the structure and composition of food samples are the Raman spectroscopy (RS) and its modifications as an alternative vibrational spectroscopic [4,34]. According to Santos et al. [34] "RS has the potential to become a rapid on-line screening tool for the pork producers to quickly select meats with superior quality and/or cull poor quality to meet market demand/expectations". Generally, of special value are the methods considered based on quick, cheap, objective and non-invasive measurements, possible to apply in production conditions "on-line".

The presented work aimed to estimate the usefulness and efficiency of the chosen physicochemical indicators, potentially measurable in industrial meat processing plant conditions, for the determination of the quality of meat and its culinary and processing usefulness.

2. Material and Methods

Investigations were carried out on 495 fatteners presented in Table 1.

Table 1. Characteristic of analysed material.

Parameter	Value
Number of animals (n)	495
gilts	235
castrates	260
Hot carcass weight (kg)	84.98 ± 7.45
Carcass meatiness by FOM (%)	56.22 ± 4.04

Explanations: results in table are given as mean ± standard deviation.

The analyzed fatteners came from one commercial farm and were commodity crossbreds. Maintenance and nutrition conditions were the same for all animals throughout the rearing. Complete industrial feeds, produced and balanced by the feed manufacturer, were given according to age (three types of complete mixtures served according to the procedure used on the farm). The fatteners were slaughtered at 95–115 kg live weight (age 140–150 days). Transport and slaughter conditions and also post–slaughter procedures were the same for all animals. Fatteners were slaughtered 2–4 h after transportation using an electric stunner and bleeding lying down.

Measurements of the warm carcass with skin but without kidney fat and kidneys were obtained on electronic scales, precise to 100 g. The lean content in the carcass was determined on warm, hanging carcasses using the ULTRA-FOM 100 (SFK-Technology, Herlev, Denmark) ultrasonic apparatus to measure the thickness of the back fat and the *Longissimus dorsi* above the last vertebra [35].

The quality of fresh and chilled meat, as well as its culinary and technological usefulness, was estimated after slaughter in the tissue of the *Longissimus dorsi musculus* (the *Longissimus lumborum*—LL part) and in LL muscle samples taken behind the last vertebra. Acidity of the muscle tissue (pH values) was measured directly in the LL muscle 35 min. (pH_1) and 24 h (pH_{24}) *post mortem* using a calibrated pistol pH—meter Master with a spear tip electrode (produced by Dramiński, Olsztyn, Poland) with temperature compensation.

Rate of adenosine triphosphate (ATP) breakdown expressed by R_1 = inosine-5′-monophosphate/adenosine triphosphate (IMP/ATP) indicator, was determined 45 min *post mortem* according to Honikel and Fischer [14]. Electrical conductivity (EC) was measured with an LF-Star conductometer (Matthaüs, Noblitz, Germany) (1.2 kHz and automatic

temperature compensation) 120 min *post mortem* (EC_2). Meat color (CIE L*, a*, b* system) was measured using a Minolta chroma meter (model CR310, Minolta, Osaka, Japan), 24 h *post mortem*. In the current study, only the L* value reflecting the lightness of meat color was analyzed. Water holding capacity (WHC) was determined 24 h *post mortem* by the filter paper method according to the Grau and Hamm [36] method modified by Pohja and Ninivaara [37]. Drip loss (DL) was determined 48 h *post mortem* according to Prange et al. [38]; meat samples (approxiamte 100 g) have been cut from a carcass at 24 h *post mortem* and immediately weighed. The samples are then placed in a plastic bag. After the storage (24 h) time at the temperature under investigation (1–4 °C) samples are weighed again. Drip loss (%) was calculated as a share of differentials in the weight of the sample with respect to the initial weight of the sample. The technological yield of meat (TY) in curing and thermal processing (72°), expressed by the indicator TY was determined 24 h *post mortem* according to Naveau et al. [39] as modified by Koćwin-Podsiadła et al. [40]. The meat tenderness (MT)—determined 144 h *post mortem* was expressed by shear force (N/cm^2) using an Instron 1140 apparatus (Instron Corp., Canton, MA, USA) with Warner–Bratzler device.

Total protein content and intramuscular fat content (IMF) of LL muscle—determined according to procedures recommended by the AOAC [41].

The samples from the m. *Longissimus lumborum* were analyzed for the glycolytic potential (GP), glycogen and lactate content (45 min *post mortem*). The glycogen content was determined by the enzymatic method according to Dalrymple and Hamm [42] and the level of lactate according to Bergmeyer [43]. The GP of muscle tissue, measured in micromoles of lactate per 1 g of muscle tissue, was calculated according to the formula proposed by Monin and Sellier [44]:

$$GP = (2 \times \text{glycogen}) + \text{lactate}$$

The estimation of the usefulness of the measurements GP, glycogen, lactate, pH_1, pH_{24}, R_1, L* and EC_2 for the determination of the quality properties of meat and its culinary and technological usefulness was carried out on the basis of coefficients of simple phenotypic correlation (r) and regression (b), as well as coefficients of canonical correlation (C_R) and composed determination coefficients ($R_C{}^2$) (respective squared value) (Statistica; SatSoft, Tulsa, OK, USA).

The canonical analysis is based on the idea of the canonical variable as a function that best represents the original variables (measurements), selected in such a way as to ensure that the correlation within pairs of canonical variables could be maximal [45,46]. Such an analysis makes it possible to determine the degree of correlation between two sets of variables, a set of independent variables—X with a set of dependent variables—Y. The degree of correlation of a given pair of canonical variables is shown by the coefficient of canonical correlation C_R, while the composed coefficient of determination $R^2{}_C$ renders it possible to determine what part of the whole variability of the set Y is explained by the effect of the set X. The sets of independent variables (explaining) (X_1–X_{10}) contained parameters useful for diagnosing the characteristics of meat quality and the criteria most commonly used for meat classification. Within the sets of dependent variables (Y_1–Y_6) are the characteristics of quality of the meat that are the most valuable from the point of view of the consumer and the meat processing industry. Furthermore, the sets of dependent variables Y_7–Y_{10} contained traits that are diagnostic criteria to evaluate the relations between them. It was also important that the correlated sets of independent (X) and dependent variables (Y) cannot contain the same parameters.

Table 2 summarizes the abbreviations used and their explanations.

Table 2. The abbreviations used and their explanations.

Abbreviation	Explanation
ATP	adenosine triphosphate
C_R	canonical correlation
DL	drip loss
EC	electrical conductivity
GP	glycolytic potential
IMF	intramuscular fat content
IMP	inosine-5′-monophosphate
L*	lightness of meat color
MT	meat tenderness
R_1	IMP/ATP ratio
R_C^2	composed determination coefficients
WHC	water holding capacity
TY	technological yield

3. Results and Discussion

Analyzing the values obtained for the coefficients of simple correlation, one can observe that the highest values with characteristics of meat quality that are not diagnostic criteria, *ie* protein and IMF content, WHC, TY, DL and MT, were recorded for the indicator of energy metabolism R_1, EC_2 and GP (Table 3).

A significant relationship was observed between R_1 and GP with protein content, MT, WHC, TY, and DL, as well as EC_2 with IMF, WHC, TY, MT and DL.

Furthermore, a highly significant ($p \leq 0.01$) relation was observed between R_1 and EC_2 (r = 0.34 **) and glycogen and lactate, components of GP (r = −0.24 ** and 0.61 **, respectively) (Table 3). A strong relation was also demonstrated between R_1 and EC_2 and pH_1 (r = −0.46 ** and −0.30 **, respectively) and between GP and glycogen (r = 0.88 **), pH_{24} (r = −0.26 **) and the L * (r = 0.27 **).

During the conversion of muscle to meat, lactic acid builds up in the tissue leading to a reduction in pH of the meat [47].

The highly significant correlation coefficients obtained between the level of lactate, glycogen and EC_2 and the level of pH_1 (r = −0.48 **; 0.31 **; −0.30 **, respectively) and R_1 (r = 0.61 **, −0.24 **, 0.34 **, respectively) indicate that these parameters are useful for the determination of the meat quality traits and characterise the glycolytic metabolism that takes place during the first 45 min *post mortem*.

Jo et al. [48] estimated the predictability of pork loin cooking losses using a rapid and minimally destructive method, showing that pH and protein content were significantly correlated with cooking losses. They used pH, CIE L *, CIE b *, moisture content and protein content as explanatory variables. The r^2 value increased in all linear regression models with the addition of the electrical conductivity values.

The negative correlations between the level of glycogen and GP and the pH_{24} (r = −0.28 ** and r = −0.26 **, respectively) confirm the strong effect of glycogen on the degree of muscle acidity *post mortem* and indicate that it can, to a considerable degree, determine a series of characteristics decisive for the quality of meat [49,50]. GP is one of the *post mortem* traits used to predict the quality of the final meat products. Despite this, the knowledge of the molecular and metabolic pathways that control this trait and the genetic basis of glycolytic metabolism is still unclear and not complete [51,52]. Muscle *post mortem* metabolism is stopped by substrate depletion or inactivation of the glycolytic enzyme phosphofructokinase-1, resulting in ATP depletion and the development of rigor mortis. Subsequently, the muscle undergoes proteolytic disruption of myofibrillar proteins, thereby improving the tenderness and flavor of the meat [53].

The correlation coefficients between GP and pH_{24}, cited by various authors [18,49,54–56], usually range between r = −0.3 and r = −0.83, depending on the type of muscle and time when the glycolytic potential was measured. Furthermore, this relationship is stronger for populations with a lower glycolytic potential and for red muscles.

Table 3. A relationship between analysed physicochemical indicators and selected quality of meat traits (n = 495).

(y)		(x)							
		pH_1	**pH_{24}**	**R_1**	**L***	**EC_2 (mS cm^{-1})**	**GP (μmol g^{-1})**	**Glycogen (μmol g^{-1})**	**Lactate (μmol g^{-1})**
pH_1	r_{xy} b_{xy}	-	−0.03	−0.46 ** −0.09	−0.12 ** −0.01	−0.30 ** −0.05	0.08	0.31 ** 0.04	−0.48 ** −0.01
pH_{24}	r_{xy} b_{xy}	−0.03	-	−0.01	−0.22 ** −0.02	−0.09	−0.26 ** −0.01	−0.28 ** −0.02	0.08
R_1	r_{xy} b_{xy}	−0.46 ** −0.15	−0.01	-	0.19 ** 0.01	0.34 ** 0.02	0.04	−0.24 ** −0.01	0.61 ** 0.03
L*	r_{xy} b_{xy}	−0.12 ** −1.98	−0.22 ** −6.12	0.19 ** 9.67	-	0.00	0.27 ** 0.03	0.16 ** 0.04	0.23 ** 0.06
EC_2 (mS cm^{-1})	r_{xy} b_{xy}	−0.30 ** −1.78	−0.09	0.34 ** 6.19	0.00	-	−0.05	−0.13 ** −0.01	0.18 ** 0.02
GP (μmol g^{-1})	r_{xy} b_{xy}	0.08	−0.26 ** −9.18	0.04	0.27 ** 2.25	−0.05	-	0.88 ** 1.71	0.19 ** 0.39
glycogen (μmol g^{-1})	r_{xy} b_{xy}	0.31 ** 2.85	−0.28 ** −3.97	−0.24 ** −3.81	0.16 ** 0.68	−0.13 ** −1.67	0.88 ** 0.45	-	−0.29 ** −0.31
lactate (μmol g^{-1})	r_{xy} b_{xy}	−0.48 ** −3.29	0.08	0.61 ** 2.56	0.23 ** 0.91	0.18 ** 2.05	0.19 ** 0.09	−0.29 ** −0.27	-
protein content (%)	r_{xy} b_{xy}	−0.15 ** −0.47	−0.01	0.16 ** 1.74	0.08	−0.05	0.13 * 0.05	0.04	0.18 ** 0.09
IMF (%)	r_{xy} b_{xy}	−0.02	0.11 * 0.61	−0.03	0.07	−0.12 * −0.22	0.00	0.01	−0.02
WHC (cm^2)	r_{xy} b_{xy}	−0.01	−0.02	0.15 ** 3.47	0.21 ** 0.47	0.13 ** 0.18	0.14 ** 2.62	0.05	0.18 ** 1.58
TY (%)	r_{xy} b_{xy}	−0.08	0.30 ** 12.75	−0.11 * −8.69	−0.14 ** −0.21	−0.13 ** −0.56	−0.14 ** −0.76	−0.14 ** −0.38	−0.00
DL (%)	r_{xy} b_{xy}	−0.14 ** −1.96	−0.35 ** −8.02	0.11 * 4.65	0.26 ** 0.32	0.21 ** 0.51	0.22 ** 2.30	0.13 ** 0.67	0.19 ** 0.92
MT (N cm^{-2})	r_{xy} b_{xy}	−0.33 ** −16.26	−0.15	0.52 ** 28.24	0.17 * 0.53	0.43 ** 2.99	0.16 * 0.38	−0.06	0.41 ** 0.32

Explanations: r_{xy}—coefficient of simple phenotypic correlation; b_{xy}—coefficient of regression x on y traits, **—significant at $p \leq 0.01$; *—significant at $p \leq 0.05$.

The slightly lower value, obtained in the present work concern phenotypic simple correlations. As stated by Larzul et al. [49], higher coefficient values are obtained for genetic correlations when the estimation is based on methods, which render it possible to eliminate the effect of environmental factors related to pre-slaughter treatment. It should be stressed, that in present study the preslaughter factors regarding both rearing conditions and transport, slaughter, or post-slaughter handling of carcasses were the same for all analyzed animals.

According to Milan et al. [57] including the GP in studies on the conditioning of pork quality allowed us to explain the reasons for acid meat, for which a low final pH (5.4–5.5) is characteristic. Scheffler et al. [58] suggested that high GP does not predict a low ultimate

pH in pork. Furthermore, Tarczyński et al. [59] suggested that among (L × Y) × Hampshire fatteners pH measured 24 h *post mortem* should not be considered as ultimate pH in pork meat quality evaluation.

Using the canonical analysis the usefulness of selected criteria and physicochemical indicators for the description of meat quality variability (sets of traits) was evaluated (Table 4). The following analysis was conducted to select sets of traits to the highest possible degree that describe variability in meat quality. This applies both to the quality assessed by the consumer at the time of purchase and in sensory evaluation during consumption of meat and its products, but is also of significance to the meat industry for the proper use of meat of a certain quality.

The obtained results indicated a high value (C_R from 0.49 ** to 0.77 **) of the glycolytic potential and its components (X_1–X_6) as well as of EC_2 and pH_{24} (X_{10}) for determining all the quality properties of the meat analysed (i.e., the set Y_1) (Table 4).

It should be emphasised that after including the parameters EC_2 and pH_{24} in the set the coefficients of canonical correlation between sets containing the GP and glycogen (X_4), the GP and lactate (X_5) and the GP, glycogen and lactate (X_6) and a collection of a wide spectrum of traits (Y_2) were slightly higher and remained at the level of C_R = 0.79 **. This may indicate that meat quality traits are determined to a similar degree by both GP with its components and the criteria of EC_2 and pH_{24}.

Analyzing the relationships obtained in the present work between the independent variable sets X_1–X_{10} and the dependent variable set Y_3, which characterises the culinary value of meat and includes IMF, MT and DL, the most favourable value of the coefficient of canonical correlation (C_R = 0.58 **) was obtained for the set X_{10}, which contains EC_2 and pH_{24}.

A similar relation was obtained in the case of a set of traits that characterize the usefulness of meat in processing—Y_4. The highest and most significant relationship ($p \leq 0.01$), C_R = 0.61 **, was observed between traits EC_2 and pH_{24} (X_{10}) and the set of dependent traits Y_4, characterizing the usefulness of meat in processing (WHC, DL, TY, protein and IMF, MT) (Table 4). A slightly lower relation was obtained with this set of dependent traits (Y_4) was obtained for the following pairs of traits: pH_1, pH_{24}, L* (X_9) and pH_1, pH_{24} (X_8)–C_R = 0.60 ** and 0.59 **, respectively. Lana and Zolla [60] pay attention to the fact that meat tenderization has further levels of complexity, controlled by heat shock proteins and metabolic enzymes, and metabolic components that participate to the process. The cited authors emphasize that "a lot of factors can intervene to sophisticate this simple plot, to the point that, starting from a standard template, the meat from each individual animal can undergo a personal, unique evolution". The process of biochemical transformation concerning the muscle-to-meat conversion is well-recognized, but many points are still confused.

Koćwin-Podsiadła et al. [20] conducted studies on 250 porkers from 3 genetic groups (Landrace, Landrace × Yorkshire, Landrace × Duroc) to separate a group of traits measured in production conditions, which determine to the greatest extent the culinary and processing value of pork. They separated five sets of independent variables and four sets of dependent variables. In the case of a set of characteristics characterising the processing value of meat (protein and IMF, WHC, RTN-indicator, centrifuge drip, weight loss in cooking) the highest coefficients of canonical correlation (C_R = 0.62*) the authors cited obtained for a set of determining traits containing pH_1, pH_{24}, EC_2, EC_{24} and L*. In turn, in the case of a set of traits that determine the culinary value of meat, expressed by IMF, MT and DL, the strongest relationship was observed for the set of independent variables containing EC_2 and pH_{24} (C_R = 0.56 *). Both canonical correlations were similar to those obtained in the present work but were statistically confirmed at $p \leq 0.05$ only.

Table 4. Values of canonical correlations and respective squared canonical correlation revealing relationship between independent sets conteining physico-chemical indicators to diagnostic of meat quality traits and dependent variables sets describing wide spectrum traits of meat quality and culinary and technological usefulness of pork (n = 495).

Correlated Sets		Independent (Determining) Variables' Sets									
		GP (X_1)	Glycogen (X_2)	Lactate (X_3)	GP, Glycogen (X_4)	GP, Lactate (X_5)	GP, Glycogen Lactate (X_6)	pH_1, R_1 (X_7)	pH_1, pH_{24}, (X_8)	pH_1, pH_{24}, L* (X_9)	EC_2, pH_{24} (X_{10})
Dependent variables sets:											
(Y_1) - pH_1 - R_1 - WHC (cm^2) - TY (%) - DL (%) - protein content (%) - IMF (%) - L* - MT (N cm^{-2})	C_R	0.49 **	0.51 **	0.67 **	0.77 **	0.77 **	0.76 **	-		-	0.72 **
	R_C^2	0.24	0.26	0.45	0.59	0.59	0.58				0.51
(Y_2) set (Y_1) and: - EC_2 (mS cm^{-1}) - pH_{24}	C_R	0.57 **	0.59 **	0.68 **	0.79 **	0.79 **	0.79 **	-		-	-
	R_C^2	0.32	0.35	0.46	0.62	0.62	0.62				
(Y_3) - IMF (%) - MT (N cm^{-2}) - DL (%)	C_R	0.26 NS	0.10 NS	0.41 **	0.44 **	0.44 **	0.44 **	0.46 **	0.53 **	0.54 **	0.58 **
	R_C^2			0.17	0.19	0.19	0.19	0.21	0.28	0.29	0.34
(Y_4) - WHC (cm^2) - TY (%) - DL (%) - protein content (%) - IMF (%) - MT (N cm^{-2})	C_R	0.38 *	0.19 NS	0.46 **	0.52 **	0.52 *	0.52 **	0.48 **	0.59 **	0.60 **	0.61 **
	R_C^2	0.14		0.21	0.27	0.27	0.27	0.23	0.35	0.36	0.37
(Y_5) - WHC (cm^2) - DL (%)	C_R	0.14 NS	0.05 NS	0.16 NS	0.19 NS	0.19 NS	0.25 NS	0.29 *	0.51 **	0.51 **	0.52 **
	R_C^2							0.08	0.26	0.26	0.27

Table 4. *Cont.*

Correlated Sets		Independent (Determining) Variables' Sets									
		GP (X_1)	Glycogen (X_2)	Lactate (X_3)	GP, Glycogen (X_4)	GP, Lactate (X_5)	GP, Glycogen Lactate (X_6)	pH_1, R_1 (X_7)	pH_1, pH_{24}, (X_8)	pH_1, pH_{24}, L* (X_9)	EC_2, pH_{24} (X_{10})
(Y_6)	C_R	0.41 **	0.25 NS	0.30 *	0.46 **	0.46 **	0.47 **	0.31 **	0.55 **	-	0.57 **
- L* - WHC (cm^2) - DL (%)	R_C^2	0.17		0.09	0.21	0.21	0.22	0.10	0.30		0.32
(Y_7)	C_R	0.14 *	0.31 **	0.64 **	0.58 **	0.59 **	0.59 **	-	-	-	0.67 **
- pH_1 - R_1	R_C^2	0.02	0.10	0.41	0.34	0.35	0.35				0.45
(Y_8)	C_R	0.34 **	0.52 **	0.58 **	0.50 **	0.49 **	0.50 **	-	-	-	-
- pH_1 - pH_{24}	R_C^2	0.11	0.27	0.34	0.25	0.24	0.25				
(Y_9)	C_R	0.39 **	0.53 **	0.64 **	0.50 **	0.50 **	0.50 **	-	-	-	-
- pH_1 - pH_{24} - L*	R_C^2	0.15	0.28	0.41	0.25	0.25	0.25				
(Y_{10})	C_R	0.33 **	0.48 **	0.39 **	0.35 **	0.35 **	0.35 **	0.67 **	-	-	-
- EC_2 (mS cm^{-1}) - pH_{24}	R_C^2	0.11	0.23	0.15	0.12	0.12	0.12	0.45			

C_R—coefficients of canonical correlation; R_C^2—respective squared canonical correlation; *—significant at $p \leq 0.05$; **—significant at $p \leq 0.01$; NS—non significant.

It is worth emphasising the higher value of the coefficient of canonical correlation (C_R = 0.77 **) obtained by the cited authors between the set containing EC_2 and pH_{24} and the set of traits characterising the value of culinary meat and including the measurement of the lightness of the color of the meat. Jo et al. [48] confirmed that adding electrical conductivity as an explanatory variable can predict cooking loss of pork loin with minimally destructive measured quality parameters, except for moisture and protein content (highly correlated with cooking loss), which are difficult to rapidly and accurately analyze in an industrial conditions.

In the present work the highest coefficients of canonical correlation between the determinant sets X_1–X_{10} and the set of traits indicating DL (Y_5) were recorded for the pair of traits EC_2 and pH_{24} (C_R = 0.52**), next for the set of traits pH_1 and pH_{24} (X_8), pH_1, pH_{24} and L* (X_9) (C_R = 0.51 **) and for pH_1 and R_1 (X_7) (C_R = 0.29 *). However, no statistically significant relationship was found between GP and its components (sets X_1–X_6) and the set Y_5, which contain WHC and DL.

The high coefficient of canonical correlation between EC_2 and pH_{24} and the set of dependent variables Y_7 containing the diagnostic criteria pH_1 and R_1, proposed by Honikel and Fischer [14] and used for many years to identify faulty meat, comprises an additional confirmation of the value of EC_2 and pH_{24} in diagnosing meat quality. The strong relation (C_R = 0.67 **) demonstrated between EC_2 and pH_{24} and the set of traits pH_1 and R_1 indicates the usefulness of electrical conductivity paired with pH_{24} as parameters that classify qualitative variations in pork. It is widely known that the low ultimate pH results in meat proteins having decreased water-holding capacity and a lighter colour.

It is also interesting to observe the higher relation (shown by the canonical analysis) between the level of lactate (X_3) and glycogen (X_2) with sets of traits covering a wide spectrum of meat quality properties (Y_1 and Y_2) and with sets containing commonly used diagnostic criteria (Y_7, Y_8, Y_9, Y_{10}) than the relationship between GP (X_1), which is an estimator of the level of muscle glycogen, and the sets mentioned (Table 4). This makes it possible to diagnose the quality of pork using a faster method, because glycogen can be determined using NMR, while the determination of the glycolytic potential requires the performance of a whole series of enzyme analyzes, as it refers to the whole process of glycogenolysis. The high relation obtained in the present work, between the level of glycogen and GP (r = 0.88 **; Table 3), which has been described as an indicator of pork quality by numerous authors [19,49,50,55], confirms the value of the level of glycogen for estimating meat quality. As reported by Le Roy at al. [61] and Larzul et al. [50], the GP has also a practical value in selection, as its value as a selection criterion has been checked and confirmed.

In summary, comparative analyzes conducted for 10 sets of independent traits demonstrated a high value of GP and its components in diagnosing a wide spectrum of meat quality properties. Both the canonical correlation coefficient (C_R = 0.79 **) and the respective squared canonical correlation (R_C^2 = 0.62) show that about 62% of the variability of set containing 11 meat quality traits is the effect of the initial level of glycogen in muscle tissue.

The high relations obtained between the sets of determinants pH_1 and R_1 (X_7), pH_1 and pH_{24} (X_8), pH_1, pH_{24} and L* (X_9) and EC_2 and pH_{24} (X_{10}) and the meat properties characterising its culinary and processing value, as well as the ability to hold water, indicate that these criteria are equally valuable and effective in the classification of faulty meat than the glycolytic potential or the level of glycogen or lactate. As a result of post-slaughter metabolism, muscles undergo various damages to cell membranes. This results in an increase in cell membrane permeability, and the composition of intracellular and extracellular fluids changes, resulting in changes in the electrical properties of meat [48,62].

An additional confirmation of the high value of diagnostic methods that include the criteria of pH_1 and R_1, pH_1 and pH_{24} and EC_2 and pH_{24} for the diagnosis of the quality properties of pork, as well as its culinary and processing value, is the fact that each of these methods may also be used in breeding due to the confirmed genetic determination of the criteria examined [63]. A close correlation was observed between pH_1

value and the polymorphism of 2 genes (*RYR1* and *Cast/RsaI*), R_1—and 4 genes (*RYR1*, *Cast/HinfI*, *Cast/RsaI* and *H–FABP/MspI*), EC_{120}—and 3 genes (*RYR1*, *RN*$^-$ *H–FABP/MspI*) and pH_{24}—and 5 genes (*PRKAG–3*, *RN*, *Cast/HinfI*, *Cast/RsaI* and *Cast/MspI*).

However, considering the fact that determining the level of the energy metabolism indicator (R_1) is connected with the need to obtain meat samples from carcasses and their adequate preparation for analyzes in a laboratory, it is recommended that for the needs of the meat processing industry, classification methods should be based on the following criteria: pH_1 and pH_{24}, pH_1, pH_{24} and L*, and EC_2 and pH_{24}. As the measurement sites for these criteria are easily accessible, the methods based on them make it possible to determine the variability in glycolytic or energy metabolism that affects meat quality over a short period of time post mortem and in production conditions 'on line'. Summarising, those methods are objective, cheap, quick, easy to perform, and most importantly, reliable.

4. Conclusions

The results of this study indicate that about 62% of the variability in meat quality is the result of the initial level of glycogen in muscle tissue. Noted relationship is of practical importance and justifies the advisability of elaboration and developing apparatus adapted to work in meat processing plants conditions for a quantitative analysis of the level of glycogen.

The strong relationship between EC_2 and pH_{24} parameters and a wide spectrum of traits of meat quality (sets covering the parameters of the culinary and processing quality of meat and indicating the volume of drip loss), as well as with the pH_1 and R_1 criteria confirms the possibility to perform a quick and cheap 'on line' classification of qualitative meat properties in meat processing plants, using EC_2 and pH_{24}.

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Institutional Review Board Statement: The experiment was performed according to the recommended EU Directive 2010/63/EU for animal experiments (EU, 2010). All the procedures for this study were conducted in accordance with the protocol of meat processing establishments authorized in the EU. The Ethics Committee's approval was not provided due to the fact that the animals were slaughtered by a meat processing plant that has a warrant authorizing the slaughter of fattening pigs as part of its business activities in the EU. All animal slaughtering activities were carried out by qualified employees of the meat processing plant. Meat samples for testing were taken from half-carcasses obtained after slaughtering the animals. No operations were performed on live animals as part of the experiment.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to the acquisition of some data from the production farm and meat processing plants.

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