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Changes in Carcass Composition, Meat Quality Traits, and Stress Levels in Culled Sows Exposed to Different On-Farm Rest Periods

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Abstract: The study investigated the effect of on-farm rest period (RP) on carcass composition, meat quality, and stress indicators of culled sows. The study was conducted on 84 Large White × Landrace culled sows, which were divided into seven groups (n = 12) with respect to the duration of the on-farm rest period: no rest period (N-RP) group and 1 to 6 weeks of on-farm rest period (1–6 RP). After completion of the on-farm RP, each group of culled sows was slaughtered and the carcass and meat quality traits were determined. Sows from 6-RP had a significantly higher dressing percentage and backfat thickness and, together with sows from 5-RP, a higher shoulder weight. The highest shoulder percentage was found in the 3-RP and 4-RP groups, while 1-RP had the highest percentage for the belly–rib part. At the same time, RP influenced the final pH values (pH_{24} SM and pH_{24} LL) measured in the *longissimus thoracis et lumborum* (LT) and in the *musculus semimembranosus* (SM), as well as drip loss, thawing loss, cooking loss, and tenderness. As far as the stress indicators are concerned, statistical differences between groups were only found in the cortisol level, which was lowest in 6-RP. The results show that RP has a positive effect on meat quality traits and carcass composition. In addition, prolonged RP has a positive effect on the levels of stress indicators.

Keywords: carcass composition; pig meat quality; cortisol levels; sow; resting period; culled

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1. Introduction

As the result of planned or unplanned culling management, sows are removed from commercial herds and transported from reproduction farms to abattoirs on a regular basis [1,2]. The reasons for this are various and include primarily reproductive disorders, old age, or lameness [3]. According to de Jong et al. (2014) [4], the most common reason for culling was insufficient reproductive performance, with no pregnancy (18%), too few piglets weaned (14%), and no oestrus (10%) given as the most frequent reasons. The authors also stated that inappropriate culling can cause major financial losses to the pig producer and that the decision to cull sows is not always straightforward.

Therefore, effective culling management and further valuable use of culled sows are considered critical factors for improving profitability in commercial pig farms [5]. Globally, sow culling rates can vary significantly between herds, ranging from 26% to 70% [4]. In the USA, Spain, Sweden, and Japan, annual culling rates show a high variability [6], ranging from 35.7 to 49.5%, thus differing from the 40% recommended by D'Allaire and Drolet (2006) [7]. In more recent report Blair and Lowe (2019) [8] stated that the average culling rate of sows in the USA is just over 50%. In Croatia currently 44.4% of sows are culled [9].

Slaughtering of culled sows and further processing of the carcasses is widespread procedure worldwide because of good technological and eating quality of their meat, which is comparable to sow meat and pork from fattening pigs, despite major differences in technological quality traits, chemical composition, and flavour content [2]. However, there are also challenges in this area, such as the deterioration of meat quality due to the management of culled sows in the logistics chain before slaughter. These often include animal welfare, production, and biosecurity issues [10]. Culled sows are generally considered less fit for transport compared to other types of pigs, as they are often weak and prone to injuries due to their overuse in the reproductive cycle [11]. In addition, a number of sows are being culled directly after weaning of the piglets, and are still lactating on the day of slaughter [12,13].

The sequence of events leading up to the slaughter of pigs is stressful in itself. Sows housed on commercial breeding farms are regularly exposed to stress factors during their production period, leading to acute or chronic stress [14,15]. Stress condition is difficult to measure, so the use of different types of stress markers is common, mostly in body fluids and tissues, such as cortisol, creatine phosphokinase, heat shock proteins, lactate dehydrogenase, beta-endorphin, ACTH, adrenaline, and noradrenaline [16]. In their study of stress biomarkers, Čobanović et al. (2020) [17] found correlations between some stress metabolites (lactate and glucose), stress hormones (cortisol and adrenocorticotropic hormone), stress enzymes (creatine kinase, aspartate aminotransferase and alanine aminotransferase), electrolytes (sodium, chloride), and acute phase proteins (haptoglobin, C-reactive protein, and albumin) and important pork quality traits such as pH values, water holding capacity, and colour. Varying cortisol levels have also been associated with meat quality traits such as pale, soft, exudative (PSE) and dark, firm, dry (DFD) meat, which reduce the processing ability of pork [18,19]. Apart from these stress-related traits, there are certain impairments in pork originating from culled sows that are quite common and could be regarded as characteristic. Some studies have reported defective and inconsistent quality of sow meat associated with disturbances in colour and tenderness, and sometimes in aroma and taste [20,21].

Outdoor rearing of culled sows has been shown to have a positive effect on some carcass and meat quality traits. Lebret et al. (1999) [22] found that outdoor rearing can positively influence carcass and muscle traits by altering some environmental factors such as climatic variations and the opportunity for physical exercise of the animals. Furthermore, histological and metabolic observations showed that outdoor rearing increased the glycolytic capacity of L-muscle and the oxidative capacity of meat [23]. In addition, the authors concluded that the positive image of this type of production system from the consumer's point of view may lead to a better added value for the products produced in this way.

Sow meat is usually recommended for the production of fresh sausages and meat patties and other minced meat products, as it has some improvements in physicochemical properties. Oliveira et al. (2021) [24] studied different formulations in the production of fresh sausage and found no negative effects on the physicochemical quality of the final product even when using 100% pork from culled sows. Similarly, de Pelegrini et al. (2008) [25], Baer and Dilger (2014) [26], and Kim and Kim (2020) [27] reported that culled animals can be used for the production of cooked, smoked and/or fermented sausages, such as salami, "Krakauer" sausage, Vienna sausages, and some other products. Another example is the traditional Slovenian smoked sausage "Kranjska klobasa" [28]. Silveira and Andrade (2021) [29] recommended production of fermented meat products using the meat of culled animals, as it has a more pronounced colour and lower moisture content.

The management of culled sows through the pre-slaughter logistic chain has a positive impact on meat quality traits. In order to reduce stress, a rest period outdoors would be beneficial for the animals to regain homeostasis and restore the biochemical properties of the muscles, leading to an improvement in meat quality. Thus, the aim of the present study was to investigate the modifications in carcass composition, meat quality traits, and stress indicators in culled sows during different rest periods on the farm.

2. Materials and Methods

2.1. Animals and Slaughter Procedures

The experimental protocol was approved by the Bioethics Committee of the Faculty of Agrobiotechnical Sciences Osijek (644-01/23-01/03), and all procedures were performed in accordance with the Croatian Animal Welfare Act and other legal acts regulating animal husbandry and welfare.

The study was conducted on 84 Large White x Landrace culled sows from the same commercial reproductive farm. At the beginning of the experiment, 12 sows that had no resting period (N-RP) before slaughter were taken to the commercial slaughterhouse for slaughter. The remaining sows (n = 72) were divided into 6 groups (n = 12) according to the duration of resting period (RP) before slaughter: 1-RP, 2-RP, 3-RP, 4-RP, 5-RP, and 6-RP, representing the groups of sows with 1 to 6 weeks RP, respectively. The age of the sows was approximately 48 months; the level of parity before culling averaged 4. During the rest period on the farm, the sows were kept in an outdoor production system with *ad libitum* access to feed and water. During the experiment, the culled sows were fed the same commercial diet (Belje plus d.d., Darda, Croatia) consisting of 12.81 MJ/ME and 13.01 g/kg of CP (crude protein). The nutritional value of the feed for the sows is shown in Table 1. At the end of experimental period, the culled sows reached an average live weight of 250 kg. After completion of the on-farm trial, each group of culled sows was transported and slaughtered in a conventional slaughterhouse by stunning with CO_2.

Table 1. Composition of sows' diets used in the study.

Composition	
Dry matter, %	88.340
Crude protein, %	13.008
ME, MJ/kg	12.81
Crude fiber, %	5.999
Crude fat, %	3.224
Ash, %	4.406
Methionine, %	0.265
Methionine + cysteine, %	0.476
Lysine, %	0.696
Threonine, %	0.452
Thryptofane, %	0.1498
Ca, %	0.7458
Phosphate, %	0.365
Vitamin K, mg/kg	4877.530
Vitamin A, IJ/kg	6400.401
Vitamin D3, IJ/kg	960.000
Vitamin E, mg/kg	40.000
Phytase	400.000
Neutral detergent fibre, %	14.677
Acid detergent fibre, %	9.500

2.2. Carcass and Meat Quality Traits

The following carcass traits were measured at the slaughter line: carcass length (distance from the cranial edge of the *os pubis* to the cranial edge of the first rib), ham length (from the anterior edge of the *symphysis ossis pubis* to the hock joint), and ham circumference. In addition, backfat thickness and *longissimus dorsi* (LD) muscle depth were determined using the "two-points" method", approved in Croatia (NN 71/2018) [30]. Measurement of pH 45 min (pH_{45}) *post mortem* was also performed at the slaughter line.

After slaughter and 24 h of cooling, the samples for meat quality traits were taken and the right halves of the slaughtered sows were dissected according to the modified "Kulmbach" method [31] (Figure 1). Subsequently, the obtained cuts were separated into muscle, fat, and bone and weighed using a Mettler-Toledo Viper SW 15 scale [32] (Mettler-Toledo, Greifensee, Switzerland).

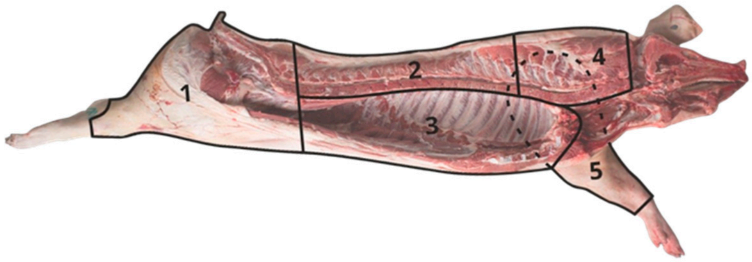

Figure 1. Scheme—cutting a pig carcass into 5 main parts: thigh (1), back (2), abdominal–rib part (3), neck (4), and shoulder (5).

Indicators of meat quality analysed included: pH values measured 24 h (pH_{24}) *post mortem*, drip loss, instrumental colour, texture, and glycolytic potential (GP). PH_{24} values were measured on *the longissimus thoracis et lumborum* (LT) and on the *musculus semimembranosus* (SM) using a portable pH metre (HI 99613, Hanna Instruments, Woonsocket, RI, USA). Drip loss data were obtained using the EZ-DripLoss method [33] after cooling at 4 °C for 24 h. Meat colour (CIE L*, a*, b*) was measured after the samples were exposed to air for at least 1 h. The average of three measurements was obtained using a Minolta CR-410 colourimeter (Minolta Camera Co. Ltd., Tokyo, Japan). A white ceramic calibration plate with a D65 light source and a 10-degree standard observer was used for calibration. Thawing loss was determined on frozen samples that were air thawed overnight at 4 °C. Pork tenderness was determined on 1.27 mm thick samples using a 1 mm Warner-Bratzler shear attachment on the TA.XTplus Texture Analyser and expressed in Newtons (N). A higher Warner-Bratzler shear force (WBSF) indicates lower tenderness (Stable Micro Systems, London, UK). Thereafter, cooking loss was calculated as the percentage of water lost during cooking of the samples for instrumental tenderness evaluation. For the determination of GP (glycolytic potential), muscle samples (5–10 g) were taken from the SM muscle at the earliest possible time (max. 45 min) after bleeding. The samples were immediately frozen in liquid nitrogen and stored at −80 °C until further analysis. Subsequently, the samples were analysed for GP according to Monin and Sellier (1985) [34] as follows: GP = 2([glycogen] + [glucose] + [glucose-6-phosphate]) + [lactate].

2.3. Blood Sample Collection and Analytical Procedure

Each week at the same time of day (08:00 a.m.), blood was taken from all animals (n = 12) of the analyzed groups (1-6-RP), i.e., a total of 72 samples during the entire period of analysis. Blood was taken from the jugular vein in tubes containing the anticoagulant lithium heparin (Becton Dickinson, Plymouth, England, UK). After centrifugation of the samples ($1500\times g$, 10 min at 4 °C), the plasma was separated and frozen at −80 °C until further analysis. Biochemical parameters (glucose, creatine kinase, and lactate) were determined using an automated clinical chemistry analyser (Beckman Coulter AU680, Beckman Coulter, München, Germany). Cortisol concentration was determined with a cortisol ELISA kit (Tecan, IBL International GmbH, Hamburg, Germany) and measured in duplicate with a Bio-Rad microplate reader (Bio-Rad, Watford, UK) at 450 nm.

2.4. Statistical Analysis

Data were processed in the R environment [35] using the one-way procedure ANOVA and the Tuckey HSD test was used to determine significance between the analysed groups.

3. Results and Discussion

3.1. Carcass Composition

The carcass composition of the groups of sows studied is shown in Table 2. No significant differences ($p < 0.05$) in live body weight and hot carcass weight were found between the groups. However, the highest dressing percentage was observed in the sow 6-RP group and the lowest in the 3-RP and 4-RP groups, respectively. The results of the dressing percentage obtained for all groups of animals were similar to those obtained by Lebret and Guillard (2005) [23] for culled sows that rested for 11 days after weaning in conventional (indoor) or outdoor housing. If on-farm resting period and lairage time are extended, carcass yield decreases due to the induced catabolism of the body storages [36]. The dressing percentage of sows differed significantly between groups, probably due to the large variance in sow live weights, while in hot carcass weight, no significant difference was observed.

Table 2. Mean values and standard deviations of quality indicators and carcass composition of slaughtered sows included in the research.

Trait	N-RP	1-RP	2-RP	3-RP	4-RP	5-RP	6-RP
Live body weight, kg	239 ± 27.9	235 ± 16.4	250 ± 34.7	232 ± 20.4	229 ± 18.9	226 ± 25.9	230 ± 31.2
Hot carcass weight, kg	88.3 ± 10.7	90.8 ± 7.15	93.6 ± 12.7	89.9 ± 7.68	91.6 ± 6.38	92.9 ± 10.9	97.9 ± 10.4
Dressing percentage, %	73.9 ^{ab} ± 1.61	74.5 ^{ab} ± 1.94	73.6 ^{ab} ± 2.28	72.4 ^{b} ± 3.13	72.6 ^{b} ± 1.80	73.2 ^{ab} ± 1.95	75.7 ^{a} ± 3.23
Backfat thickness, mm	21.5 ^{ab} ± 5.65	19.8 ^{ab} ± 7.03	19.6 ^{ab} ± 3.78	16.4 ^{b} ± 4.41	19.5 ^{ab} ± 5.61	18.0 ^{ab} ± 4.24	23.9 ^{a} ± 6.05
LD muscle depth, mm	86.2 ± 7.21	87.4 ± 7.83	91.1 ± 7.88	87.2 ± 3.49	87.2 ± 6.59	91.4 ± 8.83	88.3 ± 6.33
Carcass length, cm	125.0 ± 7.08	126.0 ± 4.06	126.0 ± 4.07	126.0 ± 3.20	125.0 ± 3.75	126.0 ± 5.99	124 ± 3.97
Ham length, cm	44.4 ± 2.25	43.4 ± 1.88	44.8 ± 1.58	44.1 ± 1.14	43.9 ± 2.55	43.5 ± 2.25	44.6 ± 1.43
Ham circumference, cm	90.3 ± 4.13	91.3 ± 4.14	93.0 ± 5.45	91.7 ± 3.69	92.5 ± 3.56	92.3 ± 4.54	93.2 ± 3.36
Ham weight, kg	23.3 ± 2.35	23.4 ± 2.44	24.1 ± 3.30	22.4 ± 1.83	23.8 ± 2.06	24.2 ± 3.19	25.0 ± 2.38
Ham percentage, %	26.4 ± 0.82	25.7 ± 1.06	25.7 ± 0.67	25.0 ± 1.45	26.0 ± 1.32	26.0 ± 1.18	25.6 ± 1.01
Shoulder weight, kg	13.1 ^{b} ± 1.66	13.5 ^{b} ± 0.98	14.4 ^{ab} ± 1.80	14.9 ^{ab} ± 1.18	15.1 ^{ab} ± 1.52	15.7 ^{a} ± 2.45	15.8 ^{a} ± 2.04
Shoulder percentage, %	14.8 ^{b} ± 1.09	14.8 ^{b} ± 0.81	15.4 ^{ab} ± 0.95	16.6 ^{a} ± 0.76	16.5 ^{a} ± 1.54	16.8 ^{a} ± 1.28	16.1 ^{ab} ± 0.87
Loin weight, kg	11.9 ± 1.78	12.3 ± 1.31	11.8 ± 1.75	11.3 ± 1.95	11.3 ± 0.91	11.8 ± 2.26	12.9 ± 1.78
Loin percentage, %	13.5 ± 1.00	13.5 ± 0.86	12.6 ± 0.81	12.5 ± 1.28	12.3 ± 0.88	12.6 ± 1.28	13.20.96
Neck weight, kg	8.80 ± 1.54	8.65 ± 1.59	8.86 ± 1.44	9.26 ± 1.05	9.57 ± 1.31	9.56 ± 1.05	10.4 ± 1.42
Neck percentage, %	9.95 ± 1.24	9.50 ± 1.39	9.48 ± 1.17	10.3 ± 0.87	10.4 ± 1.24	10.3 ± 0.66	10.6 ± 0.95
Belly–rib part weight, kg	17.2 ± 4.26	18.6 ± 1.93	20.1 ± 2.95	16.4 ± 2.06	17.4 ± 2.85	16.8 ± 2.63	19.7 ± 3.13
Belly–rib part, %	19.2 ^{ab} ± 3.04	20.5 ^{a} ± 1.46	21.4 ^{a} ± 0.55	18.2 ^{b} ± 1.21	18.9 ^{b} ± 2.13	18.0 ^{b} ± 1.52	20.0 ^{ab} ± 1.45

^{a,b}—Means with different superscripts within a column and within resting period differ at $p < 0.05$.

Significant differences ($p < 0.05$) between the groups were also found in backfat thickness measured at the position for the determination of lean meat percentage (LMP) according to the two-points method approved in Croatia (NN 71/2018) [30], shoulder weight and percentage of shoulder in the carcass, and percentage of belly–rib cut in the carcass. No significant differences ($p > 0.05$) were found between the RP groups for the other characteristics studied. Previous studies reported an average backfat thickness of 27.2 mm [37], 29.4 mm [38], and 21.1 mm [5] for different carcass weight classes of culled sows, i.e., 175–199.9 kg in the former two studies and 183.5 kg in the latter, which were more similar to the fat thickness of the present study. Song et al. (2020) [5] argued that differences in fat thickness may be due to fat loss during pregnancy and lactation, differences in genotype, or production system.

No significant differences were found between the sow groups in muscle depth or other traits that might indicate muscle growth or other changes in body composition during the resting period (carcass length, ham length, and ham circumference). This confirms the general rule that muscle tissue grows significantly slower with increasing age, after reaching the so-called point of growth saturation [39]. The highest shoulder weight was observed in the 5-RP and 6-RP groups, and the lowest in the 1-RP and N-RP groups. The results obtained show that shoulder weight and percentage of shoulder in the carcass increased with increasing the duration of rest. Aziz et al. (1993) [38] reported that shoulder weight and percentage of shoulders increased together with the weight of the warm carcass, but the authors did not take resting time into account in their experimental design. In addition, the dissection method used was different and there is a considerable time lag between their experiment and the present study, so their results should be taken with caution when comparing them with the present study.

The yield of the belly–rib part (which includes hamburger bacon and belly in kilogrammes) did not differ between the groups, but the proportion of the belly–rib part in the carcass was significantly affected by the treatment. Sows from the 2-RP and 1-RP groups had the highest percentage of belly–rib parts in the carcass and did not differ statistically ($p > 0.05$). However, sows from the 3-RP, 4-RP and 5-RP groups were significantly different from these groups, which had relatively lower proportions of belly–rib parts. The 6-RP and the N-RP groups exhibited mean values in this trait that were not different ($p > 0.05$) from the groups with high (1-RP and 2-RP groups) and low (3-RP, 4-RP, and 5-RP groups) proportions of belly–rib part in the sow carcasses. According to Aziz et al. (1995) [20], the proportion of belly–rib part depends on the weight and fat content of the sow's carcass.

The dissection of the most important tissues (muscle, fat, and bones) is shown in Table 3. The differences between the groups in the absolute (kg) and relative (%) share of bone have no practical effect on the value of the carcasses, therefore they are not presented in this analysis. There were no significant differences ($p > 0.05$) in muscle tissue content between the groups analysed. However, the percentage of muscle tissue differed between the investigated groups. The lean meat percentage (LMP) was highest in the 3-RP group and lowest in the 1-RP group ($p < 0.05$). No significant differences in LMP was observed between the other groups analysed. According to our knowledge there are only a few studies dealing with the carcass composition of culled sows [38,40,41]. Most other studies on carcass composition focus on lighter pigs which are subjected to classification or heavy pigs aimed for processing into pork products [42–44]. Lean pig genotypes are selected for an accelerated growth rate and better carcass composition with lower fat content and higher muscle content, as explained in the study by Irshad et al. (2012) [45]; however, LMP estimation can also be a good tool to categorize culled sow carcasses for pork processors [40]. In most of the literature cited here, the resting period before slaughter is unknown or not applied at all, as it is not common in conventional pork production.

Table 3. Mean values and standard deviations (in parentheses) of the results for the dissection of the main parts of slaughtered sows into the most important tissues.

Trait	N-RP	1-RP	2-RP	3-RP	4-RP	5-RP	6-RP
Total muscle, kg	39.7 ± 4.63	40.1 ± 4.28	42.7 ± 5.95	41.8 ± 3.74	41.8 ± 2.87	42.7 ± 5.78	44.7 ± 5.14
Total muscle, %	$45.1^{ab} \pm 2.42$	$44.1^{b} \pm 1.93$	$45.6^{ab} \pm 1.27$	$46.5^{a} \pm 1.34$	$45.7^{ab} \pm 1.68$	$45.9^{ab} \pm 1.67$	$45.6^{ab} \pm 1.36$
Total fat, kg	$9.33^{b} \pm 2.24$	$9.63^{b} \pm 1.67$	$9.51^{b} \pm 1.98$	$9.22^{b} \pm 1.44$	$10.7^{ab} \pm 1.23$	$11.8^{a} \pm 2.28$	$12.6^{a} \pm 1.37$
Total fat, %	$10.5^{b} \pm 1.93$	$10.6^{b} \pm 1.85$	$10.1^{b} \pm 1.13$	$10.2^{b} \pm 1.01$	$11.6^{a} \pm 0.96$	$12.6^{a} \pm 1.40$	$12.9^{a} \pm 1.10$
Ham muscle, kg	16.5 ± 1.52	16.7 ± 1.94	17.2 ± 1.9	16.2 ± 1.19	16.8 ± 1.54	16.8 ± 2.45	17.5 ± 1.74
Ham muscle, %	$71.1^{ab} \pm 3.05$	$71.5^{ab} \pm 2.81$	$71.4^{ab} \pm 1.74$	$72.4^{a} \pm 1.63$	$70.8^{ab} \pm 1.53$	$69.3^{b} \pm 2.03$	$70.1^{ab} \pm 1.14$
Ham fat, kg	$3.79^{b} \pm 0.99$	$3.81^{b} \pm 0.85$	$4.00^{ab} \pm 0.88$	$3.44^{b} \pm 0.69$	$4.13^{ab} \pm 0.56$	$4.62^{a} \pm 0.83$	$4.82^{a} \pm 0.52$
Ham fat, %	$16.2^{ab} \pm 3.45$	$16.3^{ab} \pm 3.20$	$16.5^{ab} \pm 1.90$	$15.2^{b} \pm 2.13$	$17.4^{ab} \pm 1.86$	$19.1^{a} \pm 2.60$	$19.3^{a} \pm 1.15$
Shoulder muscle, kg	$8.94^{b} \pm 1.33$	$9.08^{b} \pm 0.88$	$9.86^{ab} \pm 1.20$	$10.2^{ab} \pm 0.867$	$10.4^{ab} \pm 1.04$	$10.5^{a} \pm 1.59$	$10.8^{a} \pm 1.48$
Shoulder muscle, %	68.21 ± 3.64	67.39 ± 2.55	68.80 ± 2.71	68.88 ± 1.59	69.19 ± 1.89	67.27 ± 1.40	68.68 ± 2.04
Shoulder fat, kg	$2.1^{b} \pm 0.51$	$2.40^{b} \pm 0.37$	$2.57^{abc} \pm 0.59$	$2.82^{c} \pm 0.32$	$2.80^{c} \pm 0.51$	$3.20^{a} \pm 0.76$	$3.04^{a} \pm 0.44$
Shoulder fat, %	$23.96^{b} \pm 6.79$	$26.76^{ab} \pm 5.67$	$25.93^{ab} \pm 4.90$	$27.56^{ab} \pm 2.31$	$26.81^{ab} \pm 3.77$	$30.30^{a} \pm 4.17$	$28.21^{ab} \pm 3.15$
Loin muscle, kg	7.04 ± 0.98	7.10 ± 0.76	7.62 ± 1.16	7.46 ± 1.28	6.89 ± 0.67	7.58 ± 1.47	8.20 ± 1.31
Loin muscle, %	$59.12^{c} \pm 3.31$	$57.92^{c} \pm 3.38$	$64.45^{ab} \pm 3.49$	$66.19^{a} \pm 3.93$	$61.01^{bc} \pm 2.92$	$64.46^{ab} \pm 2.22$	$63.43^{ab} \pm 2.88$
Loin fat, kg	$2.34^{ab} \pm 0.76$	$2.44^{ab} \pm 0.56$	$2.23^{ab} \pm 0.63$	$1.93^{b} \pm 0.58$	$2.22^{ab} \pm 0.59$	$2.43^{ab} \pm 0.73$	$2.89^{a} \pm 0.56$
Loin fat, %	$19.45^{ab} \pm 5.33$	$19.81^{ab} \pm 3.83$	$18.67^{ab} \pm 3.73$	$16.96^{b} \pm 3.46$	$19.45^{ab} \pm 4.09$	$20.40^{ab} \pm 3.27$	$22.45^{a} \pm 3.63$
Neck muscle, kg	6.30 ± 1.07	6.16 ± 1.25	7.00 ± 1.58	6.88 ± 0.83	6.51 ± 0.78	6.79 ± 0.78	7.05 ± 0.98
Neck muscle, %	$71.67^{bc} \pm 2.85$	$71.07^{bc} \pm 3.30$	$78.33^{a} \pm 7.60$	$74.33^{ab} \pm 5.54$	$68.22^{c} \pm 3.49$	$71.02^{bc} \pm 2.38$	$68.00^{c} \pm 2.70$
Neck fat, kg	$1.09^{b} \pm 0.34$	$0.975^{b} \pm 0.20$	$0.71^{b} \pm 0.21$	$1.02^{b} \pm 0.28$	$1.52^{a} \pm 0.51$	$1.54^{a} \pm 0.22$	$1.85^{a} \pm 0.47$
Neck fat, %	$12.22^{bc} \pm 2.44$	$11.33^{c} \pm 1.61$	$8.32^{c} \pm 3.17$	$11.04^{c} \pm 2.49$	$15.77^{ab} \pm 4.16$	$16.24^{a} \pm 2.03$	$17.86^{a} \pm 3.74$

^{a,b,c}—Means with different superscripts within a column and within resting period differ at $p < 0.05$.

An increasing trend in the fat content can be observed during the investigation in the present study. At the beginning of the experimental period, a significantly lower ($p < 0.05$) amount of dissected fat was found in groups N-RP, 1-RP, 2-RP, and 3-RP than in groups 5-RP and 6-RP. A similar situation can be observed for the fat percentage. No significant differences were found in this trait between the N-RP, 1-, 2-, 3-, and 4-RP groups. Their values were significantly lower ($p < 0.05$) than those of the 4-, 5-, and 6-RP groups, which did not differ among themselves. Numerous studies describe muscle and fat content in pigs in relation to sex [46,47] or weight classes [48,49]. For example, Abell et al. (2012) [40] found higher muscle content and lower fat content in lighter sow weight classes (11.4% to 2.9%), with fat content increasing and muscle content decreasing with increasing slaughter weight (9.4% to 4.6%). However, no studies that have included culled sows with different rest periods before slaughter addressing this matter were found in the existing literature.

As with the total muscle tissue content, no statistically significant differences ($p > 0.05$) were found in the muscle tissue content in the hams, but there were differences in their relative share (%). The LMP in the hams of sows from the 3-RP group was significantly ($p < 0.05$) higher than that of the 5-RP group. The average LMP in the hams of sows from the other groups did not significantly differ ($p > 0.05$) from these two groups or between each other. The highest content of fat tissue in the hams of culled sows was found in groups 5-RP and 6-RP, which differed ($p < 0.05$) from the fat content in the hams of the sows from groups 1-RP and 3-RP. The fat content in the hams of sows from 2-RP and 4-RP did not differ ($p > 0.05$) from the other groups studied. In all of the dissected cuts, the 6-RP group, which was the heaviest, had the highest ham muscle weight and ham fat weight. In the study on the use of digital imaging to assess the values of culled sows, Taylor (2021) [39] found that hams were heavier in sow carcasses with the highest carcass weight. The fat content in the hams of the sows from this study followed the same pattern, in contrast with the muscle content, which was the highest in the sows with a lower carcass weight.

The muscle tissue content in the shoulders of the sows from the N-RP group and sows from the 1-RP group was lower than 5-RP and 6-RP ($p < 0.05$). The meat content in the shoulders of sows from the 2-RP, 3-RP, and 4-RP groups was intermediate between these values, with no statically significant differences found between them or compared with the other groups ($p > 0.05$). No significant differences ($p > 0.05$) in LMP were found in the shoulders of the sows studied. Sows from the N-RP group and those from the 1-RP group had the lowest weight of fat tissue in the shoulders, and these values were different ($p < 0.05$) from the fat tissue weight in the shoulders of sows from the 3-RP and 4-RP groups which were significantly different ($p < 0.05$) from the highest values of weight of the fat determined in the shoulders of sows that rested on the farm for 5 and 6 weeks. The sows that had rested for 2 weeks were not significantly different from the 5-RP and 6-RP group. Taylor (2021) [41] found that the muscle content in the shoulder was lower in sows with higher body weights (250 kg and above), while the fat content increased with body weight (from 9.1% to 11.1%). As for the percentage of fatty tissue in the shoulders of the sows studied, the highest values were observed in the 5-RP group, which were significantly different ($p < 0.05$) from those obtained in the N-RP group. The other groups had similar mean values and did not differ significantly ($p > 0.05$) from each other or from the groups with the highest and lowest values.

There were no significant differences between the investigated groups in the loin muscle tissue weight ($p > 0.05$). On the other hand, significant differences were found between groups in the percentage of the muscle in the loins. The 3-RP group of sows had the highest loin muscle tissue percentage and differed significantly ($p < 0.05$) from the N-RP and 1-RP groups. This was followed by groups of sows from the 6-RP, 5-RP, and 2-RP groups, which also differed ($p < 0.05$) from the aforementioned groups, but not from the 3-RP group ($p > 0.05$). In contrast, the 4-RP group of sows differed significantly ($p < 0.05$) only from the highest value of this traits found in sows in the 3-RP group.

The highest weight of fat tissue in the loins of the sows was found in the 6-RP group, and it was significantly different ($p < 0.05$) from the weight of the fat tissue found in the sows from the 3-RP group, which was the lowest. The other groups did not differ ($p > 0.05$) from these two groups. The same relationships were found for the relative proportion of fat tissue in the loins of the sows studied.

There were no significant differences between the investigated groups ($p > 0.05$) in the weights of the muscle tissue in the neck. However, the highest muscle tissue percentage in the neck was found in the 2-RP group of sows, which was significantly different ($p < 0.05$) from all groups, except the 3-RP. This was followed by the muscle tissue percentage of sows from the 3-RP group, which was not significantly different from the N-RP, 1-, 2-, and 5-RP, but the differences were significant ($p < 0.05$) when compared with the 4-RP and 6-RP. These groups also had the lowest muscle tissue percentage in the neck and differed ($p < 0.05$) from all of the investigated groups in this trait. The fat tissue content of the neck showed an increasing trend during the researched period. The sows from the N-RP group and those from the 1-, 2-, and 3-RP groups did not differ significantly from each other in the amount of fat tissue dissected ($p > 0.05$), but these values were significantly lower ($p < 0.05$) compared with the sows from 4-, 5-, and 6-RP, which also did not differ from each other ($p > 0.05$). However, the percentage of fat tissue in the neck of sows in the 4-, 5-, and 6-RP groups differed significantly ($p < 0.05$) compared with the 1-, 2-, and 3-RP groups, for which the lowest values of this trait were obtained. For the same trait, the N-RP group of sows differed ($p < 0.05$) from the 5-RP and 6-RP groups, while the differences compared with the other groups were not statistically significant ($p > 0.05$).

3.2. Meat Quality

The results of the meat quality indicators together with the differences between the groups for the investigated traits are shown in Table 4. There were no differences between the groups for pH_{45} SM and pH_{45} LL ($p > 0.05$), however significant differences were found between groups for pH_{24} SM and pH_{24} LL ($p < 0.05$). The highest pH_{24} SM was observed in the N-RP and 1-RP group and the lowest pH_{24} was recorded in the 4-RP group. These groups were significantly different ($p < 0.05$) from the 2-, 3-, 5-, and 6-RP groups of sows, for which meat quality traits can be considered as desirable for meat processing [50]. The highest pH_{24} LL values were observed in the 1-RP group of sows, from which the N-RP, 5- and 6-RP groups did not significantly differ ($p > 0.05$). The most favourable values for this trait were determined in the 2-, 3-, and 4-RP groups, which were significantly different ($p < 0.05$) from the 1-RP group, but not from the other groups. Ultimate pH is considered to be a factor that greatly influences pork quality as it affects protein denaturation and thus meat colour, tenderness, and water-holding capacity [51]. The results for the pH_{24} values obtained in present study were similar to those reported by Hoa et al. (2020) [2], Song et al. (2020) [5], and Oliveira et al. (2022) [24]. In contrast, Sindelar et al. (2003a) [52] found somewhat higher pH_{24} values (5.91) than the values presented here, while Lebret et al. (1999) [22] reported a lower ultimate pH value in the LL muscle of culled sows. It should be noted that in the study of Sindelar et al. (2003a) [52] these values were measured in culled sows with an unknown resting period before slaughter, and in the study by Lebret and Guillard (2005) [23], the culled sows rested outdoors and indoors for 11 days. In general, differences in pH values may be caused by genetic background and/or pre-slaughter stress, both of which influence the rate of *post mortem* pH decline in meat. According to Scheffler et al. (2013) [53] and Shen et al. (2015) [54], ultimate pH and glycolytic potential are closely related, as glycolytic potential is the fastest predictor of pork quality. However, for glycolytic potential (GP), which is defined as the initial level of glycogen required for the development of acidity in meat during *post mortem* glycolysis, we did not determine statistically significant differences between investigated groups ($p > 0.05$).

EZ-drip values represent the measure of water release (%) from loin muscle samples and for pork values above 5% are generally considered to be too high when assessing processability into dry fermented products. These values were exceeded in all groups, except for 1-RP and 6-RP, which differed ($p < 0.05$) from the other groups and from each other, with the lowest EZ-drip value being exhibited by 1-RP group. According to Otto et al. (2004) [55], EZ-drip values are negatively correlated with pH. This can also be observed from our results where the group with the lowest EZ-drip value exhibited the highest pH_{24}. Consistent with the results of this study, Aziz and Ball (1995) [20] and Song et al. (2020) [5] reported similar values for water release (5.75 and 5.60, respectively) in culled sows in their studies.

Table 4. Mean values and standard deviations of meat quality indicators of the sows included in the research.

Trait	N-RP	1-RP	2-RP	3-RP	4-RP	5-RP	6-RP
$pH_{45\,SM}$	6.51 ± 0.22	6.35 ± 0.27	6.41 ± 0.27	6.44 ± 0.18	6.48 ± 0.19	6.53 ± 0.16	6.35 ± 0.19
$pH_{45\,LL}$	6.42 ± 0.19	6.42 ± 0.15	6.36 ± 0.23	6.51 ± 0.19	6.45 ± 0.16	6.36 ± 0.17	6.33 ± 0.21
$pH_{24\,SM}$	5.71 ^{a} ± 0.15	5.81 ^{a} ± 0.19	5.57 ^{b} ± 0.07	5.55 ^{b} ± 0.05	5.53 ^{c} ± 0.15	5.55 ^{b} ± 0.13	5.61 ^{b} ± 0.12
$pH_{24\,LL}$	5.66 ^{ab} ± 0.07	5.76 ^{a} ± 0.19	5.59 ^{b} ± 0.06	5.55 ^{b} ± 0.06	5.57 ^{b} ± 0.06	5.66 ^{ab} ± 0.14	5.68 ^{ab} ± 0.12
GP, µMol/g	154.0 ± 76.6	125.0 ± 88.3	134.0 ± 100.0	137.0 ± 59.2	131.0 ± 61.1	155.0 ± 103.0	121.0 ± 71.8
EZ-drip, %	8.34 ^{a} ± 3.21	1.48 ^{b} ± 0.92	6.29 ^{a} ± 2.80	5.68 ^{a} ± 2.77	6.43 ^{a} ± 1.95	5.77 ^{a} ± 2.90	3.92 ^{c} ± 1.92
L*	48.5 ± 3.74	46.5 ± 3.52	48.5 ± 3.91	48.5 ± 2.93	47.8 ± 2.05	49.7 ± 1.74	47.3 ± 3.10
a*	20.1 ± 1.51	20.5 ± 1.79	20.5 ± 0.77	21.2 ± 1.44	21.0 ± 1.41	21.3 ± 1.26	20.1 ± 1.15
b*	5.11 ± 1.75	5.30 ± 1.38	5.24 ± 1.45	5.99 ± 1.14	5.34 ± 1.17	6.66 ± 0.73	5.34 ± 0.71
Thawing loss, %	14.0 ^{a} ± 2.88	7.66 ^{c} ± 2.31	9.51 ^{c} ± 1.89	8.83 ^{c} ± 1.80	10.3 ^{b} ± 1.53	11.1 ^{b} ± 1.93	6.80 ^{c} ± 1.55
Cooking loss, %	38.1 ^{a} ± 5.47	33.9 ^{b} ± 3.57	36.6 ^{ab} ± 2.04	35.3 ^{ab} ± 2.61	35.7 ^{ab} ± 1.72	36.2 ^{ab} ± 2.50	32.8 ^{b} ± 3.32
WBSF, N	66.9 ^{b} ± 11.8	82.8 ^{a} ± 14.6	86.9 ^{a} ± 10.4	77.1 ^{ab} ± 10.	72.7 ^{ab} ± 8.86	73.5 ^{ab} ± 7.18	74.9 ^{ab} ± 9.47

^{a,b,c}—Means with different superscripts within a column and within resting period differ at $p < 0.05$; GP—glycolytic potential; WBSF—Warner-Bratzler shear force.

No significant differences were found in the colour parameters (L*, a*, b*) between the analysed groups ($p > 0.05$). The L* values refer to the reflection of light and values below 50 indicate a darker colour of the pork [56]. The results show that all of the analysed groups had L* lower that 50, indicating a darker meat colour. Darker meat colour is characteristic for meat from older pigs, especially sow meat and is not always associated with DFD (dark, firm, and dry) meat, which is undesirable in the processing of dry fermented products [57]. In their study Sindelar et al. (2003a) [52] found that darker meat colour in older pigs was associated with a higher myoglobin concentration in sow pork. Compared with the results of previous studies on meat from culled sows [2,23], CIE L* values in our study were lower, while CIE a* and CIE b* values were higher. These values ranged from 45.9 to 51.50 for CIE L*, 9.3 to 11.10 for CIE a*, and 5.11 to 6.66 for CIE b*. The observed differences between those studies and our study could be attributed to genetic influence and treatment before and after slaughter. On the other hand, Sindelar et al. (2003a) [52] reported similar results to ours for CIE L*, a* and b* (46.45, 21.33, and 6.13, respectively), while Oliveira et al. (2022) [24] found similar CIE L* values (48.2), but lower CIE a* (11.3) and higher CIE b* (13.4).

Thawing loss was highest in the N-RP group and significantly ($p < 0.05$) differed from the other groups. Significantly ($p < 0.05$) lower values were found for the meat of sows from groups 4-RP and 5-RP, followed by groups 1-, 2-, 3-, and 6-RP, which exhibited the lowest values of thawing loss and significantly ($p < 0.05$) differed from the other groups.

Cooking loss was significantly higher for meat samples from N-RP group compared to the other groups studied ($p < 0.05$). Meat samples from the 2-, 3-, 4-, and 5-RP groups did not differ from the other groups ($p > 0.05$) in this trait. Song et al. (2020) [5] and Hoa et al. (2020) [2] compared cooking losses between gilts and culled sows and reported differences between them. Cooking loss values in our study ranged from 32.8 to 38.1 and were higher than those reported by Song et al. (2020) [5] (26.18), Hoa et al. (2020) [2] (19.62), and Oliveira et al. (2022) [24] (18.5). These differences could be attributed to different resting periods implemented before slaughter and also excessive thermal shrinkage.

Warner-Bratzler shear force (WBSF) values refer to meat tenderness, which was highest in the N-RP group and lowest in the 1-RP and 2-RP groups of sows, and were statistically significant ($p < 0.05$). A higher shear force indicates a decrease in tenderness, which leads to a lower sensory tenderness score (increased firmness). Higher weight gains (Čandek Potokar et al., 1998) [58] and an increase in irreducible collagen in older pigs (Fang et al., 1999) [59] lead to changes in meat textural characteristics. According to Cross et al. (1973) [60] and Oliveira et al. (2022) [24], meat from older animals is tougher and more structured, which is mainly due to greater stiffness and thickening of the intramuscular connective tissue and is consistent with our results.

3.3. Blood Parameters

The results for the stress indicators are presented in Table 5. From the presented results it can be seen that the cortisol level, as an indicator of long-term stress, decreases towards the end of the study period, but also that the differences are significant only between the sows in groups 1-RP and 2-RP compared with the sows in group 6-RP ($p < 0.05$). However, there is a statistical tendency ($p < 0.07$) for the differences between the groups of sows from 1-RP and 3-RP, as well as 1-RP and 5-RP. The same was found for the differences between the groups of sows from 2-RP and 3-RP and the groups from 2-RP and 5-RP ($p < 0.05$). This supports the conclusion that the stress level in the analysed sows still decreases after 2 weeks of rest. No statistically significant differences were found in the other blood parameters between the examined sows culled from reproduction ($p > 0.05$).

Table 5. Mean values and standard deviations of stress indicators in the blood of sows included in the research.

Trait	1-RP	2-RP	3-RP	4-RP	5-RP	6-RP
Cortisol, nmol/L	417.25 ^{a} ± 202.31	491.30 ^{a} ± 18.20	291.24 ^{ab} ± 81.46	330.03 ^{ab} ± 279.58	271.27 ^{ab} ± 127.06	254.06 ^{b} ± 115.21
Glucose, mmol/L	4.58 ± 0.34	4.45 ± 0.42	4.76 ± 1.72	5.04 ± 1.50	4.48 ± 0.57	4.95 ± 1.28
Creatine kinase, U/L	518.57 ± 300.21	459.33 ± 168.75	716.08 ± 455.76	1034.90 ± 953.70	622.64 ± 253.04	543.50 ± 177.16
Lactate, mmol/L	8.64 ± 5.46	5.88 ± 2.54	6.82 ± 4.50	7.02 ± 3.98	6.91 ± 3.09	10.20 ± 7.23

^{a,b} Means with different superscripts within a column and within resting period differ at $p < 0.05$.

The standard approach for studying stress and welfare in farm animals is to measure the activity of the hypothalamic–pituitary–adrenal (HPA) axis and to determine cortisol in the blood plasma as a standard procedure [61]. The biological responses to acute challenges such as weaning animals, mixing animals from different social groups, re-exposure, or transport have been extensively studied and, like most stressors, activate biological stress systems in a more or less standard way and increase the blood cortisol levels [62,63].

In the present study, significantly ($p < 0.05$) higher cortisol levels were found in 1-RP and 2-RP compared with the last group (6-RP). Higher cortisol levels in these groups could be the result of environmental stressors, such as transport to a new location, a new housing environment, new feed, and, most importantly, the formation of new social groups. A decline in cortisol levels during the weeks could be a sign of adaptation to the new environment and social status. Although other studies show that even if the triggering stimulus is maintained, plasma cortisol levels usually decrease after the acute response, as described in the experiment in pigs by Jensen et al. (1996) [64] and in the review by Mormède et al. (2007) [63] in other species. In the investigations in the present study, no behavioural signs of acute stress were observed after the initial fights to establish the social hierarchy, so it can be concluded that the lower cortisol levels are a sign of recovery from the initial stressful situation.

There are other measures of HPA axis activity that are influenced by the biological effects of glucocorticoids, such as plasma glucose levels. The mechanism of stress-induced hyperglycaemia is complex and involves a synergistic influence between glucagon, catecholamines, and glucocorticoid hormones and reduced insulin secretion [65]. In the present study, no statistically significant differences ($p > 0.05$) were found in blood glucose levels during the study period.

Pigs [66], as well as other domestic species [67], exposed to altered environmental conditions such as transport, microclimate, and nutrition, become stressed, leading to physiological changes such as increased activity of enzymes and other metabolites such as lactate. The increased levels of creatine kinase in the blood of animals at the slaughterhouse are an indication of how stressful the working conditions were prior to slaughter and how severely the muscles were damaged during handling [67]. In the present study, no significantly different levels ($p > 0.05$) of creatine kinase or lactate were found between the groups of sows studied during the research period.

4. Conclusions

The results of this study show that different rest periods on the farm influence the carcass composition and meat quality of culled sows; even a 2-week rest period significantly improved the overall meat quality. Sows culled from reproduction and rested on-farm for 5 or 6 weeks had significantly higher backfat thickness, shoulder weight, and percentage than sows that had a shorter rest period. In addition, the results show significant differences in the dressing percentage of sows, which were highest at the end of the rest period on the farm (6 weeks).

The overall quality of the meat improves with the length of the resting period. Meat from culled sows that rested for more than 2 weeks had more favourable ultimate pH values and a fairly good water-holding capacity. Regarding the colour and tenderness, all of the samples examined had a darker meat colour and were less tender, which is typical for the meat of animals slaughtered at an older age. The results showed that cortisol levels decreased after the second week of rest, indicating adaptation to new environmental conditions. No significant differences were found in blood glucose, lactate and creatine kinase levels between the studied groups.

Overall, the presented results showed that meat quality, carcass composition, and stress indicators, especially cortisol, indicate that sows should be rested on farm at least two weeks. However, the best results in terms of these parameters were obtained for culled sows that rested on the farm for 5 and 6 weeks before slaughter. A more accurate decision on the length of the on-farm rest period could be made through a simple feasibility study starting with a 2-week rest period and evaluating the following the costs and benefits of a longer on-farm rest period for each successive week.

An extended resting period for culled sows on the farm has a positive effect on the quality of their carcasses and meat, and allows for their use as a valuable source of raw material for processing into various pork products.

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