

Article

Analysis of Meat Juice Leakage from Refrigerated Culinary Pork, Beef, and Chicken Meat into the Unit Packaging: Estimation of Reference Limits for Distribution and Retail in Poland

Krzysztof Dasiewicz , Mirosław Słowiński , Iwona Szymańska *  and Aneta Cegielka * 

Institute of Food Sciences, Department of Food Technology and Assessment, Warsaw University of Life Sciences—SGGW, Nowoursynowska St. 166, 02-787 Warszawa, Poland; krzysztof_dasiewicz@sggw.edu.pl (K.D.); mirosław_slowinski@sggw.edu.pl (M.S.)

* Correspondence: iwona_szymanska@sggw.edu.pl (I.S.); aneta_cegielka@sggw.edu.pl (A.C.)

Featured Application

The results obtained in this study were used to estimate the levels of meat juice leakage in fresh, chilled culinary meat subjected to vacuum packaging and modified atmosphere packaging, which can then serve as reference values for all participants in the distribution chain to assess the quality of fresh culinary meat during distribution and at retail stages. The work significantly contributes to enhancing the quality standards of fresh meat and boosting consumer confidence in vacuum-packaged and modified atmosphere meat products.



Academic Editors: Małgorzata Karwowska and Justyna Bątkowska

Received: 19 September 2025

Revised: 17 October 2025

Accepted: 21 October 2025

Published: 24 October 2025

Citation: Dasiewicz, K.; Słowiński, M.; Szymańska, I.; Cegielka, A.

Analysis of Meat Juice Leakage from Refrigerated Culinary Pork, Beef, and Chicken Meat into the Unit Packaging: Estimation of Reference Limits for Distribution and Retail in Poland.

Appl. Sci. **2025**, *15*, 11394. <https://doi.org/10.3390/app152111394>

Correction Statement: This article has been republished with a minor change. The change does not affect the scientific content of the article and further details are available within the backmatter of the website version of this article.

Copyright: © 2025 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license

(<https://creativecommons.org/licenses/by/4.0/>).

Abstract

Meat juice leakage is a natural phenomenon, evident in culinary meat packaging, and is a key indicator of meat quality. This study aimed to evaluate the amount of meat juice leakage into the packaging during culinary pork, beef, and chicken storage in a refrigerated display case simulating retail conditions (2–4 °C, 12 days). The study included 1800 high-quality culinary meat samples, i.e., free of technological defects, packaged in vacuum (VAC) and modified atmosphere (MAP), with and without absorbent pads, obtained from meat processing plants. On the 12th day of storage, the leakage was determined in the meat portions using the gravimetric method, and pH and color (CIEL*a*b*) were measured using instrumental methods. It was found that the leakage level from culinary meat ranged from 2.10% for pork shoulder VAC to 10.70% for pork loin VAC, in slices, being influenced ($p < 0.01$) by each grouping factor: meat type, meat cut, and package type. Regardless of the packaging method, culinary chicken meat had a lower pH ($p < 0.001$) than pork and beef. The study also found significant negative correlations between pH and leakage in most culinary meat cuts, as shown by the results for ham VAC ($r = -0.66$), ham MAP ($r = -0.59$), and heel of round MAP ($r = -0.50$). Among meat color parameters, the most significant variability was observed for lightness (L^*), whose mean value differed significantly depending on the type of meat ($p < 0.001$) and the meat cut ($p < 0.001$), and within the same culinary cut—except beef tenderloin and chicken breast fillet—also depending on the type of packaging ($p < 0.05$). Based on the results obtained in this study, covering a large number of culinary meat samples, it was suggested that recommended leakage levels, i.e., those that raise no concerns regarding meat quality, could range from 2% for shoulder and pork neck (both VAC) to just over 10% for tenderloin slices (packaged using the MAP and VAC methods). Our findings can be used by both meat producers and quality control authorities to monitor the quality of culinary meat, e.g., they may help determine maximum permissible leakage levels and design meat packaging methods to reduce leakage. Ultimately, these measures will enhance consumer confidence in meat

production and quality. Additionally, the results systematize knowledge on meat leakage, providing valuable insights for scientists who support producers and retailers in their efforts to minimize this issue.

Keywords: meat quality; refrigerated storage; pork; beef; chicken; vacuum packaging; modified atmosphere; meat juice leakage

1. Introduction

Meat juice leakage is a key factor in evaluating meat's technological, processing, and culinary quality. Although a natural occurrence, the leakage of meat juice has significant technological, sensory, and economic effects on meat-cutting plants and influences consumers' perception of culinary meat quality. The literature defines meat juice leakage as "the natural process of water loss from meat under the influence of gravitational forces or technological factors." Consequently, it can take various forms, such as natural loss of meat juice from a portion of meat (often referred to as drip loss), leakage during storage—particularly in packaged meat—and fluid loss during processing, including thawing or thermal treatment [1–3]. Although meat juice leakage remains of interest to food technologists and food quality control authorities, a universally accepted definition of the term has not yet been established or adopted.

For consumers purchasing culinary meat, juice leakage, particularly in individually packaged portions, is frequently viewed negatively and may be erroneously linked to spoilage [4–6]. This juice leakage, also referred to as natural exudate, is a physiological phenomenon that occurs during meat storage. While it is a natural process, the degree of juice leakage can considerably impact consumers' perceptions of the quality of the product.

Lisiak et al. [7] emphasize that a significant amount of liquid in meat packaging can lead consumers to perceive the product as less fresh, lower in quality, or potentially improperly stored. As a result, meat juice leakage is considered undesirable in commercial practices. While it poses no microbiological risk, it may negatively impact the product's visual appeal and influence consumer purchasing decisions. For consumers, the aesthetics of packaging and the perceived freshness of a product play vital roles in its acceptance. The presence of visible moisture inside the package is frequently viewed as a flaw, leading to a "wet" appearance that is less appealing. This perception not only diminishes the sensory evaluation of the meat but also decreases the net weight of the product. Consequently, from the consumer's viewpoint, this translates to receiving less actual product for the same price.

To address this issue, meat producers frequently use absorbent pads in their packaging to bind the "unsightly" leakage and make it invisible. It is important to understand that consumer attitudes toward the leakage of meat juice may stem from a lack of awareness that it is a natural occurrence. This phenomenon is influenced by muscle tissue composition, its histological structure, and the changes it undergoes after slaughter as it transforms into meat [8,9].

Water constitutes the primary component of meat, comprising more than 75% of its weight in lean cuts. In animal carcasses, water is primarily located in muscle tissue, resulting in fatty meat having significantly less water than lean meat [10,11]. Water exists in various forms within muscle tissue, categorized as bound, immobilised, and free. Water binding primarily occurs through interactions between water molecules and proteins in myofibrils and connective tissue. Structured water is chemically attached within the internal structure of proteins and is associated with polar and ionised groups on protein surfaces,

forming monomolecular layers. Some bound water consists of water molecules combined with those in monomolecular layers, creating additional ordered layers. Sarcoplasmic proteins bind only a small fraction of water compared to myofibril proteins. Bound water accounts for about 5% of the total water content in meat and cannot be removed by gravity or mechanical pressure [12,13]. However, the water bound to proteins through hydration can be released when proteins undergo denaturation due to lowered pH levels or exposure to high temperatures [14,15]. The amount of bound water remains relatively constant during rigor mortis's onset and refrigerated meat's subsequent maturation [15].

Approximately 95% of the water found in muscle tissue is classified as free water. It occurs as loosely bound molecules distributed within intracellular capillary spaces—primarily between myofibrils and in the intercellular regions of the muscle [9,11,12]. These spaces, where water accumulates, are located between myosin and actin filaments, among adjacent myofibrils, and between myofibrils and the sarcolemma (cell membrane). The dimensions of these capillary spaces are not constant; they vary depending on pH, sarcomere length, ionic strength, and the rigor mortis and meat maturation stage. Consequently, the volume of these spaces can change up to threefold, affecting the amount of water retained within the muscle structure [2,15]. Because the capillary forces are relatively weak, they cannot hold water in the tissue, facilitating its loss during meat storage and processing [14,15].

The water retention capacity of capillary systems in muscle tissue decreases after an animal is slaughtered due to changes that occur during the conversion of muscle to meat, including rigor mortis and maturation. As the structure of the muscle changes and pH levels decrease in the post-mortem period, some of the retained water is lost from the meat as leakage [11,16,17]. Consequently, interrelated factors such as the amount of free drip during meat storage and the water-holding capacity of the meat are crucial in evaluating this raw material's technological and culinary suitability [18]. To ensure that culinary meat remains juicy, technologists must focus on retaining as much water as possible in a bound form [18–20].

Consumers still appreciate culinary meat that is sold in pieces or slices. Globally, including in Poland, portions of culinary meat are increasingly available through a self-service system rather than being prepared by a seller at a retail outlet. This shift has led to a growing popularity of individual packaging, which enhances meat safety and streamlines the distribution process. Currently, the most commonly used options for packaging raw chilled culinary meat are vacuum packaging (VAC) and modified atmosphere packaging (MAP) [4,21–24]. It is important to note that the exudate released from meat is not merely water, but rather a complex solution composed of both organic compounds—such as myoglobin, hemoglobin, peptides, free amino acids, nucleotides, creatine, and trace amounts of lipids—as well as inorganic constituents, including sodium, potassium, calcium, and phosphate ions. This composition indicates the natural components found in muscle cell fluid and influences the physicochemical properties of the exudate. Consequently, the meat juice not only impacts the nutritional value and sensory qualities of the meat but also serves as a key indicator of its technological quality and commercial viability [9,25,26]. The presence of leakage in the packaging not only negatively impacts consumer perception of culinary meat and meat's nutritional value but can also decrease the meat's shelf life, as the liquid provides a conducive environment for microbial growth. From the perspective of meat producers, the leakage of meat juice leads to economic losses, with mass reductions in raw meat during trade potentially reaching several percentage points [27]. Consequently, this leakage phenomenon is both a qualitative and technological challenge and a significant economic issue [28]. While the leakage of meat juice is a natural phenomenon and cannot be eliminated, its volume can be minimised through proper handling of raw chilled meat—

such as addressing quality issues like PSE (Pale, Soft, Exudative) or acidic meat—and by optimising the cooling, packaging, and storage conditions of culinary meat [19,29–31].

The leakage of meat juice into the package is a significant concern for regulatory authorities, which often do not include the weight of this leakage in the total weight of the meat portion. This practice can lead to accusations against producers for inaccurately declaring the net weight of the meat on packaging and misleading consumers, as shown in one of the judgments of the administrative court in Poland [32]. However, establishing a precise “maximum permissible” amount of meat leakage is challenging due to the various factors influencing it. According to Lisiak et al. [7], the findings from drip loss measurements conducted by multiple researchers on domestic (Polish) pig populations—encompassing different breeds and crossbreeds, as well as animals receiving feed additives that alter the fatty acid composition of their lipids—reveal significant variability in this parameter. The studies typically involved groups of several dozen animals, with drip loss analyzed in muscles corresponding to the primary carcass cuts: the loin (*m. longissimus dorsi*), ham (*m. biceps femoris*), and shoulder (*m. triceps brachii*). The highest drip loss was observed in pigs of the line 990 containing Pietrain genetics (7.70%), and in crossbreeds (Landrace × Yorkshire) × (Duroc × Pietrain), showing values of 7.66%. Relatively high drip loss values were also recorded for Landrace × Yorkshire (7.03%), Landrace × Duroc (6.59%), and Landrace (6.99%) pigs, whose parental material originated from Danish imports. These findings indicate that crossbreeds involving Pietrain and Landrace breeds tend to produce meat with the highest drip loss, suggesting a lower water-holding capacity of their muscle tissue. It is important to note that the calculated maximum and minimum values for the loin pertain to test samples weighing approximately 100–150 g and are based on observations made 48 h post-mortem, which is the standard methodology employed in scientific studies. However, variations in muscle exudate can occur from the same piece of meat if the observation period is extended, the packaging method is altered, or a larger muscle portion is analyzed. These factors significantly influence both the rate and extent of water loss.

Nevertheless, it is important to attempt to estimate the average amounts of meat juice leakage for culinary meat from different animal and poultry species, as this serves the interests of producers, consumers, and quality control authorities alike. Therefore, this study aims to determine the amount of meat juice leakage that occurs in the packaging of culinary meat—specifically pork, beef, and chicken—under optimal conditions. The meat samples, free of technological defects, were packaged in vacuum (VAC) and modified atmosphere (MAP) and stored in a refrigerated display case at 2–4 °C. This setup mimicked retail conditions for 12 days, until the last day of the meat shelf life as declared by the producers. Additionally, the study should estimate the acceptable limits of such leakage for the most popular culinary meat cuts from the aforementioned animal species in Poland.

2. Materials and Methods

2.1. Obtaining, Preparing, and Packaging of Meat Samples

The study material consisted of culinary pork, beef, and chicken meat, which are the most popular among Polish consumers. The meat was obtained directly from meat processing plants that handle the cutting of animal and chicken carcasses, as well as the packaging and distribution of both culinary meat and meat intended for further processing. In accordance with good manufacturing practice, meat cuts intended for culinary use were carefully selected at the processing plants, eliminating raw materials exhibiting quality defects. Therefore, the test samples were culinary meat cuts without quality deviations.

The culinary meat samples were packaged using a MAP and VAC system. Half of the meat samples in both packaging systems were packaged with a pad to absorb meat juice

leakage (absorption pad), while the other half were packaged without an absorbent pad. In the case of the MAP system, meat cuts were placed in rigid polyethylene terephthalate (PET) containers, which were filled with the gas mixture (80% oxygen and 20% carbon dioxide) and sealed using a packaging machine, Multivac (Multivac Ltd., Natalin, Poland) or ULMA (ULMA Packaging GmbH, Memmingen, Germany), depending on the production plant. For VAC packaging, culinary meat portions were inserted into polyamide/polyethylene (PA/PE) bags and sealed with the previously mentioned packaging machines.

The pork cuts were sourced from three industrial plants with different production scales. The research material included samples of culinary portions weighing 300–400 g from the following parts: ham, loin, shoulder, neck, and ham (*semimembranosus* muscle) from pigs raised in an organic system. The loin was prepared both as a whole portion and as slices. The total number of pork samples was 1080 (3 meat processing plants $\times$ 4 packaging systems $\times$ 5 culinary cuts $\times$ 15 samples = 900 tested samples and 1 organic meat processing plant $\times$ 4 packaging systems $\times$ 1 cut $\times$ 45 samples).

Beef portions were collected from the culinary cuts of round and beef rump at three meat processing plants, which varied in production volume. Each portion weighed between 300 g and 400 g, similar to pork. A total of 360 beef samples were tested (3 meat processing plants $\times$ 4 packaging systems $\times$ 2 elements $\times$ 15 samples). For chicken meat, the research material consisted of breast muscles (chicken breast fillet and tenderloin) collected from three slaughter plants using spray-air chilling. From each plant, sixty fillets and sixty tenderloins were collected (20 from three different poultry farmers), resulting in a total of 120 poultry meat samples.

The packaged meat samples were transported to the research laboratory under refrigerated conditions (2–4 °C). Upon arrival, the samples were immediately, i.e., without breaking the cold chain, placed in a refrigerated cabinet equipped with self-closing glass doors, LED lighting, six shelves, an internal refrigeration unit, and temperature monitoring (IGLOO, Stary Wiśnicz, Poland). While storing the packaged meat portions in the cabinet, the temperature was maintained at 2–4 °C, and lighting was regulated to simulate the display of meat in a refrigerated retail case. All culinary meat samples were analyzed on the last day of refrigerated storage, which is considered the most critical day for consumer assessment of meat quality.

2.2. Methods

2.2.1. Measurement of Proximate Chemical Composition

The chemical compositions of pork, beef, and chicken culinary meat were determined according to the PN-A-82109 standard [33] using a near-infrared transmission (NIT) spectrometry method with the artificial neural networks (ANN) calibration. The FoodScan™ 2 device from Foss Analytical A/S (Hillerød, Denmark) was used. Each meat sample was ground twice in a meat grinder (Diana 886.8, Zelmer, Rzeszów, Poland) using a 2 mm mesh. The ground and thoroughly mixed samples (about 200 g) were placed in the glass cuvette and subjected to measurement in the apparatus chamber. The total water, fat, protein, and collagen contents (in %) were determined [34]. The measurements were taken twice for each meat variant, and the average values were used as the final results.

2.2.2. Determination of Meat Juice Leakage

Meat juice leakage into the packaging was determined by a gravimetric method [35], using an AG4000C AXIS AG laboratory scale (AXIS Ltd., Gdańsk, Poland) equipped with a mechanical calibration system with an internal weight, ensuring measurement accuracy during operation. First, the package containing the meat was weighed, then opened, and a portion of the meat was removed. The empty package was dried with a paper towel

and weighed again. For packages with an absorbent pad, the pad was removed, gently dried with a paper towel, and weighed along with the package. Meat juice leakage was calculated as a percentage of the mass using the following formula:

$$Leakage = 100 - \left[\frac{M_2 - T}{M_1} \times 100 \right] \%, \quad (1)$$

where M_1 is the weight of the meat before packaging [g], M_2 is the gross weight (package with product) [g], and T is the tare weight (the weight of the packaging after removing any pieces of meat, and in the case of packages with an insert, after gently draining it) [g].

2.2.3. Measurement of pH Value

The pH of the meat portions was measured according to the ISO 2917 standard [36]. A TESTO 206-pH2 device (Testo SE & Co. KGaA, Titisee-Neustadt, Germany) equipped with a combined glass-calomel electrode and temperature compensation. The electrode and temperature sensor were inserted directly into the meat tissue [37], and the pH value was recorded once the measurement on the display stabilised (after about 2 min). The measurement was taken at three places in the sample, and the final result was averaged.

2.2.4. Measurement of Color Parameters

The meat color parameters were measured in the CIEL*a*b* color space using a CR-400 colorimeter (Konica Minolta, Tokyo, Japan). A 2° standard observer and D65 illumination were employed. Before measurements, the instrument was calibrated against the white standard ($Y = 84.2$, $x = 0.3202$, $y = 0.3373$). The measurements were taken on the cross-sectional surface of the meat samples immediately after removal from the packaging. The following color parameters were determined: $+L^*$ (lightness), $\pm a^*$ (redness/greenness), and $\pm b^*$ (yellowness/blueness) [38]. The measurement was performed in each sample at four different points, and the results for the color parameters L^* , a^* , and b^* were averaged.

2.3. Statistical Analyses

The test results for culinary meat samples were calculated (mean, minimum, maximum, median values, and standard deviations) and presented in tables. The collected raw data underwent statistical analysis, employing parametric tests to assess differences between groups: Student's *t*-test was utilized for comparisons between two groups, while one-way analysis of variance (ANOVA) was applied for three or more groups. A significance level of $\alpha = 0.05$ was established, with differences deemed statistically significant when the *p*-value was less than 0.05. Additionally, in the case of the ANOVA test, Tukey's post hoc test was conducted to identify homogeneous groups [39]. Moreover, a Pearson correlation test was performed for variables within the same samples. Correlations were considered statistically significant when the *p*-value < 0.05 . The degree of correlation between two variables was interpreted as follows: $r < \pm 0.20$ —remarkably weak; $\pm 0.20 \leq r < \pm 0.40$ —weak; $\pm 0.40 \leq r < \pm 0.60$ —moderate; $\pm 0.60 \leq r < \pm 0.80$ —strong; $r \geq \pm 0.80$ —remarkably strong (a “+” sign indicates a positive correlation, while a “−” sign indicates a negative correlation) [40]. All the statistical analyses were performed using Statistica™ version 13.3 PL software (StatSoft Inc., Tulsa, OK, USA).

3. Results and Discussion

The meat examined in this study displayed a typical chemical composition for the given species, as detailed in Table 1. On average, beef, poultry, and lean pork (including pork loin and ham) contained 72.98–75.50% water, 21.59–23.36% protein, and 2.07–4.79% fat. In contrast, fatty pork (such as shoulder and neck cuts) had two to three times higher

fat content and comparatively lower protein and water levels than the other meat types analyzed. The collagen content varied by meat type, with the highest levels found in beef, likely due to its origin from older animals. It is important to note that collagen does not affect the amount of meat juice loss during storage, as its water-binding capacity is primarily observed following heat treatment.

Table 1. Proximate chemical composition of different cut types of culinary pork, beef, and chicken meat packaged using the MAP and VAC methods, after 12 days of refrigerated storage (mean value $\pm$ standard deviation).

Cut Type	Water (%)	Fat (%)	Protein (%)	Collagen (%)
Pork				
Ham	74.91 $\pm$ 1.28	3.41 $\pm$ 2.13	21.59 $\pm$ 1.29	0.86 $\pm$ 0.14
Loin in pieces	73.18 $\pm$ 0.99	3.88 $\pm$ 1.19	22.70 $\pm$ 0.72	0.87 $\pm$ 0.09
Loin in slices	72.98 $\pm$ 0.89	3.91 $\pm$ 1.04	22.12 $\pm$ 0.43	0.85 $\pm$ 0.07
Shoulder	70.61 $\pm$ 1.80	10.16 $\pm$ 2.23	19.61 $\pm$ 0.99	1.20 $\pm$ 0.25
Neck	71.52 $\pm$ 1.70	8.66 $\pm$ 2.08	19.15 $\pm$ 0.73	0.98 $\pm$ 0.24
Organic ham	74.17 $\pm$ 0.95	2.60 $\pm$ 0.95	23.36 $\pm$ 0.51	0.90 $\pm$ 0.18
Beef				
Heel of round	75.24 $\pm$ 1.01	2.11 $\pm$ 0.75	22.53 $\pm$ 0.57	1.59 $\pm$ 0.38
Rump	73.41 $\pm$ 1.81	4.79 $\pm$ 1.38	21.05 $\pm$ 1.13	1.73 $\pm$ 0.32
Chicken				
Breast fillet	75.49 $\pm$ 0.82	2.07 $\pm$ 0.24	22.38 $\pm$ 0.85	0.73 $\pm$ 0.12
Breast tenderloin	75.50 $\pm$ 0.75	2.38 $\pm$ 0.42	22.24 $\pm$ 0.89	0.75 $\pm$ 0.33

The results in this study regarding the levels of basic chemical components in beef, pork, and chicken meat align with data cited in the literature. Cobos and Dias [41] report that meat consists of approximately 72–75% water, and that protein is the predominant nutrient, making up 19% of its weight. The average lipid content in meat ranges from 2.5% to 5%. Lipid levels in meat, however, exhibit the most significant fluctuations, varying from 1% to 15%. Concerning differences between meat species, the authors [41] state, based on USDA (United States Department of Agriculture) data, that pork meat contains an average of 72.90% water, 20.48% protein, and 5.41% fat. In contrast, chicken meat contains 75.46% water, 21.39% protein, and 3.08% fat. Our study found a slightly lower fat content in chicken meat, which does not exceed 2.38%. Similar data concerning the proximate chemical composition of meat are presented by Soren and Kumar Biswas [42], emphasising that this raw material's nutrient content varies based on species, age, breed, feed supplementation, and animal weight. According to these authors, 100 g of lean beef contains approximately 75.0 g of water, 22.3 g of protein, and 1.8 g of fat; 100 g of lean pork contains 75.1 g of water, 22.8 g of protein, and 1.2 g of fat; and 100 g of chicken meat contains 75.0 g of water, 22.8 g of protein, and 0.9 g of fat. In our study, poultry meat also exhibited a lower fat content than pork and beef.

According to Ahmad et al. [43], meat is one of the most nutrient-rich foods, fulfilling most of the human body's requirements and thus playing a vital role in maintaining health. Therefore, it should be an essential part of a balanced diet. The authors report that the average water content in meat is slightly over 70%, protein approximately 23%, and fat ranges from 8% to 20%. According to data cited by Devi et al. [3], the average protein and fat contents in beef, pork, and chicken are 30.40 g/100 g and 3.5–9.3 g/100 g, 24 g/100 g and 3.7–10.1 g/100 g, 24.68 g/100 g and 1.1–9.7 g/100 g, respectively.

Mir et al. [20] reported that chicken breast meat (without skin) is characterized by low fat content, i.e., it contains less than 3 g of fat/100 g. In our study, the fat content in

chicken breast fillet was found to be about 2.1%, and in chicken breast tenderloin, about 2.4% (Table 1).

Zduńczyk et al. [37] noted that the rearing system can influence the nutritional value of meat. The authors found that raw pork tenderloin from conventional farming contained 72.22% moisture, 22.70% protein, and 4.95% fat, while pork tenderloin from organic farming contained an average of 3.75% fat, 72.86% moisture, and 22.75% protein. In our study, it was found that, regardless of the packaging system, organic pork ham was characterised by ($p < 0.05$) lower protein content and higher ($p < 0.05$) fat content than conventionally bred pork ham.

3.1. Meat Juice Leakage, pH, and Color Parameters of Refrigerated Culinary Pork Packaged Using the MAP and VAC Methods

The type of culinary cut significantly affected the amount of juice leakage from pork packaged and stored under refrigerated conditions, regardless of whether the packaging was VAC or MAP (Table S2). The lowest leakage was observed in the shoulder (mean 2.10–6.51%) and the neck (mean 2.56–4.98%; Table 2). This can be explained by the relatively lower water content, lower fat content, and higher pH in these cuts (Tables 1 and 2). For lean meat, the average drip was 4.48–6.95% for ham from pigs raised organically, 5.66–8.53% for ham from conventionally raised pigs, and 7.99–10.70% for pork loin. No effect of slicing on the drip was observed for pork loin. As a result of slicing meat, the number of damaged muscle fibres increases, resulting in greater leakage [44].

The low leakage values obtained in this study (Table 2) are satisfactory. According to the literature, leakage in fresh meat packaging is often viewed negatively by consumers, as it is associated with inferior quality products. For producers of meat and meat products, a higher water-holding capacity in meat—linked to reduced leakage—is essential because it signifies better processing and culinary quality. Meat that retains more water is a desirable raw material, enabling the production of items with higher yields and more appealing juiciness [45]. Meat juice leakage, as one of the key quality characteristics of fresh meat, is also mentioned in earlier works on pork [46], beef [26], and chicken meat [20,47].

There is a well-established relationship between the ultimate pH of meat after maturation and the amount of meat juice leakage. Meat with a very high ultimate pH (greater than 6.3) usually has a significant capacity to hold water. In contrast, meat with a very low ultimate pH (between 5.4 and 5.3) tends to experience greater water loss, which is visible as leakage, compared to similar raw material with a normal final pH (between 5.6 and 5.8) [10].

There is limited information in the literature regarding meat juice leakage in culinary meats stored in packaging. A study by Przybylski et al. [46] compared pork's technological and sensory qualities from different quality classes. These authors found that the average drip loss value for all 109 pork samples measured after 48 h was 4.71%. This parameter was slightly lower for pork classified as normal meat, with an average drip loss of 4.58%. In a study on pork meat quality by Filho et al. [48], the average water loss due to leakage was recorded as 3.13% after 24 h and 5.19% after 48 h.

A tendency for increased leakage was noted in meat packaged with absorbent pads. However, it remains challenging to clearly determine how the type of packaging—whether vacuum (VAC) or modified atmosphere (MAP)—affects the amount of leakage (see Tables S3–S8).

According to data presented by Sakowska et al. [4], using different types of packaging for meat intended for retail trade significantly reduces mass losses, particularly storage leakage. In traditional packaging—such as polystyrene trays with polyvinyl chloride overwrap—these losses can exceed 10%. However, when employing vacuum or modified atmosphere packaging (MAP), storage leakage can be reduced by more than 50%. The authors report that the average amount of leakage for pork stored in conventional, vacuum,

and MAP packaging is 8–10% for traditional packaging, 2–5% for vacuum packaging, and 0–7% for MAP.

Table 2. The amount of meat juice leakage [%] into the packaging, pH, and color parameters of pork packaged by the MAP and VAC method, without (–) and with an absorbent pad (+), after 12 days of refrigerated storage (mean value $\pm$ standard deviation (median)).

Cut Type	MAP+	MAP–	VAC+	VAC–
Leakage [%]				
Ham	6.86 $\pm$ 2.52 (2.52)	5.66 $\pm$ 2.04 (5.33)	8.53 $\pm$ 2.14 (8.25)	6.51 $\pm$ 2.41 (6.21)
Loin in pieces	10.42 $\pm$ 1.56 (10.25)	9.11 $\pm$ 1.69 (9.09)	9.02 $\pm$ 1.47 (9.11)	9.14 $\pm$ 6.20 (9.10)
Loin in slices	10.59 $\pm$ 1.97 (10.6)	9.12 $\pm$ 2.91 (8.29)	10.70 $\pm$ 1.58 (10.94)	7.99 $\pm$ 1.64 (7.98)
Shoulder	6.28 $\pm$ 0.25 (6.25)	3.23 $\pm$ 2.19 (2.87)	6.21 $\pm$ 0.13 (6.20)	2.10 $\pm$ 1.29 (1.97)
Neck	4.98 $\pm$ 1.62 (5.00)	3.01 $\pm$ 1.49 (2.87)	2.56 $\pm$ 1.27 (2.39)	2.39 $\pm$ 1.28 (2.16)
Organic ham	6.95 $\pm$ 1.98 (6.99)	4.48 $\pm$ 2.47 (4.52)	6.45 $\pm$ 2.58 (6.53)	5.73 $\pm$ 2.01 (5.73)
pH				
Ham	6.05 $\pm$ 0.14 (6.04)	5.98 $\pm$ 0.26 (6.00)	5.97 $\pm$ 0.20 (5.96)	6.03 $\pm$ 0.18 (6.01)
Loin in pieces	5.94 $\pm$ 0.09 (5.93)	5.88 $\pm$ 0.08 (5.87)	5.91 $\pm$ 0.14 (5.90)	5.88 $\pm$ 0.14 (5.87)
Loin in slices	5.86 $\pm$ 0.15 (5.86)	5.81 $\pm$ 0.22 (5.82)	5.86 $\pm$ 0.15 (5.89)	5.88 $\pm$ 0.12 (5.86)
Shoulder	6.28 $\pm$ 0.25 (6.25)	6.15 $\pm$ 0.14 (6.16)	6.21 $\pm$ 0.13 (6.20)	6.27 $\pm$ 0.22 (6.27)
Neck	6.26 $\pm$ 0.32 (6.16)	6.25 $\pm$ 0.24 (6.21)	6.38 $\pm$ 0.21 (6.37)	6.25 $\pm$ 0.22 (6.23)
Organic ham	5.92 $\pm$ 0.59 (5.94)	6.01 $\pm$ 0.24 (5.89)	6.08 $\pm$ 0.33 (6.05)	5.89 $\pm$ 0.30 (5.85)
L*				
Ham	42.20 $\pm$ 3.77 (42.01)	43.14 $\pm$ 3.85 (43.33)	45.42 $\pm$ 3.00 (45.34)	46.05 $\pm$ 3.15 (46.68)
Loin in pieces	50.91 $\pm$ 3.30 (51.40)	51.91 $\pm$ 2.86 (52.11)	52.67 $\pm$ 2.66 (52.94)	52.94 $\pm$ 2.51 (52.89)
Loin in slices	51.88 $\pm$ 2.77 (51.35)	50.69 $\pm$ 3.68 (50.15)	53.68 $\pm$ 3.72 (53.08)	52.69 $\pm$ 2.77 (52.11)
Shoulder	41.95 $\pm$ 1.66 (41.85)	42.18 $\pm$ 2.20 (41.58)	45.01 $\pm$ 2.82 (44.79)	42.74 $\pm$ 2.34 (42.85)
Neck	40.66 $\pm$ 2.92 (40.68)	41.46 $\pm$ 2.82 (41.45)	42.66 $\pm$ 3.08 (42.41)	43.96 $\pm$ 3.58 (43.97)
Organic ham	43.19 $\pm$ 6.34 (44.71)	40.85 $\pm$ 5.42 (41.75)	42.18 $\pm$ 5.47 (42.69)	42.58 $\pm$ 4.09 (42.72)
a*				
Ham	10.90 $\pm$ 2.93 (10.77)	10.23 $\pm$ 2.16 (10.22)	11.39 $\pm$ 2.93 (11.34)	9.60 $\pm$ 2.38 (9.31)
Loin in pieces	6.03 $\pm$ 1.46 (5.79)	5.94 $\pm$ 1.33 (5.79)	6.12 $\pm$ 1.34 (5.87)	5.60 $\pm$ 1.20 (5.47)
Loin in slices	7.30 $\pm$ 1.51 (7.06)	7.51 $\pm$ 1.91 (6.89)	6.85 $\pm$ 1.34 (6.63)	6.99 $\pm$ 1.33 (6.89)
Shoulder	13.32 $\pm$ 1.61 (13.39)	13.25 $\pm$ 1.71 (13.25)	14.65 $\pm$ 2.05 (14.56)	14.12 $\pm$ 2.23 (14.05)
Neck	14.38 $\pm$ 1.89 (14.55)	14.80 $\pm$ 1.88 (14.54)	15.81 $\pm$ 2.06 (16.10)	15.23 $\pm$ 1.62 (15.10)
Organic ham	10.70 $\pm$ 1.98 (10.61)	10.65 $\pm$ 1.68 (9.93)	10.95 $\pm$ 1.54 (11.06)	10.55 $\pm$ 2.06 (10.54)
b*				
Ham	4.78 $\pm$ 1.00 (4.82)	4.95 $\pm$ 1.37 (4.99)	8.45 $\pm$ 1.27 (8.45)	7.54 $\pm$ 1.46 (7.45)
Loin in pieces	4.59 $\pm$ 0.86 (4.57)	4.99 $\pm$ 0.85 (5.01)	6.80 $\pm$ 0.92 (6.75)	7.05 $\pm$ 1.15 (6.94)
Loin in slices	1.77 $\pm$ 2.86 (3.30)	2.22 $\pm$ 2.78 (3.32)	4.24 $\pm$ 3.17 (5.99)	4.56 $\pm$ 3.16 (5.32)
Shoulder	5.62 $\pm$ 0.93 (5.61)	5.75 $\pm$ 0.72 (5.77)	9.77 $\pm$ 1.50 (10.09)	8.52 $\pm$ 1.70 (8.41)
Neck	5.30 $\pm$ 0.81 (5.42)	6.09 $\pm$ 1.18 (6.06)	9.60 $\pm$ 1.88 (10.08)	9.24 $\pm$ 1.85 (9.45)
Organic ham	5.89 $\pm$ 1.96 (6.11)	5.58 $\pm$ 2.29 (5.83)	5.64 $\pm$ 2.21 (5.64)	6.56 $\pm$ 1.83 (6.48)

Regarding meat pH, no significant differences were found between the packaging types. However, there were notable differences in color brightness (see Tables S3–S8). Meat packaged in MAP exhibited greater color brightness than VAC-packaged meat. This is primarily due to the higher oxygen levels in the MAP, which enhance the formation of oxymyoglobin. Additionally, the carbon dioxide (CO₂) in the packaging atmosphere dissolves in the outer layer of the meat, leading to slight acidification and helping to stabilise the pink color [49].

According to reports by Świdorski and Sakowska [50] and Sakowska et al. [4], the type of packaging used for retail meat influences its color by altering the chemical form of

myoglobin. Fresh meat can contain myoglobin in one of three chemical forms: deoxymyoglobin, oxymyoglobin, or metmyoglobin, which correspond to purple-red, light red, and brown colors, respectively. In packaging with high oxygen concentrations, such as modified atmosphere packaging (MAP), myoglobin oxidises spontaneously to oxymyoglobin, resulting in a light-red appearance in the pork. Conversely, vacuum-packaged meat retains deoxymyoglobin, which presents as a purple-red color on the pork's surface. In modified atmospheres with low oxygen concentrations, myoglobin oxidises to metmyoglobin, giving the meat a grey-brown hue.

Cassens et al. [5] compared the impact of three types of packaging popular in the US market: polyvinyl chloride overwrap (PVC) packaging, carbon monoxide-modified atmosphere packaging, and high-oxygen-modified atmosphere packaging, on the quality of pork chops. The authors demonstrated that although PVC packaging is standard in the retail trade of pork products, the use of MAP ensures a more uniform and stable color of this meat. For L^* and a^* values, there was an interaction ($p < 0.05$) between packaging type and storage time. Pork chops stored in a refrigerated rack for 5 days in MAP packaging had a significantly darker color and higher a^* values than the meat enclosed in PVC packaging.

The correlation analysis (Table S13) revealed a significant negative correlation between the amount of drip and pH for the following products: ham packaged in vacuum (VAC) and modified atmosphere packaging (MAP), loin in pieces packaged in MAP, shoulder packaged in MAP, pork neck packaged in both VAC and MAP, and ham from pigs raised in an organic system and packaged in VAC. Additionally, there was a significant positive correlation between the amount of drip and color brightness for ham and loin in pieces packaged in VAC, shoulder packaged in MAP, and ham from pigs farmed in an organic system packaged in both MAP and VAC.

In summary, the leakage from pork meat primarily depended on the type of cut tested, with the packaging system and absorbent pad having a lesser influence.

3.2. Meat Juice Leakage, pH, and Color Parameters of Refrigerated Culinary Beef Packaged Using the MAP and VAC Methods

The type of beef cut had a significant impact on the amount of meat juice leakage into the packaging, but it did not influence the pH value. Notably, significant differences were observed in the color parameters (see Tables S9–S11). Meat with a lower fat content, such as heel of round, exhibited a higher average leakage of 5.51–8.02%, compared to beef rump, which had an average leakage of 2.61–5.38% (see Table 3).

In general, beef tends to lose proportionately more drip than pork. During chill storage, the rate of drip loss increases with storage temperature, and the amount of drip will increase with storage time. Low storage temperatures will reduce the amount of drip [41].

Beef packaged in a modified atmosphere (MAP) tended to leak less than beef packaged in a vacuum (VAC). For the round, a higher amount of leakage was observed in both types of absorbent-lined packaging, but not in the case of the beef rump (Table 3). According to Lee [51], VAC-packaged meat is significantly more prone to purge loss during storage, with losses nearly double those observed in samples stored in MAP. Łopacka et al. [52] noted a drip loss of approximately 2.6% for beef steaks refrigerated for 12 days. Similarly, Strydom and Hope-Jones [53] reported a purge loss of around 3.4% for VAC-packaged beef loin after 14 days of refrigeration. Furthermore, in the study of Reyes et al. [54], VAC-packaged beef strip loin steaks exhibited about 7.3% purge loss during a simulated retail display.

Correlation analysis (Table S16) revealed a significant negative relationship between the amount of meat juice leakage and pH in the heel of the round packaged in MAP and VAC, as well as in the beef rump packaged in MAP. Wagoner et al. [35] and Younis et al. [55] also observed that a lower pH in beef correlates with an increased purge loss, which can be attributed to the reduced water-holding capacity of the proteins.

Table 3. The amount of meat juice leakage [%] into the packaging, pH, and color parameters of beef packaged by the MAP and VAC method, without (–) and with an absorbent pad (+), after 12 days of refrigerated storage (mean value $\pm$ standard deviation (median)).

Cut Type	MAP+	MAP–	VAC+	VAC–
Leakage [%]				
Heel of round	5.62 $\pm$ 2.41 (5.72)	5.61 $\pm$ 1.96 (5.66)	8.02 $\pm$ 1.46 (8.08)	5.51 $\pm$ 1.79 (6.63)
Rump	4.31 $\pm$ 1.43 (4.15)	2.84 $\pm$ 1.37 (2.61)	5.38 $\pm$ 2.07 (4.96)	2.61 $\pm$ 1.41 (2.24)
pH				
Heel of round	6.09 $\pm$ 0.27 (5.95)	6.00 $\pm$ 0.21 (5.94)	5.97 $\pm$ 0.16 (5.97)	6.02 $\pm$ 0.23 (5.95)
Rump	6.05 $\pm$ 0.21 (6.03)	6.07 $\pm$ 0.22 (6.06)	6.04 $\pm$ 0.16 (6.03)	5.95 $\pm$ 0.18 (5.96)
L*				
Heel of round	37.16 $\pm$ 3.72 (36.43)	37.88 $\pm$ 3.16 (38.15)	35.30 $\pm$ 4.81 (35.76)	34.87 $\pm$ 4.27 (34.19)
Rump	34.84 $\pm$ 3.00 (35.43)	34.76 $\pm$ 3.13 (34.57)	33.87 $\pm$ 3.23 (34.76)	34.04 $\pm$ 3.71 (33.85)
a*				
Heel of round	19.64 $\pm$ 4.20 (20.36)	20.17 $\pm$ 5.65 (20.01)	18.39 $\pm$ 2.43 (17.65)	16.58 $\pm$ 1.60 (16.81)
Rump	21.08 $\pm$ 1.97 (20.63)	22.29 $\pm$ 2.06 (22.57)	17.73 $\pm$ 2.19 (17.44)	19.42 $\pm$ 1.78 (19.01)
b*				
Heel of round	11.51 $\pm$ 1.05 (11.35)	10.84 $\pm$ 1.96 (11.12)	7.26 $\pm$ 2.33 (7.99)	5.72 $\pm$ 1.89 (5.89)
Rump	9.80 $\pm$ 1.04 (9.88)	10.57 $\pm$ 1.36 (10.55)	5.39 $\pm$ 1.38 (5.14)	6.50 $\pm$ 1.32 (6.38)

3.3. Meat Juice Leakage, pH, and Color Parameters of Refrigerated Culinary Chicken Meat Packaged Using the MAP and VAC Methods

The type of chicken cut has a significant impact on the amount of storage leakage, regardless of the packaging used (see Table S12). Chicken fillets exhibit a lower level of leakage, with an average of 4.20–4.36%, compared to deep fillets, which show an average leakage of 5.28–7.61% (refer to Table 4). Both cuts have a similar chemical composition, but the differences in leakage are primarily due to the damage to the muscle surface during the cutting process. The fillet is covered with perimysium, while the deep fillet is obtained by cutting from the sternum and ribs, exposing the muscle fibres and increasing leakage.

Table 4. The amount of meat juice leakage [%] into the packaging, pH, and color parameters of chicken meat packaged by the MAP and VAC method, without (–) and with an absorbent pad (+), after 12 days of refrigerated storage (mean value $\pm$ standard deviation (median)).

Cut Type	MAP+	MAP–	VAC+	VAC–
Leakage [%]				
Breast fillet	4.36 $\pm$ 1.38 (4.06)	4.20 $\pm$ 1.51 (4.31)	5.93 $\pm$ 2.16 (5.92)	4.67 $\pm$ 1.79 (4.14)
Breast tenderloin	6.13 $\pm$ 1.64 (5.91)	5.77 $\pm$ 1.65 (5.35)	7.61 $\pm$ 1.90 (7.42)	5.28 $\pm$ 2.10 (4.93)
pH				
Breast fillet	5.96 $\pm$ 0.25 (5.94)	5.73 $\pm$ 0.20 (5.90)	5.96 $\pm$ 0.20 (5.96)	5.95 $\pm$ 0.16 (5.92)
Breast tenderloin	5.99 $\pm$ 0.11 (5.99)	5.96 $\pm$ 0.18 (6.01)	6.03 $\pm$ 0.12 (6.01)	6.01 $\pm$ 0.09 (6.01)
L*				
Breast fillet	52.34 $\pm$ 2.86 (51.86)	52.25 $\pm$ 2.66 (52.07)	51.35 $\pm$ 2.72 (51.09)	51.44 $\pm$ 2.06 (51.59)
Breast tenderloin	50.36 $\pm$ 1.71 (50.23)	50.01 $\pm$ 1.41 (50.02)	49.44 $\pm$ 1.82 (49.79)	48.23 $\pm$ 1.39 (48.23)
a*				
Breast fillet	2.78 $\pm$ 1.16 (2.89)	3.66 $\pm$ 1.35 (3.83)	3.96 $\pm$ 0.99 (3.97)	1.05 $\pm$ 1.09 (3.87)
Breast tenderloin	2.55 $\pm$ 1.40 (2.76)	2.97 $\pm$ 0.70 (2.98)	3.27 $\pm$ 0.81 (3.17)	3.71 $\pm$ 1.01 (3.23)
b*				
Breast fillet	3.82 $\pm$ 1.72 (3.96)	2.28 $\pm$ 2.29 (2.29)	0.99 $\pm$ 1.63 (0.72)	1.05 $\pm$ 1.35 (0.98)
Breast tenderloin	3.11 $\pm$ 1.40 (2.99)	3.13 $\pm$ 1.14 (3.01)	1.01 $\pm$ 0.84 (1.02)	0.80 $\pm$ 1.55 (0.96)

The type of packaging and the use of an absorbent pad influenced the amount of leakage in both types of chicken meat (see Tables S13 and S14). The highest level of leakage was observed in samples packaged in a vacuum (VAC) that included an absorbent pad.

There was no significant correlation between meat juice leakage and pH levels in chicken meat (Table S17).

According to the results obtained by Kaić et al. [47], the EZ-DripLoss rate in chicken breast meat, measured over five days, varied based on the sample preparation method. For meat samples cut in the vertical fibre direction, with core diameters of 10 mm, 20 mm, and 30 mm, the drip loss after 120 days was recorded at 5.75%, 5.58%, and 9.07%, respectively. In contrast, for samples cut in the horizontal fibre direction, the drip loss for the same core diameters was 5.20%, 4.99%, and 9.12%, respectively.

Chmiel et al. [56] evaluated the changes in quality of chicken breast meat muscles packaged in an atmosphere of normal air (on polystyrene trays wrapped in PVC foil) and in a modified atmosphere with a mixture of gases: 75% O₂ and 25% CO₂. They confirmed that chicken breasts packaged in MAP were characterised by higher quality and longer shelf life compared to PVC-wrapped meat, which was exhibited by slower and less intensive quality changes. Meat in MAP was characterized by greater drip loss compared to meat wrapped in PVC foil; on the 7th day of storage in a display case, the average values were 4.7% and 3.2%, respectively. The pH level of chicken breast meat on the 7th day was similar, measuring 6.0 for meat in MAP and 5.8 for meat in PVC packaging. Regarding color parameters, the type of packaging significantly affected only the L* value. For meat displayed in a case on day 7, the breast muscles of MAP (Modified Atmosphere Packaging) chickens were lighter, with an L* value of 52.5, compared to those in PVC (Polyvinyl Chloride) packaging, which recorded an L* value of 47.8. The a* and b* color parameters were both low for meat in both MAP and PVC packaging, with values of 3.6 and 2.9 for MAP, and 1.9 for both parameters in PVC packaging.

Another study [57] aimed to assess the impact of different packaging systems on key quality parameters of broiler chicken breast muscles. The chicken muscles were packaged using three methods commonly used in meat processing plants: MAP, vacuum, and an EPS polystyrene tray wrapped in foil. The results showed significant differences in the quality characteristics of the meat after seven days of storage, depending on the packaging method used. Vacuum-packaged chicken breast muscles exhibited a notably higher drip loss percentage of 2.68% compared to 1.11% for the MAP-packaged muscles. Additionally, the vacuum-packaged chicken had a slightly lighter color and a significantly higher redness than the MAP-packaged meat. For the muscles stored in both VAC and MAP packaging, the average values for the L* and a* color parameters were 58.69 and 60.09, and 11.30 and 12.57, respectively. There was no significant difference in the pH levels of chicken breast muscles between the two packaging methods, with pH values recorded at 5.76 for vacuum packaging and 5.86 for MAP.

One of the many labelling requirements for foodstuffs is to provide their net weight. This situation typically does not lead to significant issues. However, certain products are susceptible to weight loss during storage or while on retail shelves. Packaged meat is an example of such products. According to Polish law, Article 8, Section 1 of the Act on Prepackaged Goods [58] states: “The packer, importer, or person commissioning packaging is responsible for ensuring that the packaged goods meet the requirements specified in the Act. In particular, they are responsible for ensuring that the actual quantity corresponds to the nominal quantity stated on the individual package.” Therefore, it is the responsibility of the company to ensure that the declaration on the label is accurate. The company is responsible for developing a control system and packaging method that ensures that the products meet the above-described requirements and comply with the declared

characteristics and parameters at every stage and throughout the product's shelf life. When making decisions, the manufacturer should consider the expected losses. This legal framework is essential for commercial and technological reasons. Excessive leakage of meat juice into the packaging can create contentious issues between the parties involved in the meat trade. As demonstrated, leakage of meat juice into MAP or VAC packages containing meat is a natural phenomenon and unavoidable in production practice. However, the average leakage rate was defined, and despite testing meat without meat defects (typical pH and color component L* values), significant leakage of meat juice was observed. Therefore, based on the research, practical compromise recommendations were proposed for the meat industry and inspection authorities regarding possible levels of meat juice leakage (Table 5).

Table 5. The possible levels of meat juice leakage from different pork, beef, and chicken cuts packaged by the MAP and VAC method, without (–) and with an absorbent pad (+), after 12 days of refrigerated storage.

Cut Type	MAP+	MAP–	VAC+	VAC–
Pork				
Ham	6%	7%	7%	9%
Loin in pieces	10%	9%	9%	9%
Loin in slices	9%	11%	8%	11%
Shoulder	3%	5%	2%	3%
Neck	3%	5%	2%	3%
Organic ham	4%	7%	6%	6%
Beef				
Heel of round	6%	6%	7%	8%
Rump	3%	4%	3%	5%
Chicken				
Breast fillet	4%	4%	5%	5%
Breast tenderloin	6%	6%	5%	7%

The average values represent the recommended limits for meat juice leakage in fresh meat packaged and stored in refrigeration for up to 12 days. If the leakage exceeds these limits by more than two percentage points, it should be regarded as potentially abnormal. In such cases, official food control agencies should conduct tests to check for the presence of added water. To ensure consumer clarity, it is advisable that meat packaging include a clear label stating: “Meat juice leakage is a natural phenomenon and does not indicate a product defect.”

4. Conclusions

The exudation of meat juice while storing meat with normal quality attributes represents a typical and naturally occurring phenomenon, irrespective of the animal species or the packaging method used.

Generally, lean meat without technological defects tends to exhibit a higher exudate level than fatty meat. This can be attributed to its lower fat content and the absence of fat deposits, which in fattier cuts may act as physical barriers that limit water migration and reduce visible drip formation.

The results indicate the acceptable limits for meat leakage in culinary pork: 2–3% for vacuum-packed (VAC) pork neck and 11% for modified atmosphere packaged (MAP) sliced loin. For beef, the acceptable limits are 5% for VAC rump and 8% for VAC heel of round. For chicken, the limits are 5% for VAC breast fillet and 7% for VAC breast tenderloin. The reference values of meat juice exudation proposed in this study could be considered acceptable thresholds for properly handling fresh meat in Poland. Exceeding these values may suggest that the product originates from meat with reduced technological quality

or from meat undergoing treatments to increase its water-holding capacity or overall hydration. Establishing maximum allowable leakage thresholds for culinary meats could benefit both regulatory bodies and consumers. Another effect is likely to boost consumer confidence in meat producers and the quality of the meat they buy. Nevertheless, this aspect requires further experimental validation to confirm its diagnostic significance.

It would therefore be reasonable to undertake further investigations focused on assessing the relationship between the injection of small amounts of water or sodium chloride solution into raw meat and the extent of meat juice exudation observed during refrigerated storage. Such studies could contribute to a better understanding the factors influencing drip formation and support establishing reliable quality reference standards for fresh meat in retail distribution.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/app152111394/s1>, Table S1. Statistical analysis of the effect of meat type on its juice leakage, pH, and L*, a*, b* color parameters (ANOVA, Tukey test). Table S2. Statistical analysis of the effect of cut type on juice leakage, pH, and L*, a*, b* color parameters of pork (ANOVA, Tukey test). Table S3. Statistical analysis of the effect of package type on juice leakage, pH, and L*, a*, b* color parameters of pork ham (ANOVA, Tukey test). Table S4. Statistical analysis of the effect of package type on juice leakage, pH, and L*, a*, b* color parameters of pork loin in pieces (ANOVA, Tukey test). Table S5. Statistical analysis of the effect of package type on juice leakage, pH, and L*, a*, b* color parameters of pork loin in slices (ANOVA, Tukey test). Table S6. Statistical analysis of the effect of package type on juice leakage, pH, and L*, a*, b* color parameters of pork shoulder (ANOVA, Tukey test). Table S7. Statistical analysis of the effect of package type on juice leakage, pH, and L*, a*, b* color parameters of pork neck (ANOVA, Tukey test). Table S8. Statistical analysis of the effect of package type on juice leakage, pH, and L*, a*, b* color parameters of organic pork ham (ANOVA, Tukey test). Table S9. Statistical analysis of the effect of cut type on juice leakage, pH, and L*, a*, b* color parameters of beef (t-Student test). Table S10. Statistical analysis of the effect of package type on juice leakage, pH, and L*, a*, b* color parameters of beef heel of round (ANOVA, Tukey test). Table S11. Statistical analysis of the effect of package type on juice leakage, pH, and L*, a*, b* color parameters of beef rump (ANOVA, Tukey test). Table S12. Statistical analysis of the effect of cut type on juice leakage, pH, and L*, a*, b* color parameters of chicken (t-Student test). Table S13. Statistical analysis of the effect of package type on juice leakage, pH, and L*, a*, b* color parameters of chicken breast fillet (ANOVA, Tukey test). Table S14. Statistical analysis of the effect of package type on juice leakage, pH, and L*, a*, b* color parameters of chicken breast tenderloin (ANOVA, Tukey test). Table S15. Statistical analysis of the correlation strength (r) between leakage, pH, and L* color parameters of different pork cuts packed using VAC or MAP methods (Pearson correlation test). Table S16. Statistical analysis of the correlation strength (r) between leakage, pH, and L* color parameters of different beef cuts packed using VAC or MAP methods (Pearson correlation test). Table S17. Statistical analysis of the correlation strength (r) between leakage, pH, and L* color parameters of different chicken cuts packed using VAC or MAP methods (Pearson correlation test).

Author Contributions: Conceptualization, M.S. and K.D.; methodology, I.S.; software, I.S.; validation, A.C. and M.S.; formal analysis, M.S.; investigation, M.S., K.D., A.C. and I.S.; resources, A.C. and I.S.; data curation, M.S. and I.S.; writing—original draft preparation, M.S., A.C. and I.S.; writing—review and editing, K.D.; visualization, I.S.; supervision, M.S.; project administration, M.S.; funding acquisition, M.S. All authors have read and agreed to the published version of the manuscript.

Funding: #FunduszePromocji.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Authors can provide research data files via email upon request to interested readers.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

- Cheng, Q.; Sun, D.-W. Factors Affecting the Water Holding Capacity of Red Meat Products: A Review of Recent Research Advances. *Crit. Rev. Food Sci. Nutr.* **2008**, *48*, 137–159. [CrossRef]
- Warner, R. Measurement of meat quality. Measurements of Water-Holding Capacity and Color: Objective and Subjective. In *Encyclopedia of Meat Sciences*; Elsevier: Amsterdam, The Netherlands, 2014; pp. 164–171, ISBN 9780123847348.
- Devi, R.; Rasane, P.; Kaur, S.; Singh, J. Meat and Meat Losses: Influence on Meat Quality. *Int. J. Res. Anal. Rev.* **2019**, *6*, 762–787.
- Sakowska, A.; Guzek, D.; Głabska, D.; Konarska, M.; Wierzbička, A. Charakterystyka Wybranych Systemów Pakowania Mięsa w Odniesieniu Do Preferencji Konsumentów i Aspektów Ekonomicznych. *Zesz. Nauk. Szkoły Głównej Gospod. Wiej. W Warszawie Probl. Rol. Świat.* **2014**, *14*, 203–213. [CrossRef]
- Cassens, A.M.; Ramanathan, R.; Van Overbeke, D.L.; Mafi, G.G. Effects of Pork Quality Types, Packaging, and Degree of Doneness on Trained Sensory and Instrumental Tenderness, Color, and Consumer Perception. *Meat Muscle Biol. (MMB)* **2021**, *5*, 1–12. [CrossRef]
- Wojtulewicz, K.; Florowski, T.; Florowska, A. Aktualne problemy jakości rynkowego mięsa kulinarnego w opinii konsumentów. *Przem. Spoż.* **2021**, *75*, 25–30. [CrossRef]
- Lisiak, P.; Włodawiec, P.; Borzuta, K.; Grześkowiak-Lisiak, E.; Janiszewski, P. Masa mięsa netto—Analiza prawna i metodologiczna. *Gosp. Mięsna* **2023**, *5*, 10–16. Available online: <https://gospodarkamiesna.pl/gospodarka-miesna-nr-5-2023/> (accessed on 1 September 2025).
- Huff-Lonergan, E. Fresh Meat Water-Holding Capacity. In *Improving the Sensory and Nutritional Quality of Fresh Meat*; Elsevier: Amsterdam, The Netherlands, 2009; pp. 147–160, ISBN 9781845693435.
- Watanabe, G.; Motoyama, M.; Nakajima, I.; Sasaki, K. Relationship between water-holding capacity and intramuscular fat content in Japanese commercial pork loin. *Asian-Australas. J. Anim. Sci.* **2018**, *31*, 914–918. [CrossRef]
- Honikel, K.O. Water-holding capacity of meat. In *Muscle Development of Livestock Animals: Physiology, Genetics and Meat Quality*; Pas, M.F., Everts, M.E., Haagsman, H.P., Eds.; CABI Publishing: Cambridge, MA, USA, 2004; pp. 389–400.
- Huff-Lonergan, E.; Lonergan, S.M. Mechanisms of water-holding capacity of meat: The role of postmortem biochemical and structural changes. *Meat Sci.* **2005**, *71*, 194–204. [CrossRef] [PubMed]
- Zhang, M.; Mittal, G.S.; Barbut, S. Effects of Test Conditions on the Water Holding Capacity of Meat by a Centrifugal Method. *LWT—Food Sci. Technol.* **1995**, *28*, 50–55. [CrossRef]
- Boler, D.D.; Woerner, D.R. What is meat? A perspective from the American Meat Science Association. *Anim. Front.* **2017**, *7*, 8–11. [CrossRef]
- Puolanne, E.; Halonen, M. Theoretical Aspects of Water-Holding in Meat. *Meat Sci.* **2010**, *86*, 151–165. [CrossRef]
- Hishida, M.; Kaneko, A.; Yamamura, Y.; Saito, K. Contrasting Changes in Strongly and Weakly Bound Hydration Water of a Protein upon Denaturation. *J. Phys. Chem. B* **2023**, *127*, 6296–6305. [CrossRef]
- Warriss, P.D. Post-Mortem Changes in Muscle and Its Conversion into Meat. In *Meat Science*, 2nd ed.; CABI Digital Library: Wallingford, UK, 2010; pp. 65–76. Available online: <https://cabidigitallibrary.org> (accessed on 1 September 2025).
- Wajdzik, J. Aspekty Jakościowe Pakowanego Mięsa Kulinarnego. Ogólnopolski Informator Masarski. 2018. Available online: <https://informatormasarski.pl/maszyny-i-technologie/aspekty-jakosciowe-pakowanego-miesza-kulinarnego/> (accessed on 1 September 2025).
- Warner, R.D. The Eating Quality of Meat: IV—Water Holding Capacity and Juiciness. In *Lawrie's Meat Science*; Elsevier: Amsterdam, The Netherlands, 2023; pp. 457–508, ISBN 9780323854085.
- Makała, H. Zastosowanie metody komputerowej analizy obrazu do oznaczenia zdolności utrzymania wody własnej przez mięso. *Postępy Nauk. I Technol. Przemysłu Rolno-Spożywczego* **2015**, *70*, 57–68.
- Mir, N.; Rafiq, A.; Kumar, F.; Singh, V.; Shukla, V. Determinants of Broiler Chicken Meat Quality and Factors Affecting Them: A Review. *J. Food Sci. Technol.* **2017**, *54*, 2997–3009. [CrossRef]
- Kerry, J.P.; O'Grady, M.N.; Hogan, S.A. Past, Current and Potential Utilisation of Active and Intelligent Packaging Systems for Meat and Muscle-Based Products: A Review. *Meat Sci.* **2006**, *74*, 113–130. [CrossRef]
- Zalewska, M.; Marcinkowska-Lesiak, M.M.; Półtorak, A.; Wyrwicz, R.; Zaremba, R. Wpływ Sposobu Pakowania Na Zachowanie Barwy Mięsa i Przetworów z Mięsa Wieprzowego. *Postępy Tech. Przetwórstwa Spożywczego* **2012**, *2*, 127–132.
- Ripoll, G.; Albertí, P.; Casasús, I.; Blanco, M. Instrumental meat quality of veal calves reared under three management systems and color evolution of meat stored in three packaging systems. *Meat Sci.* **2013**, *93*, 336–343. [CrossRef]
- Chen, X.; Zhao, J.; Zhu, L.; Luo, X.; Mao, Y.; Hopkins, D.L.; Zhang, Y.; Dong, P. Effect of Modified Atmosphere Packaging on Shelf Life and Bacterial Community of Roast Duck Meat. *Food Res. Int.* **2020**, *137*, 109645. [CrossRef] [PubMed]

25. Elbir, Z.; Oz, F. Determination of creatine, creatinine, free amino acid and heterocyclic aromatic amine contents of plain beef and chicken juices. *J. Food Sci. Technol.* **2021**, *58*, 3293–3302. [\[CrossRef\]](#)
26. Liu, J.; Ellies-Oury, M.-P.; Stoyanchev, T.; Hocquette, J.-F. Consumer Perception of Beef Quality and How to Control, Improve and Predict It? Focus on Eating Quality. *Foods* **2022**, *11*, 1732. [\[CrossRef\]](#) [\[PubMed\]](#)
27. Logan, B.G.; Bush, R.D.; Biffin, T.E.; Hopkins, D.L.; Smith, M.A. Measurement of Drip Loss in Alpaca (Vicugna Pacos) Meat Using Different Techniques and Sample Weights. *Meat Sci.* **2019**, *151*, 1–3. [\[CrossRef\]](#)
28. Oswell, N.J.; Gilstrap, O.P.; Pegg, R.B. Variation in the terminology and methodologies applied to the analysis of water holding capacity in meat research. *Meat Sci.* **2021**, *178*, 108510. [\[CrossRef\]](#)
29. Christensen, L.B. Drip loss sampling in porcine m. longissimus dorsi. *Meat Sci.* **2003**, *63*, 469–477. [\[CrossRef\]](#)
30. Otto, G.; Roehe, R.; Looft, H.; Thoelking, L.; Kalm, E. Comparison of different methods for determination of drip loss and their relationships to meat quality and carcass characteristics in pigs. *Meat Sci.* **2004**, *68*, 401–409. [\[CrossRef\]](#)
31. Daszkiewicz, T.; Burczyk, E. The Effect of Meat Sample Preparation on the Results of Drip Loss and Cooking Loss Analysis. *Food Biotechnol. Agric. Sci. (FBAS)* **2005**, *79*, 11–15.
32. NSA Centralna Baza Orzeczeń Sądów Administracyjnych, III SA/Po 181/22- Wyrok WSA w Poznaniu, 181/22. Available online: <https://orzeczenia.nsa.gov.pl/doc/8F1459B16D> (accessed on 1 September 2025).
33. Polish Standard PN-A-82109:2010; Meat and Meat Products—Determination of Fat, Protein and Water Content—Near Infrared Transmission Spectrometry (NIT) Method Using Calibration on Artificial Neural Networks (ANN). Polish Committee for Standardization: Warsaw, Poland, 2010.
34. Ślęzak, M.; Czub, G.; Świątek, M.; Niżnikowski, R.; Głowacz, K. The application of the near-infrared spectroscopic (NIRS) technique in assessment of chemical composition of the lamb meat. *Sci. Ann. Pol. Soc. Anim. Prod.* **2013**, *9*, 69–76. Available online: <https://zootechnical.com/article/153484/pl> (accessed on 1 September 2025).
35. Wagoner, M.; Reyes, T.; Zorn, V.; Coursen, M.; Corbitt, K.; Wilborn, B.; Starkey, C.; Brandebourg, T.; Belk, A.; Bonner, T.; et al. Vacuum Packaging Maintains Fresh Characteristics of Previously Frozen Beef Steaks during Simulated Retail Display. *Foods* **2022**, *11*, 3012. [\[CrossRef\]](#)
36. International Standard ISO 2917. Meat and Meat Products—Measurement of pH—Reference Method, 1–5. Available online: <https://cdn.standards.iteh.ai/samples/24785/9861ea639264453ea88995b72d9c4ba5/ISO-2917-1999.pdf> (accessed on 1 September 2025).
37. Zduńczyk, W.; Tkacz, K.; Pietrzak-Fiećko, R.; Bottari, B.; Modzelewska-Kapituła, M. Pork as a Source of Nutrients in a Human Diet—Comparison of Meat Obtained from Conventional and Organic Systems Offered in the Polish Market. *NFS J.* **2024**, *37*, 100199. [\[CrossRef\]](#)
38. American Meat Science Association. AMSA Meat Color Measurement Guidelines. 2012. Available online: https://meatscience.org/docs/default-source/publications-resources/hot-topics/2012_12_meat_clr_guide.pdf (accessed on 1 September 2025).
39. Mishra, P.; Singh, U.; Pandey, C.M.; Mishra, P.; Pandey, G. Application of Student's t-Test, Analysis of Variance, and Covariance. *Ann. Card. Anaesth.* **2019**, *22*, 407–411. [\[CrossRef\]](#) [\[PubMed\]](#)
40. Ikhwan, M.F.; Mansor, W.; Khan, Z.I.; Adzhar Mahmood, M.K.; Bujang, A.; Haddadi, K. Pearson Correlation and Multiple Correlation Analyses of the Animal Fat S-Parameter. *TEM J.* **2024**, *13*, 155–160. [\[CrossRef\]](#)
41. Cobos, Á.; Díaz, O. Chemical Composition of Meat and Meat Products. In *Handbook of Food Chemistry*; Cheung, P.C.K., Ed.; Springer Berlin Heidelberg: Berlin/Heidelberg, Germany, 2014; pp. 1–32, ISBN 9783642416095.
42. Soren, N.M.; Biswas, A.K. Methods for Nutritional Quality Analysis of Meat. In *Meat Quality Analysis*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 21–36, ISBN 9780128192337.
43. Ahmad, R.S.; Imran, A.; Hussain, M.B. Nutritional Composition of Meat. In *Meat Science and Nutrition*; Arshad, M.S., Ed.; InTech: Houston, TX, USA, 2018; ISBN 9781789842333.
44. James, S.; James, C. Raw Material Selection: Meat and Poultry. In *Woodhead Publishing Series in Food Science, Technology and Nutrition, Chilled Foods. A Comprehensive Guide*, 3rd ed.; Martyn Brown; Woodhead Publishing Series in Food Science, Technology and Nutrition, Chilled Foods; Woodhead Publishing: Sawston, UK, 2008; pp. 61–82, ISBN 9781845692438.
45. Barbut, S. Measuring Water Holding Capacity in Poultry Meat. *Poult. Sci.* **2024**, *103*, 103577. [\[CrossRef\]](#)
46. Przybylski, W.; Jaworska, D.; Boruszewska, K.; Borejko, M.; Podsiadły, W. Jakość technologiczna i sensoryczna tładliwego mięsa wieprzowego. *Żywność Nauka Technologia Jakość* **2021**, *1*, 116–127.
47. Kaić, A.; Janječić, Z.; Žanetić, A.; Kelava Ugarković, N.; Potočnik, K. EZ-DripLoss Assessment in Chicken Breast Meat Using Different Sample Areas, Fiber Orientation, and Measurement Intervals. *Animals* **2021**, *11*, 1095. [\[CrossRef\]](#)
48. Filho, R.D.A.T.; Cazedey, H.P.; Fontes, P.R.; Ramos, A.D.L.S.; Ramos, E.M. Drip loss assessment by different analytical methods and their relationships with pork quality classification. *J. Food Qual.* **2017**, *6*, 9170768. [\[CrossRef\]](#)
49. Nair, M.N.; Mancini, R.A. Packaging—Modified and Controlled Atmosphere. In *Encyclopedia of Meat Sciences*; Elsevier: Amsterdam, The Netherlands, 2024; pp. 617–623, ISBN 9780323851985.

50. Świdorski, F.; Sadowska, A. Pakowanie mięsa w warunkach zmodyfikowanej atmosfery i próżni. (meat packing in modified atmosphere and vacuum conditions). *Postępy Tech. Przetwórstwa Spożywczego* **2011**, *1*, 98–102.
51. Lee, K.T. Shelf-Life Extension of Fresh and Processed Meat Products by Various Packaging Applications. *Korean J. Packag. Sci. Technol.* **2018**, *24*, 57–64. [[CrossRef](#)]
52. Łopacka, J.; Półtorak, A.; Wierzbicka, A. Effect of MAP, Vacuum Skin-Pack and Combined Packaging Methods on Physicochemical Properties of Beef Steaks Stored up to 12 Days. *Meat Sci.* **2016**, *119*, 147–153. [[CrossRef](#)] [[PubMed](#)]
53. Strydom, P.E.; Hope-Jones, M. Evaluation of Three Vacuum Packaging Methods for Retail Beef Loin Cuts. *Meat Sci.* **2014**, *98*, 689–694. [[CrossRef](#)] [[PubMed](#)]
54. Reyes, T.M.; Wagoner, M.P.; Zorn, V.E.; Coursen, M.M.; Wilborn, B.S.; Bonner, T.; Brandebourg, T.D.; Rodning, S.P.; Sawyer, J.T. Vacuum Packaging Can Extend Fresh Color Characteristics of Beef Steaks during Simulated Display Conditions. *Foods* **2022**, *11*, 520. [[CrossRef](#)]
55. Younis, M.; Arab, W.S.; Hamad, A.; Sabike, I.I. Assessing the Variability in Camel and Beef Meat Quality: Implications for Consumer Acceptance. *Benha Vet. Med. J.* **2025**, *48*, 74–78. [[CrossRef](#)]
56. Chmiel, M.; Hać-Szymańczuk, E.; Adamczak, L.; Pietrzak, D.; Florowski, T.; Cegiełka, A. Quality Changes of Chicken Breast Meat Packaged in a Normal and in a Modified Atmosphere. *J. Appl. Poult. Res.* **2018**, *27*, 349–362. [[CrossRef](#)]
57. Kot Vel Ławecka, K.; Banaszewska, D.; Biesiada-Drzazga, B. The Effect of Packaging Systems on Selected Quality Characteristics of Poultry Meat. *Acta Sci. Pol. Zootech.* **2019**, *18*, 3–12. [[CrossRef](#)]
58. Ustawa z Dnia 7 Maja 2009 r. o Towarach Paczkowanych (Act on Prepackaged Goods), Dz.U. 2009 nr 91 poz. 740, pp. 1–32. Available online: <https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20090910740> (accessed on 1 September 2025).

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.