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# Effects of slaughter weight and backfat depth on trimming, curing, and deboning losses and quality traits of Italian dry-cured ham

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ABSTRACT

This study aimed at assessing the effects of two infra-vitam traits, specifically the slaughter weight (SW) and the ultrasound backfat depth (BCKF) on several post-mortem and quality traits of typical Prosciutto Veneto protected designation of origin (PDO) dry-cured ham. The trial was conducted on a population of 423 pigs fed using different strategies to generate a high variation in SW (175 ± 15.5 kg) and BCKF (23.16 ± 4.14 mm). All the left thighs were weighed at slaughter and the ham factory during the different processing phases. The fat cover depth of green trimmed hams was measured. Data were analyzed with a linear model including SW classified in tertiles, BCKF as a covariate, SW × BCKF interaction, sex, batch, and pen nested within batch. Our results highlighted that, for each 10 kg increase in SW, trimmed and seasoned ham weights increased by 0.76 and 0.54 kg, respectively. The increase in SW significantly reduced relative curing and deboning losses but did not affect ham fat cover depth and trimming losses. A rise in BCKF increased the ham fat cover depth and trimming losses and decreased the curing and deboning losses. Increases in SW and BCKF improved quality traits of the seasoned ham including fat cover depth, visible marbling, inner lean firmness, and fat color. These findings confirm the feasibility of increasing SW and BCKF, which will result in a reduction in the relative losses associated with the dry-curing process while improving the quality of the seasoned ham.

## 1. Introduction

Lean growth rates of modern pig genotypes have risen significantly in recent years (Shurson and Kerr, 2023). As a consequence, an increase in weight at slaughter (SW) and carcass adiposity has been recommended for pigs raised for dry-cured ham production (Bosi & Russo, 2004; Latorre et al., 2009; Čandek-Potokar & Škrlep, 2012; Gallo et al., 2017). However, the increase in SW and adiposity could influence the losses related to the processing of green hams, and consequently the seasoned ham's quality (Latorre et al., 2008; Malgwi et al., 2021).

Losses occur at various stages of the processing. Primarily, significant losses stem from trimmings, which happen both at the slaughterhouse and later at the ham factory. Existing studies have shown that these losses vary with the weight and the adiposity of the ham (Bosi & Russo, 2004; Čandek-Potokar & Škrlep, 2011). In addition, the ham loses weight due to dehydration during salting, resting, and seasoning (Bonfatti & Carnier, 2020). Salt exposure extracts water from the ham's internal tissues, while the salt is partially dissolved and penetrates, by diffusion, into the internal part of the muscle. The ham fat cover depth is a barrier that impacts the pattern of water extraction and salt penetration. Thus, the dehydration pattern affects the absorption of salt, the rapidity of protein and lipid breakdown, as well as the texture, sensory profile, and organoleptic characteristics of the ham (Bonfatti & Carnier, 2020; Pinna et al., 2020). This process is associated with a marked loss of

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weight and consequently of saleable material. An additional loss of material is caused by the practice of deboning. This process involves the removal of the femur and other parts of the thigh, depending on the type of ham (Pagliarini et al., 2016). Deboning is followed by compression to improve the ham sliceability (Gallo et al., 1994). In this context, no studies have quantified the impact of increasing SW and ultrasonic backfat thickness at slaughter (BCKF) on the ham weight losses during salting, resting, seasoning, and deboning.

In addition, the modification of SW and BCKF would also impact other quality traits of the seasoned ham (Latorre et al., 2008). In dry-cured ham plants, the quality of dry-cured hams is evaluated according to linear scoring systems applied by qualified personnel to a variety of ham traits that are crucial for the market appreciation of the products. Some of the most common evaluations of hams at the end of ripening include the round shape, fat cover thickness and firmness, fat color, visible marbling, muscle displacement, lean color, and lean firmness (Malgwi et al., 2022). To date, only a few studies have explored this aspect, and the trials conducted have been based on evaluations performed on green hams, with results extrapolated for the cured product (Rodríguez-Sanchez et al., 2014; Bonfatti & Carnier, 2020; Dall'Olio et al., 2020).

This research evaluates the impact of SW and BCKF on ham weight losses resulting from trimming, dehydration, and deboning, as well as on a set of traits that reflect the quality of the seasoned hams.

## 2. Material and methods

The experimental procedures of this study were submitted and approved by the institutional animal care committee at the University of Padova [Organismo preposto per il Benessere Animale" (OPBA, approval document #36/2018)] based on the European Union requirements, the Italian National legislation, and the OPBA guidelines for experiments conducted with animals.

### 2.1. Experimental design and pig rearing

Data for this study were derived from a previous feeding trial (Malgwi et al., 2021). Briefly, 4 batches ranging from 104 to 112 pure Goland C21 pigs were used. The pigs of each batch were divided into 4 treatment groups, with 2 pens per treatment, and an average of 13.5 pigs/pen, balanced for barrows and gilts. Moreover, the mean and standard deviation of initial body weight were similar across pens (88 ± 11 kg).

The experimental treatments were planned to generate a large variation among groups in weight at slaughter, and in the carcass, green, and dry-cured ham characteristics (Malgwi et al., 2021; Toscano et al., 2023). Details about the rearing strategies, including ingredients and chemical composition of the diets are reported in Malgwi et al. (2021).

### 2.2. Evaluation of raw hams at slaughter

The day before slaughter, the pigs were weighed with an electronic scale and the BCKF was measured with an A-mode ultrasonic device (Renco Lean-meater series 12, Renco Corporation, Minneapolis, USA) above the last rib at approximately 5.0 to 8.0 cm from the midline (Schiavon et al., 2015). Carcasses were scalded, de-haired, eviscerated, and split down the midline according to commercial procedures. One hour later the carcasses were dissected according to the typical commercial procedure (Russo, 1989), and left raw hams were weighed. The raw hams were chilled at 0–2 °C for 24 h, trimmed, and weighed again to compute the trimming losses at the slaughterhouse. These losses were summed to those achieved at the ham factory, and the total trimming losses were considered for further analysis in the current study. The subcutaneous fat depth of the hams was measured in two points, as shown in Fig. 1. A first measurement (P1) was taken on the lateral face of the thigh, at the level of the head of the femur where the *biceps femoris* and the *quadriceps* muscle converge, where the subcutaneous fat is at its minimum depth. A second measurement (P2) was taken on the medial face of the thigh, in correspondence with the *semimembranosus* muscle at the level of the commercial part of the ham named "corona" (P2). These measurements are compliant with the official rules of PDO dry-cured hams (EC, 1992), and were performed using a caliper for P1 and a portable ultrasound system (Aloka SSD 500 equipped with UST-5512 7.5 MHz linear transducer probe, Hitachi Medical Systems S.p.A., Milan, Italy) for P2.

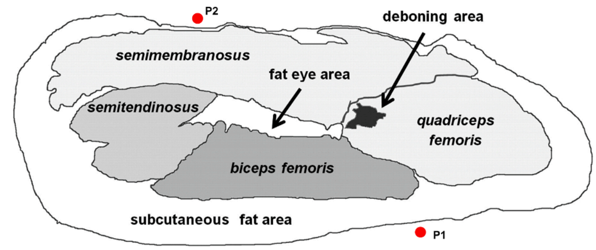


**Fig. 1.** Digital image of the cross-section of a dry-cured ham showing the exact position of P1 and P2 measurements. Figure modified from Bonfatti et al. (2011).

Muscle pH was measured in triplicate on the *semimembranosus* muscle 2 and 24 h after slaughter using a Crison Basic 25 portable pH meter equipped with a Crison 5033 penetration probe (Crison, Barcelona, Spain).

### 2.3. Evaluation of the hams at the ham factory

The day after the slaughter all the left trimmed hams, chilled at 4 °C, were sent to the ham factory (Attilio Fontana S.A.S., Montagnana, Italy) to be processed according to the rules of Prosciutto Veneto PDO consortium (European Commission EC, 2016). The dry-curing process is described in detail hereafter. Upon arrival at the ham factory, the thighs were weighed, trimmed, and then completely covered with salt for a 6-day salting process. Then, they underwent brushing and massaging to ensure even salt absorption and complete bleeding. A second salting phase occurred, lasting a further 5 to 8 days, depending on the weight of each ham, according to the rule of 1 day of salting per kg of ham weight. Desalting with compressed air followed to prevent microbial contamination, along with pressing to complete the bleeding and salt absorption. Next, the hams were hung with a string in a cold room for two weeks after perforating the distal part of the leg with a drill. Grooming, particularly around veins, and iliac bone reduction were completed with a knife to ensure a flat exposed ham surface and homogeneous drying. They then underwent a 90-day resting period in refrigerated rooms (2-4° C) with an air humidity between 70 and 80 %. Subsequently, the hams were washed with warm water to soften, prevent crust formation, remove surface salt, and initiate proteolysis. After overnight drying at room temperature, they underwent approximately 40 days of pre-seasoning at controlled temperatures to facilitate gradual drying. Areas not covered by skin were coated with a mixture of rice flour and lard. Finally, the hams entered the ripening phase, lasting about 13 months to complete drying and enhance flavor. A repeat grouting occurred after 4 to 5 months to maintain uniform hardness for slicing.

During the process, the hams were weighed several times to study the dynamic of weight losses during the curing process, as outlined in Fig. 2. The weights of hams have been used to compute the overall salting losses, the post-salting processing and seasoning losses and the deboning losses. Last, the total losses were computed as the difference between the raw ham and the deboned dry-cured ham weights.

Subjective quality evaluation was conducted by a single skilled operator with decades of experience, following the quality assurance procedures established by the ham factory. The decision to enlist only


**Fig. 2.** Weights and losses collected during the curing process of left hams.

one evaluator was justified by the within-farm comparative nature of the current research and the limited literature available on these critical traits, which significantly influence the quality and commercial value of PDO dry-cured ham.

Before deboning, the seasoned hams were scored by the same single skilled operator with decades of experience, for round shape (1 = flat, …, 3 = rounded), fat cover depth (1 = thin, …, 5 = thick), fat cover firmness (1 = soft, …, 3 = hard) and fat cover color (1 = yellow, …, 3 = white). Punctures with a horse fibula were performed to assess the resistance of the ham to penetration, indicated as ham firmness (1 = soft, …, 3 = firm), and the presence of unpleasant odors at the positions close to the *femoris* vein, the head of the femur, and the shin. Specifically, unpleasant odors have never been detected on the ham of current research and so these data were not further considered.

After deboning the same operator scored the hams for inner lean firmness (1 = soft, …, 5 = firm), muscle displacement (1 = absent, …, 3 = evident), lean color (1 = pale, …, 5 = dark), visible marbling (1 = null, …, 5 = relevant) and the size of the fat vein (1 = small, …, 3 = large). The fat vein is located along the border of the *semimembranosus* muscle with the *quadriceps* muscle (Fig. 3). The inner lean firmness was performed by palpation of the muscles inside the ham in proximity to the removed femur. Visual scoring for subjective traits such as those proposed in the current manuscript has been already applied to assess ham quality parameters (Gallo et al., 2017; NPPC, 2000) and is usually utilized at the ham factory level for the evaluation of dry-cured hams.

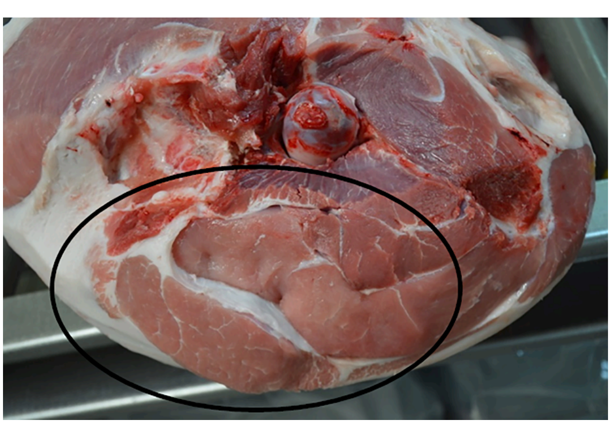

**Fig. 3.** Ham showing a relevant fat vein size and muscle displacement (black circle). The shrinkage of the intermuscular fat during seasoning might cause muscle displacement with consequent worsening of the slicing aptitude of the seasoned ham.

### 2.4. Statistical analysis

A preliminary exploratory analysis was performed to check outliers and normal distributions of the variables and to produce descriptive statistics. Values exceeding the mean plus or minus 3 standard deviations were discarded.

Before statistical analysis, pigs were classified in tertiles according to their body weight at slaughter, obtaining the following slaughter weight classes (SWC): light (159.9 ± 8.5 kg), medium (175.0 ± 3.3 kg) and heavy (192.5 ± 10.3 kg). This classification was designed to assess the impact of an increase in SW and BCKF, regardless of the diet, on processing losses and qualitative ham traits.

Data were analyzed with the proc mixed of SAS. (SAS Inst. Inc., Cary, NC) using the following hierarchical linear mixed model:

$$y_{ijklmn} = \mu + SWC_i + BCKF_j + Sex_k + (SWC \times BCKF)_{ij} + Batch_l + Pen(Batch)_m + e_{ijklmn}$$

where $y_{ijklmn}$ was the observed trait, μ was the overall intercept of the model, $SWC_i$ was the fixed effect of the $i^{th}$ tertile of SW (i = 1, …, 3), $BCKF_j$ was the $j^{th}$ effect of the backfat depth included in the model as a covariate, $(SWC \times BCKF)_{ij}$ was the interaction effect between SWC and BCKF, $Sex_k$ was the fixed effect of the $k^{th}$ sex (k: 1 = gilts, 2 = barrows), $Batch_m$ was the random effect of the $l^{th}$ batch (l = 1, …, 4), $Pen(Batch)_m$ was the random effect of the $m^{th}$ pen (m = 1, …, 8) within the Batch, and $e_{ijklmn}$ was the random residual. Batch, pen, and residual were assumed to be independently and normally distributed. As the $(SWC \times BCKF)_{ij}$ interaction was not significant, it was omitted from the final model.

Linear relationships between SW with the trimmed ham weight and the seasoned ham weight, and between salting weight loss with curing weight loss were computed and reported in graphic form.

## 3. Results

### 3.1. Descriptive statistics

Descriptive statistics for SW, BCKF, green, and dry-cured hams characteristics are reported in supplementary Table S1. The SW and BCKF averaged 175.8 kg and 23.16 mm, respectively. The ham weights collected at different temporal points of curing decreased progressively from 13.91 to 7.06 kg, after the double trimming treatment, the double salting exposure, the resting, the seasoning, and the deboning. As expected, the weight of both trimmed and seasoned hams linearly increased by 0.76 and 0.54 kg, respectively, with every 10 kg increase in SW in the current study (Fig. 4).

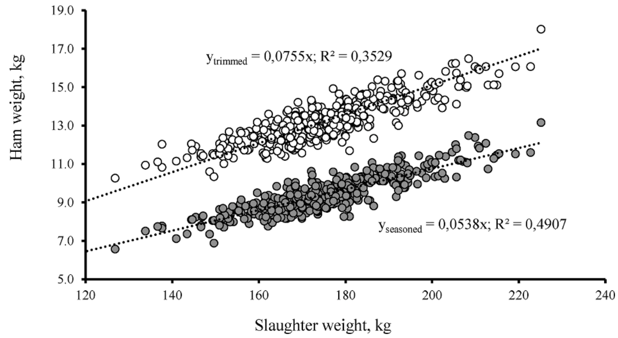


**Fig. 4.** Linear relationships between slaughter weight and the trimmed (white circles) and seasoned (dark circles) ham weight (n = 423).

The trimming procedure generated the greatest weight loss, averaging nearly 4.00 kg. The weight losses associated with the curing, mainly due to dehydration, varied from 2.86 to 4.86, with an average of 3.83 kg (CV = 8.6 %). Salting losses were on the order of 0.68 kg, accounting for 17.8 % of total curing losses. Moreover, these losses were strongly correlated with total curing losses (Fig. 5). Deboning caused an average loss of 2.38 kg. In relative terms, trimming caused a loss of nearly 22.5 % of the raw ham weight. The dry-curing losses were in the order of 28.9 % of the weight of the trimmed ham at the ham factory, and the relative deboning losses were in the order of 25 % of the ham weight at the end of seasoning. The fluid loss of weight due to salt inflow during the salting period averaged 34.62 ± 6.54 g/d, whereas post-salting dehydration had an average value of 5.42 g/d.

Descriptive statistics of dry-cured ham quality scores are given in supplementary Table S2. All descriptive dry-cured ham quality scores were characterized by large variations. On average, the dry-cured hams of this study have been evaluated as roughly intermediate for most traits with only inner lean, fibula puncture stiffness, and fat vein size displaying higher values.

### 3.2. Impact of SW, sex and BCKF on ham weight and ham weight losses

The SW had a significant impact on all the measures of ham weight at different curing stages and on the absolute ham weight losses (Table 1) and almost no influence on the trimming losses. However, when these traits were expressed in relative terms ($P > 0.10$), the SW significantly reduced losses related to curing ($P < 0.01$), deboning ($P < 0.05$), and the total relative losses both when expressed per unit of raw and trimmed ham weight ($P < 0.01$). The rate of dehydration during salting was not influenced by the SW except during the post-salting processing period ($P < 0.01$).

Conversely, sex had only a marginal influence on ham weight and weight losses, influencing only the weight losses due to deboning, both

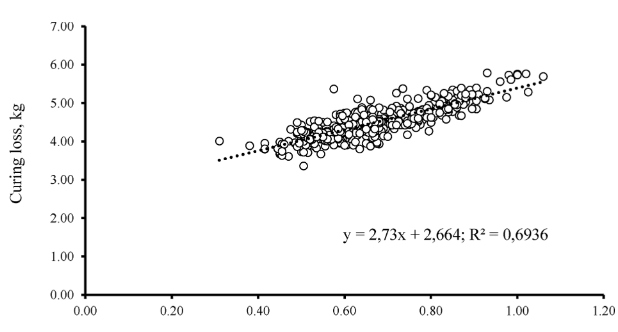


**Fig. 5.** Relationship between absolute salting (1st and 2nd salting, and 7 d out of salting) and dry-curing losses (n = 423).

absolute and relative, and the relative total weight losses, which appeared greater in barrows than gilts due to their heavier bones.

The effect of BCKF was remarkably positive ($P < 0.01$) on the raw, seasoned, and deboned ham weights. Moreover, BCKF did not affect the trimmed ham weight while weakly influenced the post-salting ham weight.

SW and BCKF had complementary impacts on the fat cover depth of green ham. Specifically, fat cover depth in P2 was influenced by SW, while BCKF had an impact on the fat cover depth in P1.

The BCKF significantly increased the absolute trimming losses and decreased the absolute processing losses except for deboning ones, which appeared to be independent of the BCKF. Conversely, with increasing BCKF, the relative trimming losses increased while all the other relative losses (salting, post-salting, and deboning) decreased. Because of compensations between positive and negative impacts, the overall influence of BCKF on the relative total losses was not significant when computed from raw hams, whereas the relative total losses decreased as BCKF increased when they were calculated from trimmed ham.

### 3.3. The relevance of SW, sex and BCKF on some technological traits of the seasoned hams

The class of SW significantly increased the round shape, the fat cover depth, and the fat vein size of dry-cured hams, while the inner lean firmness and the firmness at the horse fibula puncture decreased (Table 2).

Again, sex had only limited influence on the technological traits of the seasoned ham, although gilts had lower fat cover firmness and fat vein size than barrows, a slightly greater muscle displacement score was associated with gilts.

The BCKF significantly influenced nearly all scores related to fat, as fat vein size, fat cover depth, and visible marbling increased, while the fat cover color decreased, being whiter with increasing BCKF. Also, the firmness at the horse fibula puncture decreased at increasing BCKF.

## 4. Discussion

Although the current research involves only a single crossbred and a single processing plant, our results confirmed the relevant impact of SW and BCKF on weight loss and quality traits of dry-cured hams. In fact, SW and BCKF are frequently regulated in PDO products as they are traditionally considered early indicators of the seasoning quality. This agrees with studies that evidenced that SW and BCKF affect the quality of dry-cured hams (Bosi and Russo, 2004; Čandek-Potokar and Škrlep, 2012; Rodríguez-Sánchez et al., 2014). In the past years, Italian PDO dry-cured ham specifications required moderate growth rates, with a target weight of 160 ± 16 kg of SW at 9 months of age. To comply these specifications the rate of growth must be maintained low, so the pigs must be fed restrictively. However, a very recent revision of these specifications (European Commision EC, 2022) increased the range of carcass weights (110 to 168 kg, corresponding to approximately 134 to 205 kg of SW) at 9 months of slaughter age. Thus, a much greater growing rate is permitted. This suggests the possibility to move toward a voluntary feed allowance to increase both SW and BCKF, but the impact of this strategy on the processing losses and the quality of the seasoned ham is unknown. Recent research suggested that a voluntary feeding practice can yield pigs weighing up to 200 kg SW at 9 months of age without compromising feed efficiency, compared to the 160–170 kg SW achievable at the same age with the traditional restricted feeding one (Malgwi et al., 2021). The introduction of ad libitum feeding strategies would increase the heterogeneity of the carcass and the green ham (Gallo et al., 2014). However, this would also complicate curing procedures due to the necessity to treat hams of varying sizes differently (Rodríguez-Sánchez et al., 2014; Toscano et al., 2023).

**Table 1**
Impact of slaughter weight, backfat depth, and sex on ham weight losses at different processing stage.

| | Slaughter weight class, kg | | | | | Sex | | | | Backfat depth, mm | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | light | medium | heavy | SEM | F-value[11] | Gilts | Barrows | SEM | F-Value[11] | slope | SE | F-Value[11] |
| Ham weights, kg: | | | | | | | | | | | | |
| – raw | 15.91 | 17.15 | 18.36 | 0.16 | 177.7** | 17.14 | 17.15 | 0.15 | 0.01 | 0.0665 | 0.0139 | 22.8** |
| – trimmed | 12.36 | 13.26 | 14.22 | 0.10 | 175.4** | 13.30 | 13.26 | 0.09 | 0.21 | 0.0150 | 0.0106 | 2.0 |
| – 7 days out of salting | 11.70 | 12.59 | 13.53 | 0.08 | 181.3** | 12.62 | 12.59 | 0.07 | 0.19 | 0.0232 | 0.0100 | 5.3* |
| – seasoned | 8.70 | 9.42 | 10.21 | 0.08 | 165.6** | 9.45 | 9.44 | 0.07 | 0.10 | 0.0327 | 0.0088 | 13.8** |
| – deboned | 6.48 | 7.04 | 7.67 | 0.10 | 131.4** | 7.10 | 7.03 | 0.10 | 2.23 | 0.0295 | 0.0078 | 14.3** |
| Fat cover depth, mm [1] | | | | | | | | | | | | |
| – at P1 | 22.06 | 22.09 | 23.16 | 1.82 | 1.09 | 22.09 | 22.79 | 1.80 | 1.33 | 0.5506 | 0.0916 | 36.1** |
| – at P2 | 6.51 | 6.53 | 6.87 | 0.17 | 3.82* | 6.67 | 6.75 | 0.16 | 0.70 | 0.0207 | 0.0145 | 2.03 |
| Absolute ham weight losses, kg | | | | | | | | | | | | |
| – trimming | 3.55 | 3.88 | 4.17 | 0.07 | 62.1** | 3.85 | 3.88 | 0.07 | 0.91 | 0.0517 | 0.0060 | 74.3** |
| – curing | 3.66 | 3.84 | 4.00 | 0.06 | 46.1** | 3.85 | 3.82 | 0.06 | 0.84 | −0.0166 | 0.0040 | 17.6** |
| – salting | 0.66 | 0.67 | 0.70 | 0.04 | 4.4* | 0.68 | 0.67 | 0.04 | 0.33 | −0.0071 | 0.0013 | 29.9** |
| – after salting | 2.99 | 3.17 | 3.31 | 0.03 | 56.9** | 3.17 | 3.15 | 0.03 | 0.87 | −0.0091 | 0.0032 | 8.35* |
| – deboning | 2.22 | 2.38 | 2.55 | 0.04 | 69.7** | 2.35 | 2.41 | 0.04 | 10.3** | 0.0032 | 0.0044 | 1.2 |
| – total | 9.42 | 10.11 | 10.71 | 0.11 | 127.7** | 10.02 | 10.10 | 0.10 | 1.87 | 0.0377 | 0.0087 | 18.8** |
| Relative ham weight losses, % | | | | | | | | | | | | |
| – trimming [2] | 22.16 | 22.63 | 22.61 | 0.26 | 2.8 | 22.35 | 22.58 | 0.24 | 1.8 | 0.2139 | 0.0255 | 70.5** |
| – curing [3] | 29.68 | 28.99 | 28.23 | 0.35 | 19.9** | 29.02 | 28.92 | 0.34 | 0.5 | −0.1642 | 0.0247 | 44.2** |
| – salting [4] | 5.38 | 5.04 | 4.92 | 0.24 | 17.1** | 5.13 | 5.11 | 0.24 | 0.11 | −0.0600 | 0.0092 | 42.6** |
| – after salting [5] | 25.71 | 25.24 | 24.50 | 0.28 | 17.8** | 25.20 | 25.10 | 0.26 | 0.5 | −0.1218 | 0.0219 | 31.0** |
| – deboning [6] | 25.68 | 25.36 | 24.89 | 0.53 | 4.6* | 24.95 | 25.35 | 0.53 | 14.3** | −0.0580 | 0.0281 | 4.25* |
| – total from raw ham [7] | 59.32 | 59.00 | 58.28 | 0.38 | 10.0** | 58.64 | 59.10 | 0.36 | 7.2** | −0.0166 | 0.0255 | 0.42 |
| – total from trimmed ham [8] | 47.71 | 47.00 | 46.08 | 0.60 | 19.6** | 46.71 | 47.71 | 0.59 | 5.5* | −0.1630 | 0.0281 | 33.7** |
| Rate of dehydration, g/d | | | | | | | | | | | | |
| – salting [9] | 34.6 | 34.5 | 34.9 | 1.85 | 0.3 | 34.78 | 34.45 | 1.84 | 0.32 | −0.3817 | 0.0643 | 35.3** |
| – after salting [10] | 5.14 | 5.44 | 5.69 | 0.16 | 57.6** | 5.44 | 5.44 | 0.16 | 0.72 | −0.0152 | 0.0055 | 7.51** |

[1] P1: ham subcutaneous fat depth measured on the lateral face of the thigh, at the level of the head of the femur between *biceps femoris* and the *quadriceps* muscle; P2: ham subcutaneous fat depth measured on the medial face of the thigh, in correspondence with the *semimembranosus* muscle
[2] Computed as: [(Raw ham, kg – Ham trimmed at ham factory, kg)/Raw ham, kg] × 100
[3] Computed as: [(Ham trimmed at ham factory, kg – Seasoned ham, kg)/ Ham trimmed at ham factory, kg] × 100
[4] Computed as: [(Ham trimmed at ham factory, kg – Ham 7 d out of salting, kg)/ Ham trimmed at ham factory, kg] × 100
[5] Computed as: [(Ham 7 d out of salting, kg – Seasoned ham, kg)/ Ham trimmed at ham factory, kg] × 100
[6] Computed as: [(Seasoned ham, kg – Deboned ham, kg)/ Deboned ham, kg] × 100
[7] Computed as: [(Raw ham, kg – Deboned ham, kg)/ Raw ham, kg] × 100
[8] Computed as: [(Ham trimmed at ham factory, kg, kg – Deboned ham, kg)/Ham trimmed at ham factory, kg] × 100
[9] Computed as: [(Ham trimmed at ham factory, kg – Ham 7 d out of salting, kg)/salting duration, d] × 1000
[10] Computed as: [(Seasoned ham, kg – Ham 7 d out of salting, kg)/resting + seasoning duration, d] × 1000
[11] ** $P < 0.01$; * $P < 0.05$

**Table 2**
Impact of slaughter weight, backfat depth, and sex on the technological quality traits of dry-cured hams.

| | Slaughter weight class, kg | | | | | Sex | | | | Backfat depth, mm | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | light | medium | heavy | SEM | F-value[11] | Gilts | Barrows | SEM | F-Value[11] | Slope | SE | F-Value[11] |
| Round shape [1] | 1.75 | 1.85 | 1.92 | 0.20 | 3.10* | 1.83 | 1.85 | 0.20 | 0.14 | 0.0039 | 0.0076 | 0.27 |
| Inner lean firmness [2] | 4.32 | 4.24 | 4.05 | 0.18 | 4.44* | 4.19 | 4.21 | 0.18 | <0.10 | −0.0083 | 0.0102 | 0.66 |
| Fibula puncture firmness[3] | 3.51 | 3.39 | 3.25 | 0.21 | 4.00* | 3.42 | 3.35 | 0.21 | 1.20 | −0.0328 | 0.0101 | 10.60** |
| Lean color [4] | 2.68 | 2.50 | 2.54 | 0.20 | 1.93 | 2.57 | 2.57 | 0.20 | <0.10 | −0.0116 | 0.0114 | 1.04 |
| Muscle displacement [5] | 1.55 | 1.55 | 1.62 | 0.18 | 0.45 | 1.64 | 1.50 | 0.18 | 6.10* | −0.0006 | 0.0088 | <0.10 |
| Fat vein size [6] | 2.07 | 2.30 | 2.40 | 0.12 | 10.49** | 2.17 | 2.34 | 0.11 | 9.06** | 0.0234 | 0.0082 | 8.06** |
| Fat cover depth [7] | 2.64 | 2.74 | 3.19 | 0.19 | 22.06** | 2.83 | 2.88 | 0.18 | 0.52 | 0.0890 | 0.0093 | 90.82** |
| Fat cover firmness [8] | 1.98 | 2.03 | 2.12 | 0.15 | 1.76 | 1.96 | 2.12 | 0.15 | 9.62** | −0.0062 | 0.0080 | 0.60 |
| Fat cover color [9] | 1.76 | 1.91 | 1.87 | 0.09 | 2.03 | 1.83 | 1.86 | 0.09 | 0.20 | −0.0308 | 0.0091 | 11.45** |
| Visible marbling [10] | 2.75 | 2.76 | 2.73 | 0.08 | <0.10 | 2.77 | 2.73 | 0.09 | 0.22 | 0.0269 | 0.0121 | 4.93* |

[1] Round shape (1 = flat, …, 3 = round)
[2] Inner lean firmness (1 = soft, …, 5 = hard)
[3] Fibula puncture firmness (1 = soft, …, 5 = hard)
[4] Lean color score (1 = pale, …, 5 = dark);
[5] Muscle displacement (1 = absent, …, 3 = great)
[6] *Fat vein* size (1 = thin, …, 3 = large), fat area located along the border of the *semimembranosus* muscle with *quadriceps* muscle (in particular with the vastus longus muscle comprising the parameral portion above and that of the *biceps femoris* muscle below)
[7] Fat cover depth (1 = thin, …, 5 = thick)
[8] Fat cover firmness (1 = soft, …, 3 = hard)
[9] Fat cover color (1 = white, …, 3 = yellow)
[10] Visible marbling (1 = absent, …, 5 = abundant)
[11] ** $P < 0.01$; * $P < 0.05$

### 4.1. Influence of SW and BCKF on ham weight and adiposity

Several authors reported that increasing pig age and weight led to increased ham weight and adiposity, both favorably supporting lower curing losses and enhanced dry-cured ham quality (Bosi and Russo, 2004; Čandek-Potokar and Skrlep 2012). Rodriguez-Sánchez et al. (2014) found a higher rate of increase in trimmed and seasoned ham weight, in the order of 1.28 and 1.15 kg/kg SW, in 120–140 kg-pigs used for Teruel dry-cured ham production. Additionally, Peloso et al. (2010) reported that the trimmed ham weight increased from 0.68 to 0.86 kg for each 10-kg increase in SW in pigs of different genotypes slaughtered at 140 and 160 kg SW, respectively. However, Lo Fiego et al. (2005) found that for every 10-kg increase in SW, trimmed ham weight increased by 0.61 kg in Italian heavy pigs used for Parma ham production, under slaughtering and curing conditions similar to those used in the current research. These differences may be due to anatomical differences between pig genotypes and/or differences in SW, which may affect the growth curves of different body regions of the pigs, as well as a reflection of the differences in technological procedures applied across the different production systems.

Slaughter weight had a modest influence on the fat cover depth of the ham, which was strongly influenced by BCKF, particularly at the P1 position. The slope of the regression relating BCKF to the P1 fat cover depth was 0.55 mm for each mm increase in BCKF. This result was consistent with those of Cecchinato et al. (2013) who found that the BCKF was phenotypically correlated to the fat cover depth both in P1 ($r = 0.53$) and P2 ($r = 0.18$) positions in offspring of C21 Goland sire pig line mated with Large white derived sow. Thus, these results suggest that an increase in the fat covering at the P1 position does not directly depend on the SW, but on the fatness status of the pig.

Overall losses, due to the trimming, curing and deboning, averaged 58.8 % of the initial raw ham weight, but the range of variation was large. We found that the total losses decreased linearly by 0.67 % for each 10-kg increase in SW and by 0.17 % for each mm increase in BCKF.

Improvements in the pig BCKF could be achieved by adopting specific feeding plans with adequate energy: protein ratios (Kyriazakis and Whittemore, 2006). The observed trends in the current experiment suggest that the incidence of curing and deboning losses decreases with increasing SW and BCKF, while the incidence of trimming losses remains constant. Overall, the results of the current research suggest that an increase in SW and BCKF would cause remarkable modification of the size and adiposity of the trimmed ham, with possible impacts on its seasoning aptitudes. Moreover, a lower incidence of losses would be appreciated by the operators because these represent a loss of saleable (economic) material. Accordingly, this necessitates adaptation of the conventional procedure applied in the dry-curing process with increasing SW and BCKF.

### 4.2. Trimming losses

Trimming is a common procedure performed on green hams stored at 4° C for 24 h post-slaughter. Although trimming is required to give hams their distinctive shape before arriving at the ham factory, a second milder trimming is carried out in accordance with the local specifications. Losses due to trimming are significant and lead to a reduction of ham product, although the trimmings are used to prepare other food specialties. These losses vary depending on how much of the ham's lean and fat tissues have to be removed. In the current study, trimming losses averaged 3.87 kg (22.5 %) of the weight of the raw ham. Interestingly, SW had no influence on the relative trimming losses. Depending on the pigs' genotype, a trimming loss of 14.7 to 16.2 %, with no significant association with SW, has been reported by Lo Fiego et al. (2005) for hams originated by pigs slaughtered at 130 to 160 kg BW. Differently, Čandek-Potokar and Skrlep (2011) reported a value of 26.9 %, significantly influenced by the production management practices, and increased with increasing raw ham weight. Gallo et al. (1994) reported an average dressing loss of 2.71 kg at slaughter, corresponding to a relative trimming loss of about 28 %, in hams produced by pigs of different genetic type.

To our knowledge, there is no existing information in the literature about the influence of the BCKF on these losses. In the current research, we observed an increase in the trimming losses with increasing pig's fatness status both in absolute and in relative terms. Consequently, the positive effect exerted by BCKF on the raw ham weight was not observed on the trimmed ham weight, regardless of differences in BCKF. This suggests that the increased body fatness of the pig, which is partially reflected in increased ham fat covering, would require a more extensive trimming process at the slaughterhouse to remove the excess fat and uncover the portion of the ham's muscles needed for salt absorption in the first step of ham processing.

### 4.3. Curing losses

The main steps of the dry-curing process for Italian PDO dry-cured hams are the addition of NaCl salt and the regulation of the ambient temperature and humidity. The NaCl salt serves as a preservative by preventing microbial growth while facilitating tissue dehydration (Davidson et al., 2012). After the salting exposure, the tissues continue to become dehydrated during the resting and seasoning phases as a result of controlled ambient temperature and humidity. Along with these environmental factors and the duration of the treatments, the ham size, skin and fat covering depths also affect the dynamics of dehydration (Zappaterra et al., 2021). In the production of dry-cured ham, curing losses are crucial because they also determine the ham's water content, which affects the activity of proteolytic and lipolytic enzymes as well as sensory qualities like saltiness and texture. They also have an economic impact because they result in the loss of sellable material (Čandek-Potokar and Škrlep, 2012; Bonfatti and Carnier, 2020). Fatter hams are expected to have a lower salt content, because of the inverse relationship between fat thickness, seasoning losses and salt content (Čandek-Potokar et al., 2002; Carcò et al., 2019).

According to local tradition and regulations, the curing losses may vary substantially. In Teruel ham, after 19 months of processing, the relative weight losses were 5.32–5.88 % in the salting phase and 32.6–34.8 % at the end of the seasoning (Perez-Ciria et al., 2023). Bonfatti and Carnier (2020) reported curing losses ranging from 21.6 to 38.2 %, with an average of 27.8 %, and rate of weight losses of 21.0 and 6.0 g/d during the first salting and post-salting, respectively. The rate of weight loss was greater during salting, with an average loss of 34.6 g/day, and lower in the post-salting period, as the rate of loss decreased to 5.42 g/day in agreement with the findings of previous studies (Gallo et al., 1999; Čandek-Potokar and Škrlep, 2011; Bonfatti and Carnier, 2020). Previously, it was demonstrated that the salting losses are an early index of the total water losses of the entire dry-curing period (Dall'Olio et al., 2020). The rate of weight loss was greater during the salting process due to the osmotic and hygroscopic effects of salt covering the thigh, which facilitated the extraction of water from the inner tissues.

Furthermore, it is generally considered that heavier hams have better seasoning aptitude due to lower curing losses (Bonfatti and Carnier, 2020). However, other studies reported a weak correlation between curing losses and ham weight (Čandek-Potokar and Škrlep, 2012). The same authors reported that a better seasoning aptitude of heavier hams is primarily determined by greater ham adiposity (Čandek-Potokar and Škrlep, 2012). In the current research, both SW and BCKF significantly reduced the relative curing losses. The greater fatness status (BCKF) of the pigs was partially reflected in a greater ham fat covering, which represents a barrier that hinders salt penetration and water extraction from the inner tissues (Pérez-Santaescolástica et al., 2019). However, during salting the rate of weight loss was negatively influenced by BCKF and not by SW, whereas during the post-salting period, the rate of weight loss was reduced by BCKF and increased by SW. This could be explained by the barrier effect explicated by the fat cover depth, that would be effective in a short time, but it could become less relevant over extended periods. This is because water in the inner ham tissues can be transferred by diffusion toward more superficial tissues, less protected by the fat covering, from where dehydration could take place.

### 4.4. Deboning losses

In Italy, at the end of the seasoning period, the dry-cured hams can be marketed either intact with the bone, or they can undergo deboning, compression and subsequent vacuum packaging. However, information in the existing literature about deboning losses of dry-cured hams remains limited. Čandek-Potokar and Skrlep (2011), reported that in Kraški pršut the losses of material due to deboning averaged 26.4 ± 2.4 %. These losses were reduced by an increase in the ham weight, and they were unaffected by variations in the ham fat covering. An earlier study by Gallo et al. (1994) reported about 25.6 % deboning relative losses for pigs of different breeds slaughtered at 144 ± 11 kg. In the current research, the relative deboning losses averaged 25.30 % of the seasoned ham weight and decreased with increasing SW and BCKF. Moreover, the decrease in the relative incidence of the femur with increasing SW compared to that of the entire seasoned ham agrees with the principles of allometric growth which relates body ash to body weight characterized by a coefficient of allometry < 1 (Ruiz-Ascacibar et al., 2019).

### 4.5. Technological traits

The common practice for ham manufacturers is to screen the ham for quality traits upon arrival from the slaughterhouse. Green hams with flaws are rejected. Ham quality is also screened at the end of the process, prior to the application of the official seal on the rind of dry-cured hams. Linear scores for qualities of interest are performed by experienced operators. This check is essential for evaluating the seasoned ham's economic value. Since the product specification does not indicate an official procedure of evaluating hams, each ham factory uses grids based on its specific experience. As such, it is difficult to compare the results achieved in the current research with other data.

The round shape of the ham is a measure of the ham's muscularity. Roundness is commonly related to the use of hams from the lean pig genotype, with insufficient fat covering, excessive curing losses and poor sensory quality of the seasoned hams (Faggion et al., 2023). The ham roundness of the current research fell within the middle ranges of the classification scale, and it was mildly increased by SW, but not by BCKF. The pure Goland C21 pigs of current research cannot be categorized as lean genotypes, as they can exhibit great lipid growth even at heavier weight and good fat covering (Schiavon et al., 2022). The subcutaneous ham fat thickness is included as a selective criterion for the genetic improvement of this line (Bonfatti and Carnier, 2020).

The inner lean firmness represented a global evaluation of the outcome of the seasoning process, including an appreciation of the dry-cured hams' slicing aptitude (Morales et al., 2013). Hams with low lean firmness tend to present a pasty texture and poor slicing aptitude, often coupled with poor sensory quality. The hams of the current research were rather firm, being the average of lean firmness greater than 4 over a scale ranging from 1 to 5 points. SW slightly decreased the inner lean firmness, likely due to an increase in the residual humidity, as we observed a reduction of the relative curing losses with increasing SW.

The horse fibula puncture is practiced to evaluate the sensory quality of the ham and the resistance at the penetration of the ham tissues, avoiding the cutting of the ham. With this olfactometric technique, the piece is punctured, and an expert evaluates the smell and the resistance at penetration. Before the dry-cured hams are branded on fire, they must be compliant with the test of horse fibula. This technique is traditionally applied in various countries (Comi et al., 2014; Martín-Goméz et al., 2019). The horse fibula is the preferred material as it retains the smell of the tissues, and it quickly loses the smell at the following puncture, avoiding cross-contamination between consecutive samplings. There was some consistency between the inner lean firmness and the firmness at the horse fibula puncture. However, the latter also includes the influence of fat covering and marbling. An increased BCKF was found to reduce the resistance at penetration at the fibula puncture, likely because the resistance at penetration can be reduced in the presence of fatty tissues.

Generally, consumers pay special attention to the appearance of dry-cured hams, especially their color and fat content (Guàrdia et al., 2010; Schivazappa and Virgili, 2020). Buyers show a preference for intermediate levels of intramuscular fat, probably because they believe it is an optimal level of fat, considering both nutritional and flavor characteristics (Morales et al., 2013). Thus, the most desired is a uniform pink color, without the presence of different colors in different muscles. Visible marbling is appreciated, however, an excessive fat infiltration in the muscles is considered a defect, and the ham is classified as "grassinato". Our findings suggest that the lean color would be little influenced by an increase in SW and BCKF.

In Italy, dry-cured ham is sliced according to a perpendicular line with respect to the femur. Muscle displacement is an indirect measure of the slicing quality of the ham, and it appears as a slot between muscles due to a lack of intermuscular fat. Such defect can develop during the seasoning because of the shrinkage of the intermuscular fat layer during the seasoning period. Due to this shrinkage, the muscles are displaced, and the slice is no longer as compact as expected for a quality ham. Fat content significantly influences the texture of ham; since fat accumulates within the perimysial connective tissue and disrupts the cohesion between fiber bundles (Ruiz-Carrascal et al., 2000). Consequently, the thicker the fat layer between muscles, the greater the shrinkage of the fat layer and the risk of muscle displacement (Wood et al.,1990). The greater risk of displacement occurs in correspondence with the "fat vein", which is located along the border of the *semimembranosus* muscle with the *quadriceps* muscle. The findings of the present study revealed that neither SW nor BCKF had any impact on muscle displacement, even with the observed increase in fat vein size with higher SW classes. This underlines the lack of correlation between fat vein size and muscle displacement.

The fat cover depth of the ham is one of the most important evaluations performed in the ham factory. As discussed above, the ham cover fat should be thick enough to permit the optimal maturation of the ham (Bosi and Russo, 2004). A sufficient fat covering is necessary to prevent rapid desiccation that would cause the formation of a crust on the ham surface, to reduce the curing losses and excessive salt absorption, and to improve the sensory quality of the ham (Bosi and Russo, 2004). However, excessive fat covering is undesired by the consumer because of health concerns. Thus, the ham industry should find the best compromise between technological quality and market acceptability. It could be also considered that an increased fat deposition in the pig's body, which is partially reflected by an increased ham fat covering, is related to an increased synthesis of saturated lipid, and to an increase of the saturated/unsaturated fatty acid ratio (Kyriazakis and Whittemore, 2006). The subcutaneous fat layer of the Italian high-quality cured hams must be solid, compact, white, and composed of saturated lipids (Lo Fiego et al., 2005; EC, 1992). This is to avoid oxidation and rancidity of the unsaturated lipids that could occur during the very long duration of the curing process. The average fat cover depth of the ham of the current experiment was in the middle of the variation scale. It was found that an increase in SW and BCKF would produce a notable increase in the fat cover depth and that an increase in BCKF would produce a whiter color of the subcutaneous fat. This is consistent with the enhanced synthesis of saturated fat in the pig body that could occur with an increase in the allowance of dietary carbohydrates (NRC, 2012).

Visible intramuscular fat, or marbling, is a meat quality trait included in the breeding programs for Italian heavy pigs run by the Italian Breeder Association (ANAS) (Dall'Olio et al., 2020), in order to reduce the frequency of "grassinatura", a defect due to excessive presence of inter and intra-muscular fat in the hams of Duroc pigs (Bosi and Russo, 2004). Excessive intramuscular fat was also related to excessive softness and pastiness (Gou et al., 1995). However, the presence of intramuscular fat in adequate amounts is desired because of its beneficial influence on juiciness (Ruiz et al., 1998; Storrustløkken et al., 2015), appropriate soft texture (Ruiz-Carrascal et al., 2000), sensory quality and consumer acceptability of dry-cured ham (Muñoz et al., 2015). In the current research, there were pieces of evidence that in the pure C21 Goland pig breed, marbling could increase with increasing BCKF but not with increasing SW. Thus, it could be suggested that greater SW admitted by the revised version of the production specification would produce a modest influence on the marbling level of the pig population intended for the high-quality dry-cured ham production in Italy. However, restriction of the protein allowance below the requirement could be a better strategy to increase marbling in specific circumstances (Wood et al., 2004, Carcò et al., 2019).

## 5. Conclusions

The current manuscript examines the impact of traits measured in vivo on the losses associated with the dry-curing process and on the technological traits of the dry-cured hams. These aspects have been relatively underexplored in previous literature. Overall, our findings suggest that increased SW and BCKF could have beneficial effects on ham characteristics. In turn, this increased SW and BCKF would reduce the losses during curing, would improve the quality of the seasoned ham in terms of fat coverage, fat color, visible marbling, and would reduce hardness at the puncture of the horse fibular bone Furthermore, a 10 kg increase in SW has been associated with an increase by 0.755 kg of the trimmed weight and by 0.538 kg of the seasoned ham, whereas a 10 mm rise in BCKF has been associated with an increase of the weight of the seasoned dry-cured ham of 0.327 kg. From a practical standpoint, the results of the current research indicate that increasing the SW and BCKF is desirable, as a means to reduce the incidence of weight losses and to enhance the quality of dry-cured ham. This increase could be achieved at the farm level by maintaining the same slaughter age while enhancing the energy allowance. This can be accomplished by transitioning from restricted feeding to ad libitum feeding, or alternatively, by increasing the energy density of the diets. Depending on market conditions, such changing have the potential to boost the profitability of operators across the entire supply chain.

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## CRediT authorship contribution statement

**Stefano Schiavon:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Alessandro Toscano:** Writing – review & editing, Software, Methodology, Formal analysis, Data curation. **Diana Giannuzzi:** Writing – review & editing, Validation, Software, Formal analysis, Data curation. **Paolo Carnier:** Writing – review & editing, Resources, Project administration, Funding acquisition. **Sara Faggion:** Writing – review & editing. **Alessio Cecchinato:** Validation, Supervision, Methodology, Investigation, Conceptualization. **Isaac Hyeladi Malgwi:** Writing – review & editing. **Veronika Halas:** Writing – review & editing, Visualization, Validation, Supervision. **Luigi Gallo:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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## Appendix A. Supplementary data

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