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Possibilities of Implementing Sustainable Production of Chicken Meat by Applying an Innovative Device for Poultry Electric Stunning

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Abstract: The aim of this research was to determine the feasibility of sustainable chicken meat production, using good- and low-quality raw material and two different devices (own construction—OC, and a Dutch company's—DC) for electrical stunning at the slaughter stage. A statistical analysis was also performed to indicate which of the analyzed courses of action is the most important for the company to maintain a balance between the quality of produced meat (pH, number of hemorrhages—small and large, defectiveness, and color on the external and internal surfaces of the fillet and tenderloin), and environmental and economic aspects. It has been shown that the use of device OC for stunning poultry compared to the device DC has a positive effect on: (1) reducing the number of hemorrhages on the outer surface and inside of the fillet—mainly large hemorrhages, (2) increasing by ~50% the share of production of fillets without hemorrhages, and (3) brightening and unifying the color of the external and internal surfaces of the fillet and tenderloin. Taking the above into account, it was concluded that the goals of sustainable chicken meat production depend mainly on the type of stunning device used; therefore, it is recommended to replace the Dutch device (DC) currently used in the plant with an innovative device (OC). It is also recommended to use financial tools when concluding contracts with poultry breeders so that meat producers can implement the goals of the sustainable management policy already at the raw material stage.

Keywords: poultry meat; sustainable production; electrical stunning; hemorrhages; pH; color; quality improvement

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1. Introduction

Sustainable agriculture is an approach to food production (plant cultivation and animal breeding) that will provide a compromise on the issues of its profitability, reduction in negative impacts on the environment, and social acceptability [1]. In the poultry industry, the implementation of this strategy involves implementing practices that not only ensure economic and environmental aspects, but also guarantee animal welfare and the production of safe and high-quality meat. The "farm to fork" strategy reflects this holistic model, covering all stages of production—from breeding, through processing and distribution, to consumption—in order to ensure a sustainable supply chain [2,3]. It is forecasted [4] that poultry meat production in the world will be the fastest growing sector in the next ten years (from approx. 40 to approx. 47%), so it will play a key role in meeting the growing consumer demand for animal protein.

Industrial plants primarily implement ambitious goals for sustainable meat production by utilizing modern technologies, which frequently serve as a strategic component of enterprise management changes [5]. Despite the difficulties in clearly defining the directions of these changes, the transformation of industrial plants toward sustainable production is most often carried out by implementing innovative production methods and techniques or improving existing ones [6].

The first technological process used at the slaughter stage, which may contribute to the transformation of meat production into a more sustainable one, is the stunning process. It involves inducing birds into a state of loss of consciousness (eliminating stress and anxiety) until they bleed out (death). Important aspects of using this process are guaranteeing humane slaughter and animal welfare, as well as quality considerations that affect the economics of meat production [7]. Research results published by EFSA [8,9] show that the use of the electrical stunning method for poultry results in the production of carcasses and commercial elements of lower quality than when using alternative methods, e.g., a controlled atmosphere [10]. Meat quality has been assessed on the basis of visual characteristics (color, hemorrhages, subcutaneous hemorrhages, bone fractures) and technological parameters (pH, tenderness, durability, water-holding capacity), and the scale of production of defective meat is determined by the quality of the raw material (chickens) supplied by breeders [11]. Awareness of the significant impact of these two factors (process and raw material), in the absence of the ability to control the stunning process and raw material quality management tools, may lead to unsustainable meat production [6]. In the long run, this situation may pose a big problem for companies when selling meat to the demanding markets of EU countries and designing new products with added value.

Despite the unfavorable opinions of scientists regarding the effects of electrical stunning of poultry in a water bath, it is most often used in commercial slaughterhouses in Europe and worldwide [10]. Continuing meat production using this method is justified by the low costs of meat production, bird slaughter, resource consumption (energy, water, and labor), installation (in relation to a new plant), and maintenance compared to the gas method, and also by consumer demand (halal slaughter; high quality of whole carcasses) [12]. Companies are looking for solutions to the problem of defective meat production in the latest scientific achievements and innovative stunning techniques because the reason for the formation of visible and unacceptable-to-consumers [13] meat defects (hemorrhages) is incorrectly selected values of current parameters, i.e., the frequency, voltage, intensity, shape, and width of the pulse [8,14].

The result of many years of scientific research was the indication in Council Regulation (EC) No 1099/2009 [15] of the current values and frequency ranges (<200 Hz–100 mA; from 200 to 400 Hz 150 mA; from 400 to 1500 Hz 200 mA) recommended for stunning poultry, including chickens [9]. Girasole et al. [16] believe that the best combination of electrical parameters that allows for proper stunning without a negative impact on meat quality is a frequency of 750 Hz and a current of 200 mA. To achieve effective stunning control in 90% of birds, a minimum current is required: 150 mA at 200 Hz, 200 mA at 400 Hz, and 250 mA at 600 Hz. However, to ensure the proper stunning of chickens, the frequency should be lower than 600 Hz [17]. A different opinion is expressed by Lines et al. [18], Huang et al. [19], and Sirri et al. [20], who showed that the use of parameters recommended in Regulation 1099/2009 [15] causes a decrease in meat quality by increasing the incidence of large hemorrhages in fillets.

In light of the aforementioned considerations, a hypothesis was formulated that the type of device (OC or CX) used in the stunning process influences the technological parameters and visual attributes of the meat. The research undertaken by the authors allowed for the identification of the possibility of the sustainable production of chicken meat using different-quality raw material (good- and low-quality) supplied by breeders to the plant and devices for electrical stunning (own construction and commercial, from a Dutch company) during industrial chicken slaughter. The degree of achievement of the goal was determined on the basis of the following: (1) assessment of the commercial quality features of fillets (occurrence of hemorrhages and defects) and measurements of technological parameters (pH, color); and (2) correlation analysis (multiple regression), allowing an indication of which of the analyzed courses of action is the most important and should be taken into account in the company first to maintain a balance between the quality of produced meat and environmental and economic aspects.

2. Materials and Methods

The intended purpose and arrangement of the research was realized at a poultry plant in the central and eastern part of Poland. The Ross breed broilers were approx. 6 weeks old and weighing approx. 2.5 kg. Ross broilers are one of the most popular breeds of chickens bred for meat, known for their efficiency and rapid growth rate. The Ross breed, due to such features as (1) high feed conversion efficiency, (2) meat quality (well-developed breast fillets and a relatively large amount of meat), (3) resistance to diseases, and (4) flexibility in breeding (intensive or semi-intensive), is valued in the poultry industry, which makes it one of the most frequently selected breeds for commercial meat production [21,22]. Broilers were delivered to the plant by road in cages, then unloaded and hung on an automatic line with a capacity of 6000 pcs/h. The trial slaughter process was carried out in accordance with the requirements of humanitarian slaughter [15] and the conditions applicable in poultry farms. The process of electroplating chickens in a water bath was carried out using the following:

- ✓ differential quality of raw material (good- and low-quality)—assessed on the basis of the following criteria adopted by the plant: percentage of birds killed during transport, the degree of their peeling, and variation in weight,
- ✓ two devices for electrical stunning in a water bath: (1) innovative—own construction (OC): rectangular wave AC, f = 400 Hz, U = 100 V (patent: [23,24]) and (2) commercial—Dutch company (DC); sine wave AC, f = 200 Hz, U = 150 V, equipped with plant X in Poland.

Designated employees of the poultry plant, with several years of professional experience and competence in activities related to slaughter, carried out the experimental stunning procedure using an OC device. Their knowledge of basic behavioral patterns, signs of awareness, and sensitivity to animal stimuli, as well as the subjective (visual) assessment of a veterinarian, allowed for the assessment of the appropriate level for stunning animals and their humane slaughter. Additionally, as part of the ongoing management of the operational procedures' (risk-based) electrical stunning process, the economic operator monitored and recorded the current parameters used.

The process of alternating the animals was carried out with a 5 min interval between the experimental and control samples to ensure a comparable test system. From each experimental batch, 100 samples were taken. The number of samples (n = 100) was planned on the basis of quota selection and verified by the N HOELTER test, obtained as a result of SEM modeling.

The material for the study consisted of the muscles pectoralis major (trade name: fillet) and pectoralis minor (trade name: caterpillar), which were obtained as a result of the industrial breakdown of chilled carcasses (by water spraying, in about 2 h at an air temperature of about 2 °C) into essential elements.

2.1. pH Measurements

The pH measurements of the experimental and control samples were carried out using the pH-meter CP-411, equipped with the stitching electrode FC 200 in the thickest part of the fillet (m. pectoralis major) in 3 repetitions for each test, after the following times:

» 15 min after slaughter (pH_{15min}), n = 30 carcasses,
» approx. 2 h of cooling (pH_{2h}), n = 30 carcasses,
» approx. 9 h after slaughter (pH_{9h}), n = 30 fillets.

2.2. Visual Assessment of the Number of Hemorrhages in/on the Fillets and Their Defects

On the randomly selected 100 left fillets (without leather), a trained committee of five people (2 plant quality staff and 3 research staff) conducted a visual evaluation of the fillets in terms of the presence of hemorrhages. The assessment was made on the basis of the quantitative methodology developed by Banach [14], taking into account the current problems of the plant with the quality of the raw material supplied to it. The quality of the fillets was assessed by differentiated sizes of hemorrhages, visible from the outside and inside of the fillet: small (ø $\leq$ 10 mm) and large (ø > 10 mm).

Subsequently, the number of hemorrhages present was expressed as a percentage and referred to as "deficiency". The basis for determining this quality mark was the assumption that the occurrence of even one hemorrhage, regardless of size, qualified the fillet to the group of defective goods [14].

2.3. Color Measurements

Fillet color measurements were made using a Hunter Lab spectrophotometer, type MiniScan illuminator/observer D65/10* using the CIELab scale, where L*—brightness, a*(+)—red saturation, b*(+)—yellow saturation. Before starting the measurements, the device was calibrated using a white and black ceramic plate. Color measurements, including the external and internal surfaces of the fillet (m. pectoralis major) and tenderloin (m. pectoralis minor), were performed approximately 9 h after slaughter on 30 randomly selected samples in 3 repetitions (n = 90) for each sample, excluding places with visible defects (hemorrhages).

2.4. Statistical Analysis

Statistical analysis of the influence of the type of device (OC or DC) used in the stunning process on the analyzed technological parameters and visual characteristics of meat from good- (GQ) and low-quality (LQ) raw material was performed using the Mann–Whitney U test (IBM SPSS AMOS.29). It was used to verify the hypothesis (H_0) about the insignificance of differences between the studied variables in the two groups. The *p*-value determined on the basis of the test statistic was compared to the significance level α. Based on the negatively verified hypothesis ($p \leq \alpha \Rightarrow H_0$ was rejected and H_1 was accepted), it was found that the type of device differentiates the values of poultry meat parameters. In order to demonstrate the significance of differences between the parameters determining quality, a one-way analysis of variance was performed. Next, structural modeling was used to determine the strength and direction of linear relationships between the studied parameters [25–27]. The following variables were introduced into the model: pH (15_{min}, 2 h, and 9 h), color (L*, a*, b*), and hemorrhages (internal, external, and tenderloin). For the needs of the model and due to the variability limitations of variable color parameters measured on the external and internal surface and the tenderloin, their number was reduced to one parameter, L*, a*, and b* (without taking into account the fillet surface). The interpretation of the obtained model parameters was carried out on the basis of standardized coefficients (CMIN/DF), and the obtained measures of model fit authorized the acceptance of the multiple regression relationships presented in the model [26,28].

3. Results and Discussion

3.1. Changes in the pH of Meat After Slaughter

The results of the pH measurements of chicken meat 15 min (pH_{15min}), 2 h (pH_{2h}), and 9 h (pH_{9h}) after slaughter showed that the pH_{15min} values of meat produced from good-quality raw material (GQ) as a result of using the devices own construction (OC) and Dutch Company (DC) were at a similar level and amounted to 6.59 and 6.63, respectively. In the second hour after slaughter, the pH slightly increased to 6.74 and 7.71, and in the ninth hour after slaughter, it was 5.87 (OC) and 5.82 (DC), respectively. The average pH values of meat from chickens stunned using device OC for 9 h after slaughter were significantly

($p < 0.05$) higher than the corresponding values of pH_{2h} and pH_{9h} of meat from chickens stunned using the Dutch device (DC)—Table 1.

Table 1. pH values (after 15 min, 2 h, 9 h) of good- (GQ) and low-quality (LQ) chicken meat, stunned using devices of own construction (OC) or from a Dutch company (DC).

Raw Material Quality	pH After Slaughter	Device OC		Device DC	
		$\bar{x}$	SD	$\bar{x}$	SD
Good-Quality (GQ)	pH_{15min}	6.59 ^{a}	0.11	6.63 ^{a}	0.07
	pH_{2h}	6.74 ^{a}	0.08	6.71 ^{a}	0.06
	pH_{9h}	5.87 ^{B}	0.10	5.82 ^{A}	0.05
Low-Quality (LQ)	pH_{15min}	6.59 ^{a}	0.09	6.68 ^{b}	0.08
	pH_{2h}	6.76 ^{a}	0.08	6.78 ^{a}	0.08
	pH_{9h}	5.98 ^{A}	0.15	6.07 ^{B}	0.10

$\bar{x}$—mean value, SD—standard deviation; ^{a,b}—significant differences between rows, $p < 0.01$; ^{A,B}—significant differences between rows, $p < 0.05$; ^{a,a}—no significant differences.

In the meat of low-quality chickens (LQ), the nature of changes in the pH value was similar to that in meat from good-quality raw material, but the pH_{9h} values were higher and amounted to 5.98 when using the OC and 6.07 when using the DC device. Statistical analysis of the mean pH values of the pectoralis major muscle from low-quality chickens showed significant differences between the pH_{15min} ($p < 0.01$) and pH_{9h} ($p < 0.05$) values of the meat of chickens stunned using the OC device and the corresponding pH values of the meat of chickens stunned using the DC device (Table 1).

Moreover, it was observed that regardless of the type of stunning device used, the GQ raw material was characterized by a faster rate of pH changes over time from slaughter and lower final pH values, which indicates that the animal was healthy, rested, and not stressed. Low-quality (LQ) chicken meat was characterized by a slower rate of pH changes and higher final pH values—pH_{9h}, which in turn indicates that the animals may have been sick, tired, or stressed. The research results also confirm the visual assessment of the quality of chickens made by the plant's employees at the stage of unloading them, and the identified rate of glycolysis (pH changes) allows measurable determination of the quality class of the produced meat [29,30].

Considering the literary reports [11] that the quality of poultry meat is determined on the basis of pH_{15min} measurements, the above measurement results were analyzed for the spread of the mean pH_{15min} values of meat in each tested carcass, taking into account the ranges characterized by high meat quality (pH_{15min} = 5.9–6.2) and quality with worse technological properties, i.e., PSE: $pH_{15min} \leq 5.8$; and DFD: $pH_{15min} \geq 6.3$. Of the 120 broiler carcasses tested, all had characteristics typical of meat with a DFD defect ($pH \geq 6.3$). These results, therefore, confirm the opinion of many authors [31–33] that the pH_{15min} measurement is premature to apply the criteria for the division into PSE and DFD meat on its basis. According to Thielke et al. [34] and Hammemi et al. [35], in the meat of intensely bred chickens (Ross and Cobb), approx. 3 h after slaughter there is a mortal concentration (rigor mortis); therefore, the influence of the analyzed variable factors (appliance and raw material) on the quality class of the produced meat was determined on the basis of the analysis of the dispersion of the mean values of pH_{9h} (Figure 1a,b).

A detailed analysis of the pH_{9h} value showed that regardless of the quality of the supplied raw material (GQ and LQ), the use of the OC device allows us to obtain more repeatable results and a better technological quality of meat compared to the quality of meat of chickens stunned using the DC device. This may be due to the uniform flow of electric current through the chicken carcass during stunning and the destruction of the muscle tissue structure to the same extent [14].

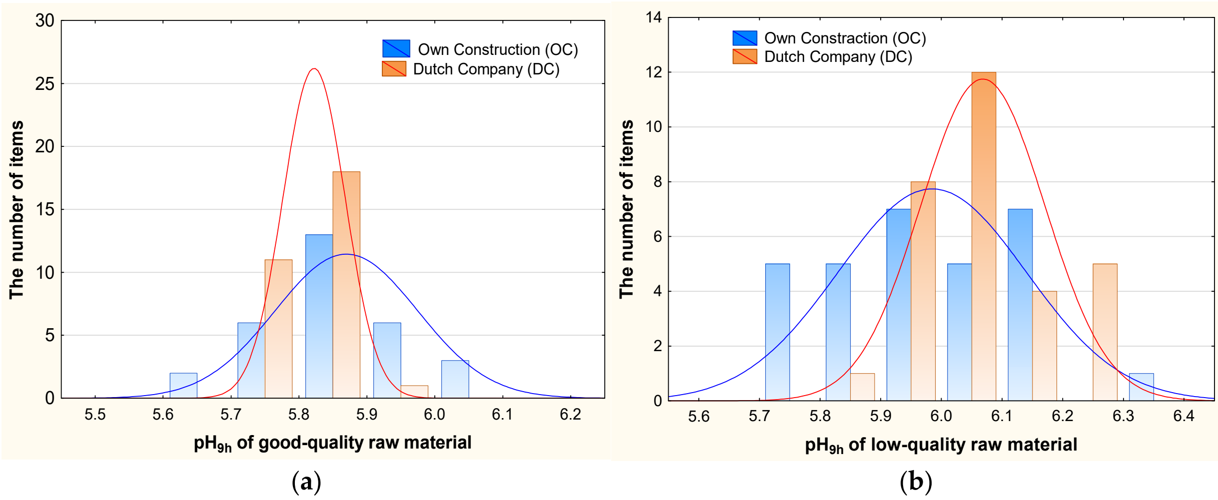


Figure 1. Scatter of mean pH_{9h} values of meat from good- (**a**) and low-quality raw material, (**b**) subjected to stunning using a device of own construction (OC) or from a Dutch company (DC).

The number of chicken carcasses stunned using the OC device classified as high-quality was at the following level: for the GQ raw material—22 pieces and for LQ—19 pieces; carcasses with the PSE syndrome (pH $\leq$ 5.8) were identified as 8/10 pieces, and with DFD syndrome (pH $\geq$ 6.3), only 1 piece as part of the LQ raw material. In the case of using a Dutch device (DC), the quality of the raw material had a significant impact on the production of carcasses of varying technological quality. This was evidenced by the following numbers of classified carcasses within the appropriate raw material groups (GQ/LQ): high-quality—19/25 pieces, with the PSE syndrome—11 pieces (GQ raw material), with the DFD syndrome—5 pieces (LQ raw material)—Figure 1.

3.2. Meat Color

Color is one of the most important features of consumer assessment of meat quality. It is guided by as many as 90% of consumers [13,36]. It proves the freshness, appetizing level, and tenderness of the meat and is also a criterion for producers to assess its technological suitability and the form of its sale—"loose" or processing. The phenomenon of unusual color or two-colored culinary elements (fillets) in poultry meat has a negative impact on their purchase and may even result in rejection (complaint) of the product by the consumer [37]. Due to the varied intensity and durability of color observed on the market [13,38,39], three measuring surfaces of meat were taken into account in the research: external (ES) and internal (IS) of the fillet, and the tenderloin.

The results of the instrumental color assessment of fillets obtained from GQ raw material (chickens) stunned using the OC device showed that the value of the L* parameter (lightness) of the ES and IS color of a fresh fillet (m. pectoralis major—PMj) was, respectively, 64.26 and 58.5, while the L* value of the tenderloin color (m. pectoralis minor—PMn) was 56.97. The L* ES and IS values of fillets and tenderloins cut from chicken carcasses stunned using the DC device were higher and amounted to, respectively, 65.03, 59.56, and 58.23. The values of the a* parameter of the ES and IS color of fillets obtained from chickens stunned using the OC device were 4.17 and 4.35 and were close to the color parameter a* of chicken fillets stunned using a DC device, the values of which were 4.18 and 4.32, respectively. The value of the a* parameter for tenderloin chicken stunned using OC was 5.75 and was greater than the a* value (4.93) for chicken tenderloin stunned using the DC device. The value of the parameter b* color of fillets and tenderloins from chickens stunned using the OC device was lower than the parameter b* color of fillets and tenderloins from chickens stunning using the DC device and amounted to, respectively, 12.77, 15.56, and 15.90. The values of the b* parameter for the color of fillets and tenderloins from chickens stunned using the DC device were, respectively, 13.03, 16.57, and 16.71 (Table 2).

Table 2. Color parameters L*, a*, b* values (mean value ± standard deviation) of the pectoralis major (PMj—fillet) and pectoralis minor (PMn—tenderloin) of the external (ES) and internal (IS) surfaces, coming from good and low raw material quality, taking into account the type of device used in the chicken stunning process—of own construction (OC) or from a Dutch company (DC).

Type of Device	Good-Quality Raw Material			Variance Analysis, Variable Surface			Low-Quality Raw Material			Variance Analysis, Variable Surface		
	m. Pectoralis Major (PMj)		m. Pectoralis Minor (PMn)				m. Pectoralis Major (PMj)		m. Pectoralis Minor (PMn)			
	ES	IS		ES-IS	IS-PMn	PMn-ES	ES	IS		ES-IS	IS-PMn	PMn-ES
							L*					
OC	64.26 ± 2.20	58.55 ± 3.81	56.97 ± 2.48	**	NS	**	61.18 ± 2.10 A	57.51 ± 2.71	55.43 ± 2.49 a	**	**	**
DC	65.03 ± 2.57	59.56 ± 3.93	58.23 ± 2.87	**	NS	**	62.14 ± 4.36 B	57.67 ± 3.07	57.46 ± 3.32 b	**	NS	**
							a*					
OC	4.17 ± 0.78	4.35 ± 0.94	5.75 ± 1.27 B	NS	**	**	4.13 ± 0.59	4.88 ± 1.00 A	5.55 ± 1.05	**	**	**
DC	4.18 ± 0.77	4.32 ± 0.89	4.93 ± 1.20 A	NS	**	**	4.39 ± 1.09	5.45 ± 1.12 B	5.35 ± 1.16	**	NS	**
							b*					
OC	12.77 ± 1.47	15.56 ± 1.17	15.90 ± 1.53 A	**	NS	**	12.17 ± 1.69	16.78 ± 1.60	16.81 ± 1.60	**	NS	**
DC	13.03 ± 1.44	16.57 ± 1.34	16.71 ± 1.52 B	**	NS	**	12.57 ± 1.57	16.37 ± 1.45	16.43 ± 1.50	**	NS	**

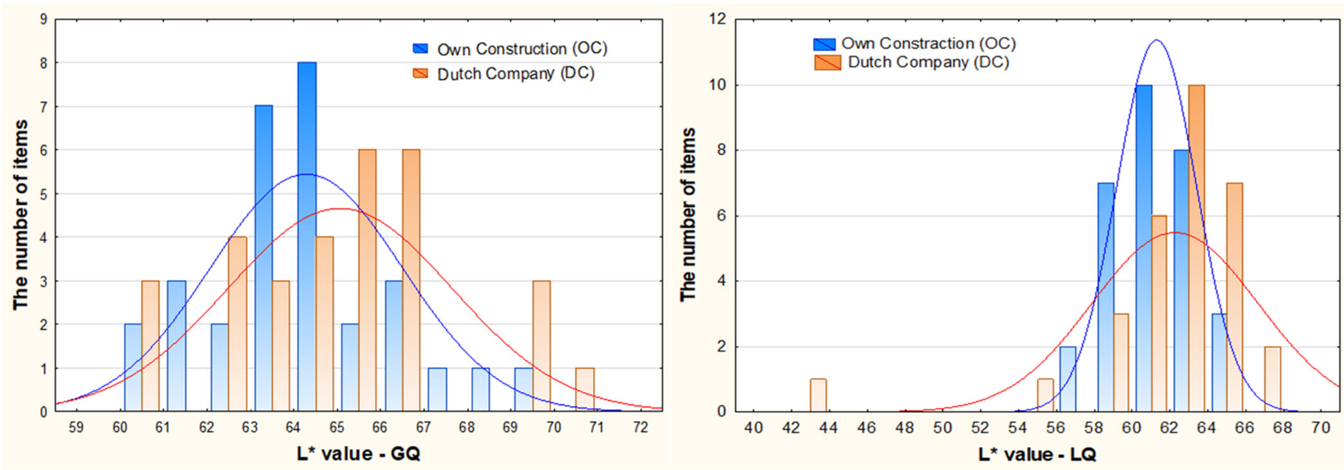
ES—external surface of fillet; IS—internal surface of fillet; NS—no significant differences; a,b—significant differences between rows (devices), $p < 0.01$; A,B—significant differences between rows, $p < 0.05$; **—significant differences between columns (surface), $p < 0.01$; *—significant differences between columns, $p < 0.05$.

The results of the instrumental color assessments of fillets from the LQ raw material (Table 2) showed that the values of the L* parameter (lightness) of their color, regardless of the tested surface and the type of stunning device, were on average 3.6% lower than the L* value of fillets obtained from GQ chicken carcasses. The values of the parameter a* of the color of the external surface (ES) of the fillet were at a similar level (approx. 4.22), while that of its internal surface (IS) was much larger (approx. 20%) than the parameter a* of the color of GQ chicken fillets, regardless of the type of device used. The values of the parameter b* of the color of the ES of the fillet, similarly to parameter a, were at a similar level (approx. 12.63), while the value of its IS was on average 3.2% larger than the parameter b of the color of GQ chickens, regardless of the type of device used. The values of the L* parameter of the color of the tenderloin from LQ chickens (Table 2) were lower on average by approx. 2% than the L* value of the tenderloin from GQ chickens, regardless of the type of device used for stunning. The values of the parameters a* and b* of the tenderloin color were at a similar level: approx. 5.40 and 16.46, respectively, regardless of the quality of the raw material and the type of device (Table 2).

The limit values of the L* parameter given in the literature on the subject to determine meat quality are not clear. Research conducted by various scientists has shown a wide range of values for this parameter. In the study by Wilkins et al. [37], the L* value was 45–67, in the study by Petracci et al. [40], 41–66, and in the study by Lesiów and Kijowski [41], it ranged from 43–56. The results of the color measurements presented in this paper show that the range of values of the L* parameter of GQ meat color was larger and amounted to 58–65 over the entire fillet surface. In the LQ raw material, however, the range was 55–62 and was similar to the range of values of this parameter obtained in our own research [42], which was set at 55–64. It was also found that, regardless of the stunning device used, the values of the L* parameter of fillet color on the ES were higher and differed significantly from the values of the L* parameter of the IS color of fillet and tenderloin. The obtained results confirm previous studies conducted by Sandusky and Heath [43] and Wilkins et al. [39], where the external surface of the fillet was lighter than the internal surface. Moreover, research conducted by scientists in various countries shows that PSE (pale, soft, exudative) meat is a large-scale quality problem in the poultry industry. In Canada, Barbut [44] estimated the occurrence of this problem in broiler chicken meat at 28%, in Texas Woelfel et al. [45] showed as much as 47%, in England about 20% [37], in China about 23% [46], and in Poland about 35% [47]. The occurrence of PSE in poultry meat is considered to be the result of accelerated post-mortem glycolysis, especially in birds more susceptible to stress [48]. The problem of chicken meat production—DFD was estimated at a low level—was approximately 10% [49] compared to the PSE defect.

In order to conduct a detailed analysis of the influence of variable factors—device and raw material quality—on the frequency and scope of occurrence of lightness of meat color, an analysis of the scatter of mean values of color parameters L* on the external surface of fillets was performed, which is mainly the basis for making purchasing decisions for customers. It was observed that fillets obtained from GQ chickens were characterized by a much lighter color (L* = 60–70) than fillets obtained from LQ chickens (L* = 56–68), and the use of the OC device, regardless of the type of raw material, was characterized by high color repeatability in the same range (L* = 60–65)—Figure 2.

This proves that it is possible to produce meat with a uniform and repeatable color (regardless of the quality of the raw material) by taking action in only one direction—replacing the device with an OC. From a practical point of view, this is especially important when packaging meat (selling meat on trays) and not creating doubts among consumers when purchasing products with different colors between individual pieces. This may lead to rejection of the goods and economic losses for the manufacturer [50]. Fletcher [38,39] conducted research on goods available in retail trade and showed that the color of chicken breast muscles (packed in trays of four pieces) was very diverse, and the level of defects in unit packages in which at least one fillet was clearly different in color was 7% for the entire batch.



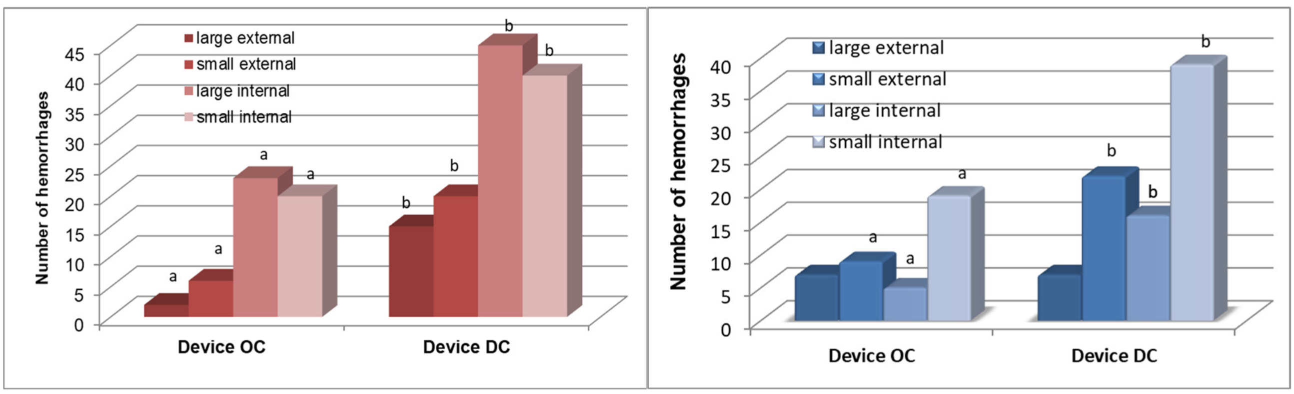
(**A**) (**B**)

Figure 2. Scatter of mean color parameter L* values of the meat from (**A**) good-quality—GQ and (**B**) low-quality—LQ chickens, stunned using an OC or DC device.

3.3. *Quantitative Assessment of Hemorrhages in/on the Fillet*

Hemorrhages are a frequently occurring quality defect, especially in the breast muscle—fillet, which is the most attractive part of the carcass in terms of price and nutritional value. Defects in the form of hemorrhages occur in the pectoral muscle on the external surface and in its deep parts and are irreversible and difficult to eliminate. Therefore, taking actions by companies to improve meat production processes and implementing quality systems allows for an increasingly profitable and sustainable meat production process.

With the above in mind, the number of small and large hemorrhages occurring in fillets, on the external and internal surfaces of the fillets, was assessed. The results of tests on meat from GQ chickens showed that the smallest number of hemorrhages, regardless of their size and fillet surface (external and internal), was obtained as a result of using a device of own construction (OC) in the process of stunning chickens. The total number of hemorrhages was 51, including 25 large and 26 small hemorrhages. After using the DC device, the number of hemorrhages occurring in the meat was more than twice as high and amounted to a total of 120 (60 large and 60 small)—Figure 3.



(**A**) (**B**)

Figure 3. Number of small and large hemorrhages on the external and internal surfaces of fillets produced from (**A**) good- and (**B**) low-quality chickens, stunned using an OC or DC device ([a,b]—significant differences between devices, $p < 0.01$).

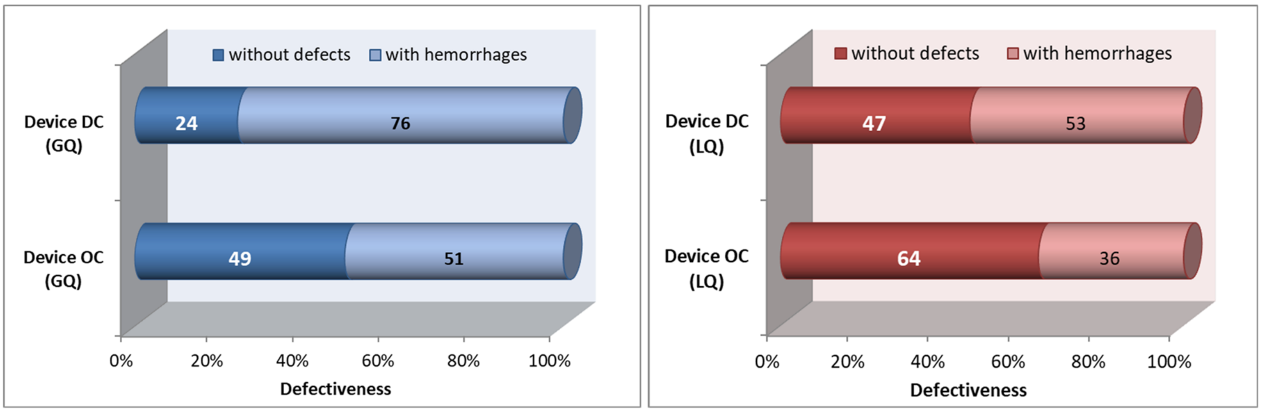
Visual assessment of the meat from LQ chickens showed the same quality improvement effect with the use of the OC, with the level of hematoma occurrence being lower than in meat obtained from GQ raw material, and also displaying the lowest number of hemorrhages. The number of hemorrhages in meat when using OC was a total of 40, including 12 large and 28 small hemorrhages, while after using the DC device, the total number of hematomas was twice as high and amounted to 84 (23 large and 61 small). The results of our own preliminary research [42,51,52] also showed a beneficial effect of using a device of own construction for stunning chickens on the number of hemorrhages in fillets and tenderloins, as well as on color and tenderness during meat storage, regardless of the storage time duration and origin of the raw material (supplier), compared to the effects obtained using devices produced by commercial companies.

It was also observed that the number of hematomas in meat from low-quality (LQ) chickens was lower than in meat from good-quality (GQ) chickens, but when using a commercial device (DC), the greatest problem was with internal hematomas. Fletcher [53] and Banach [14] showed the opposite relationship. Due to the poorer quality of the raw material, the electrical stunning process contributed to the increased occurrence of quality defects in the form of bruises and hemorrhages in the meat. According to the literature data, such a relationship may be related to the different size and body weight of chickens within a given batch of raw material because each of them has a different internal impedance and receives a different dose of current, which determines the effectiveness of the stunning and the quality of the meat [14,54,55]. The higher number of small hemorrhages (external and internal) is probably the result of inappropriate selection of electric current parameters and the occurrence of stress in birds, which causes an increase in pressure in blood vessels and capillaries, followed by their rupture and leakage of blood into the tissues [56,57]. The OC device's beneficial effect on the sustainable production of meat from both high-quality and low-quality chickens stems from its use of patented electric current parameters: a rectangular pulse shape and a frequency of 400 Hz. In contrast, the commercial device (DC) uses a sinusoidal current with a frequency of 200 Hz. Raj [58] has a different opinion regarding the selection of current parameters and the effectiveness of stunning chickens. The author showed that a sinusoidal alternating current is more effective than a pulsed current, and the key factor in choosing pulsed stunning is the pulse width [59,60]. There is also no clarity on selecting the current frequency and intensity. Regulation 1099/2009 [15] recommends using a higher intensity at a higher frequency to achieve effective stunning of poultry, although according to Lines et al. [18], Huang et al. [19], and Sirri et al. [20], the use of the recommended parameters results in a decrease in meat quality—an increase in the incidence of large hemorrhages.

Polish poultry plants, bearing in mind the desire to increase their own quality standards and the company's competitiveness in foreign markets, are implementing quality systems (QAFPs), in which the basic requirement for the commercial evaluation of culinary elements is the product having no external petechiae [61]. Therefore, as part of the research, an additional assessment of the defectiveness of meat was carried out, in which the occurrence of even one hemorrhage, even a small one, meant that the product was classified as defective meat. The results of this evaluation showed that the use of an innovative device for stunning chickens, regardless of the quality of the raw material supplied to the plant, allows for an increase in the percentage of meat without defects (without hemorrhages) compared to the effects obtained using the DC device (Figure 4).

Enterprises that have raw material of GQ and LQ and use the OC device can increase the production of meat without defects to approx. 50 and 65%, respectively, while using the current device allows for the production of high-quality meat (without defects) only at the level of 24 and 47% (Figure 4).

In a situation where the plant has limited ability to influence the quality of the supplied raw material and has a commercial device (DC) on the slaughter line, entrepreneurs may face heavy financial burdens and problems both in the wholesale and retail meat markets. Wilkins et al. [37] and Fletcher [38] claim that these problems may also be related to customers' reluctance to buy fillets with hematomas and different colors, and when selling culinary items with this type of defect in unit packages, customer reactions and behavior may become more intense.



(**A**) (**B**)

Figure 4. Assessment of defects of fillets produced from (**A**) good-(GQ) and (**B**) low-quality (LQ) chickens, stunned using an OC or DC device.

In order to confirm the validity and directions of activities planned by slaughterhouses in the implementation of sustainable meat production, the authors undertook an in-depth statistical analysis using a structural model. For the purpose of the model and due to the limitations of the variance of the fillet color parameters measured on the external, internal, and tenderloin surfaces (e.g., PMj: L^*_{ES}, L^*_{IS}, and L_{MPn}), their number was reduced to one parameter, L*, a*, and b* (without taking into account the surface of the meat). The reduction in dimensions was carried out by factor analysis using the method of analysis of the main components to arbitrarily decide one dimension. The Bartlett test and Kaiser–Meyer–Olkin statistics have shown that it is reasonable to reduce the dimensions to three variables as follows: L*, a*, and b*. This has also been confirmed by the matching measures of the proposed pattern model of dependency. By assessing the quality and fit measures of the path model (CMIN/DF value = 4.763, where the acceptable acceptance area is below five), it was found that it meets the criteria of acceptability and applicability [28]. Based on the adopted model, a correlation analysis was carried out between the examined factors (quality of raw material, device) and technological parameters (pH, L*, a*, b*) and visual parameters (number of hemorrhages) of chicken meat (Table 3).

A positive and significant relationship was found between the quality of the raw material (RMQ) and the pH measured after 2 h and 9 h ($p < 0.01$, $p < 0.001$) and the color parameter a* ($p < 0.05$), and a negative relationship was found with the color parameter L* and large internal hemorrhages—LIHs ($p < 0.001$). A greater number of significant and positive relationships ($p < 0.05$, $p < 0.01$, $p < 0.001$) were obtained between the devices (Dev.) and hemorrhages of all types—LEHs/SEHs/LIHs/SIHs (small/large/internal/external), pH15 min, and the color parameter L* (Table 3).

The obtained results of the multiple regression analysis (Table 3) prove that the chicken stunning device has a greater impact on the control of quality parameters enabling sustainable meat production than the quality of the raw material. Taking steps to replace the device used by the plant will allow you to directly manage the production volume of high-quality meat and the sales value of "premium" meat (with the QAFP mark) and, indirectly, the volume of waste generated (meat with hemorrhages). It will also enable the management of savings resulting from the lack of the need to engage employees when cutting and disposing of meat with hemorrhages (category III waste).

Table 3. Correlation analysis between raw material quality (RMQ) and stunned using device (Dev.) vs. technological parameters (pH, L*, a*, b*) and visual featureshemorrhages (LEH/SEH/LIH/SIH) of meat.

Relationship			Estimate	S.E.	C.R.	*p*	Relationship			Estimate	S.E.	C.R.	*p*
pH_{15}	←	RMQ	0.03	0.02	1.63	0.10	pH_{15}	←	Dev.	0.06	0.02	3.80	***
pH_{2h}	←	RMQ	0.04	0.01	3.00	**	pH_{2h}	←	Dev.	−0.01	0.01	−0.64	0.52
pH_{9h}	←	RMQ	0.18	0.02	8.79	***	pH_{9h}	←	Dev.	0.09	0.02	0.87	0.38
L*	←	RMQ	−0.70	0.17	−4.17	***	L*	←	Dev.	0.41	0.17	2.46	*
a*	←	RMQ	0.40	0.18	2.23	*	a*	←	Dev.	−0.01	0.18	−0.05	0.96
b*	←	RMQ	0.10	0.18	0.55	0.58	b*	←	Dev.	0.21	0.18	1.15	0.25
LEHs	←	RMQ	−0.05	0.08	−0.64	0.52	LEHs	←	Dev.	0.22	0.08	2.79	**
SEHs	←	RMQ	0.07	0.08	0.83	0.41	SEHs	←	Dev.	0.47	0.08	5.78	***
LIHs	←	RMQ	−0.53	0.07	−7.70	***	LIHs	←	Dev.	0.30	0.07	4.33	***
SIHs	←	RMQ	0.00	0.06	0.00	1.00	SIHs	←	Dev.	0.33	0.01	5.45	***

p—significance level calculated; S.E.—standard errors, C.R.—critical ratios; LEHs—large external hemorrhages; SEHs—small external hemorrhages; LIHs—large internal hemorrhages; SIHs—small internal hemorrhages. *—$p < 0.05$; **—$p < 0.01$; ***—$p < 0.001$.

4. Conclusions

Improving the quality of poultry meat, and in particular the fillet as the most valuable culinary element of the carcass, is possible by comprehensively taking into account many quality-promoting activities at individual stages of its production. However, the stunning process is still underestimated as a stage that begins slaughter and shapes the quality of meat. Poultry stunning devices currently used in plants do not always have a positive impact on the final quality of meat, while the quality of the raw material (chickens) delivered to the plant determines the efficiency and profitability of production.

The results of research carried out on the assessment of the commercial quality features and technological parameters of fillets (goal 1) and their statistical analysis (goal 2) allowed for the following conclusions to be formulated:

1. The use of the innovative device OC for stunning poultry, as opposed to a device from a Dutch company (DC), has a positive effect on the following:
   - reducing the number of hemorrhages visible on the external and internal surface of the fillet—mainly large hemorrhages, which determine the quality and durability of the meat, generate waste, and are not acceptable to consumers,
   - increasing by approx. 50% the share of production of fillets without hemorrhages, which can be classified as quality class I—"premium", with a higher unit price,
   - faster rate of post-slaughter changes and lightening of the color of the external and internal surfaces of the fillet and tenderloin, which are probably the result of the regular flow of electric current through the chicken carcasses during stunning and better bleeding during slaughter.
2. Statistical analysis showed, in turn, the following:
   - a positive and significant relationship ($p < 0.01$, $p < 0.001$) between raw material quality (RMQ) and technological parameters, and a negative relationship with the color parameter L* and large internal hemorrhages ($p < 0.001$).
   - the estimators of the relationship model indicate a greater impact of the type of device on the size and location of hemorrhages as well as technological parameters (pH, color) than the quality of the raw material; therefore, the hypothesis assuming that the type of device used in the stunning process (OC or DC) has an impact on the technological parameters and visual characteristics of meat from GQ and LQ raw material was positively verified.

3. The obtained wide range of pro-quality effects of the produced chicken meat confirm the possibility of meeting the most important requirements for its sustainable production and thus justifies the replacement of the DC device currently used in the plant with an OC device.
4. Although the quality of chickens delivered to the plant has a smaller impact on sustainable meat production than the type of equipment, the authors also recommend using financial tools when concluding contracts with poultry farmers so that meat producers can implement the goals of the sustainable management policy already at the raw material stage.
5. The above-mentioned benefits clearly prove that managing the quality of chicken meat in the stunning process using an OC device may constitute a strategic element of changes in the implementation of sustainable production management in the company, even with the varying quality of raw materials supplied to the plant.

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Institutional Review Board Statement: Ethical review and approval were waived for this study, due to activities related to animal slaughter being carried out by employees of the poultry plant with several years of professional experience and competence in this field. Their knowledge and the veterinarian's visual assessment guaranteed the effectiveness of stunning the chickens. Research procedures were carried out in accordance with European Union regulations (Council Regulation (EC) No. 1099/2009 on the protection of animals at the time of killing).

Informed Consent Statement: Not applicable.

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Conflicts of Interest: The authors declare no conflict of interest.

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