

Article

Effect of Packaging Method and Storage Time on Fatty Acid Profile and Oxidative Stability of Ground Beef Lipid Fraction During Refrigerated Storage

Marta Chmiel ^{1,*} , Agata Górka ² , Iga Piasecka-Lenartowicz ² , Ewa Ostrowska-Ligeza ² ,
Magdalena Wirkowska-Wojdyla ² , Lech Adamczak ¹  and Tomasz Florowski ¹ 

¹ Department of Food Technology and Assessment, Institute of Food Sciences, Warsaw University of Life Sciences—SGGW, 159c Nowoursynowska Street, 02-776 Warsaw, Poland; lech_adamczak@sggw.edu.pl (L.A.); tomasz_florowski@sggw.edu.pl (T.F.)

² Department of Chemistry, Institute of Food Sciences, Warsaw University of Life Sciences—SGGW, 159c Nowoursynowska Street, 02-776 Warsaw, Poland; agata_gorska@sggw.edu.pl (A.G.); iga_piasecka@sggw.edu.pl (I.P.-L.); ewa_ostrowska-ligeza@sggw.edu.pl (E.O.-L.); magdalena_wirkowska@sggw.edu.pl (M.W.-W.)

* Correspondence: marta_chmiel@sggw.edu.pl

Featured Application

The findings of this study can be applied in the meat industry to optimize packaging strategies for ground beef and improve product shelf life. The results demonstrate how different oxygen and carbon dioxide concentrations in modified atmosphere packaging influence lipid oxidation, color stability, and fat quality during refrigerated storage. The combined use of conventional quality indicators, oxidation kinetics, and thermal analysis provides a practical approach for selecting packaging systems that balance visual appeal with oxidative stability. This knowledge may support meat processors in designing packaging solutions that minimize quality deterioration, reduce food losses, and improve the commercial value of fresh ground beef products.

Abstract

This study evaluated the effect of packaging method and storage time on the fatty acid profile and lipid stability of ground beef during 21 days of storage (0–4 °C). Ground beef was packaged under vacuum (VP) and modified atmosphere packaging (MAP 80% O₂/20% CO₂ and MAP 50% O₂/50% CO₂). Lipid oxidation progressed during storage particularly in MAP 80/20 samples, where TBARS reached 3.46 mg MDA/kg of product after 21 days, compared with 0.45 mg MDA/kg of product in VP samples. Redness (a*) decreased in MAP samples but remained stable in VP. Acid value increased, reaching 4.35 mg KOH/g fat in VP and 3.62 mg KOH/g fat in MAP 50/50. Despite oxidative changes, the fatty acid profile remained relatively stable, with saturated fatty acids accounting for 52–56% and oleic acid (33.85–38.99%) being predominant. VP most effectively limited the formation of secondary lipid oxidation products, as reflected by lower TBARS values, whereas MAP promoted lipid peroxidation during storage. These findings highlight the combined impact of packaging method and storage duration on the quality and stability of ground beef.

Keywords: ground beef; vacuum packaging; modified atmosphere packaging; lipid oxidation kinetics; fatty acid profile; oxidative stability



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1. Introduction

Beef is one of the most widely consumed red meats worldwide and is frequently marketed in minced form as ground beef due to its versatility, affordability, and suitability for various culinary applications [1]. However, the grinding process significantly disrupts muscle tissue structure and increases the surface area exposed to oxygen and the development of microorganisms. As a result, interactions between lipids, pro-oxidative compounds, and endogenous enzymes are intensified [2,3]. Ground beef is more susceptible to oxidative deterioration and microbial spoilage than intact muscle cuts [4,5].

Lipid oxidation is one of the primary factors limiting the shelf life of fresh meat. It leads to the formation of primary and secondary oxidation products, including hydroperoxides and aldehydes such as malondialdehyde (MDA), which negatively affect flavor, aroma, nutritional value, and visual appearance, particularly color [3,6,7]. Oxidative processes are closely linked with myoglobin oxidation, leading to meat discoloration through metmyoglobin formation. During retail display, red meat tends to change from the bright red color desired by consumers to an undesirable color of brown metmyoglobin, as stated by Ghis et al. [5]. Since color is one of the most important quality traits used by consumers to assess meat freshness, even slight deviations from the typical red color of beef may reduce consumer acceptance [8,9].

The rate of lipid oxidation depends on multiple factors, including fatty acid composition, oxygen availability, storage temperature, and packaging conditions [3,10]. Unsaturated fatty acids are highly prone to oxidation. Their reactivity plays a crucial role in regulating shelf life, as oxidation of unsaturated fatty acids accelerates rancidity development and contributes to pigment oxidation and consequent color deterioration [11]. Thus, both the fatty acid profile and the control of lipid oxidation during storage constitute critical factors influencing the overall quality and sensory stability of meat [12].

The packaging method plays a crucial role in the oxidative stability of fresh meat, including its lipid fraction. Vacuum packaging (VP) reduces oxygen availability and slows down lipid peroxidation; however, it results in a purplish-red color due to deoxymyoglobin formation. In contrast, modified atmosphere packaging (MAP) with high-oxygen content is widely used by meat processors to preserve the bright red color of beef, by promoting and stabilizing the oxymyoglobin [13]. However, the oxygen content in MAP for meat packaging represents a technological compromise between color stability and oxidative deterioration, as high oxygen content in MAP may intensify lipid oxidation and as a consequence accelerate quality deterioration [2,14]. Therefore, reducing the O₂ content in the MAP gas mixture intended for meat packaging may offer a viable solution for improving meat quality by limiting oxidation processes. For example, Liang et al. [15] reported that the oxidative stability of pork improved when 50% O₂ (instead of 80%) was used in the MAP gas mixture.

Although numerous investigations have examined the influence of packaging methods on meat quality, most have focused on whole-muscle cuts or steak-type products rather than minced meat [10,16]. Only a limited number of studies demonstrated that MAP gas composition significantly influences the quality of ground beef, however such studies mainly evaluated conventional quality and shelf-life indicators, including color, microbiological quality, and TBARS values [4,5,13]. Relationships between fatty acid composition, lipid oxidation, and discoloration have also been investigated in beef [2,17–19]. However, calorimetric approaches have been applied mainly to characterize oxidation kinetics or thermal behavior of extracted fats and edible lipid systems [20–24], rather than to lipid fractions obtained from ground beef stored under different packaging systems. To the best of our knowledge, no previous study has comprehensively integrated conventional oxidation

markers, fatty acid profiling, oxidation kinetics, and DSC-based thermal characterisation of the lipid fraction in ground beef stored under different packaging systems.

While TBARS and acid value provide information on secondary oxidation products and free fatty acid formation, respectively, they do not fully describe the kinetic resistance of the lipid fraction to further oxidation or potential changes in its thermal behavior. Therefore, the inclusion of PDSC and DSC analyses provides complementary information, allowing a more comprehensive evaluation of packaging-related lipid deterioration. From an industrial perspective, these analyses may help determine whether packaging-related lipid deterioration is limited to the formation of oxidation products or is also associated with changes in oxidative resistance and thermal properties of the fat fraction.

The aim of the present study was to evaluate the influence of vacuum packaging and modified atmosphere packaging with two gas mixtures on lipid oxidation, fatty acid composition, oxidation kinetics, and melting behavior of ground beef during 21 days of refrigerated storage. It was hypothesized that high-oxygen MAP would accelerate oxidative processes and color deterioration, whereas vacuum packaging would better preserve lipid stability and meat quality over time.

2. Materials and Methods

2.1. Raw Material and Sample Preparation

The research material consisted of culinary ground beef standardized to a fat content of approximately 18–20%. The meat was obtained and prepared according to standard industrial procedures in a meat processing plant, as meat intended for commercial distribution. The raw material was produced from beef trimmings obtained during cutting and trimming of primal cuts and was ground using a 4.5 mm grinding plate. The material was collected from three independent production batches, each representing a separate experimental series. Approximately 4 kg of ground beef was obtained from each batch for further analyses.

2.2. Packaging Methods and Experimental Schedule

In each experimental series, ground beef was divided into approximately 250 g portions. Four packages were prepared for each packaging variant: vacuum packaging (VP), MAP 80/20, and MAP 50/50. VP samples were packed at <10 mbar using a chamber vacuum packaging machine (MULTIVAC C200, Multivac, Natalin, Poland) in polyethylene bags (200 × 170 mm; 0.075 mm thick). Ground beef samples intended for MAP were placed on rigid PET trays (205 × 160 × 80 mm; Bagstar, Marki, Poland) and sealed using a tray-sealer MAP machine (Multivac T250, Multivac, Natalin, Poland). Prior to sealing, packages were flushed with an appropriate gas mixture (Air Products, Siewierz, Poland) blended using a MAP gas mixer (Mix 9001 ME-3/200B, Mocon Europe A/S, Ringsted, Denmark). The trays were then sealed with the top lidding film (OPALEN B62, Bemis, Aylesbury, Buckinghamshire, UK). Two gas mixtures were applied: 80% O₂ and 20% CO₂ (MAP 80/20) and 50% O₂ and 50% CO₂ (MAP 50/50). Within each experimental series, one package from each packaging variant was assigned to each storage day (0, 7, 14, and 21 days). Since the experiment was performed using three independent production batches, each treatment combination was represented by three independent packages in total, each originating from a different batch. Ground beef packaged under MAP 80/20 was considered the reference treatment, as this gas mixture is commonly used for raw meat MAP. All samples were stored at 3.2 °C ± 0.7 °C until the designated analysis day. Storage temperature was continuously monitored throughout the experiment using loggers (EL-USB-2 models, Lascar Electronics Ltd., Erie, PA, USA). On each sampling day, one package from each packaging variant was randomly selected and subjected to analyses, including meat

quality parameters, determination of the fatty acid profile, and assessment of the oxidative stability of the lipid fraction.

2.3. Methods

2.3.1. Gas Composition in MAP Packages

The concentrations of O₂ and CO₂ in the MAP packages were verified according to the procedure described by Chmiel et al. [25] using a CheckMate 3 gas analyzer (Mocon Europe A/S, Ringsted, Denmark).

2.3.2. Drip Loss into the Package

The ground beef samples were weighed prior to packaging and again after the designated storage time periods. Drip loss was calculated based on the difference between the initial weight before packaging and the weight after storage, and expressed as a percentage of the initial sample weight [26].

2.3.3. Color Parameters

Color parameters were determined on the surface of ground beef samples immediately after the opening of the MAP packages. For VP samples, color measurements were performed after 30 min of blooming following package opening, to allow oxygenation of deoxymyoglobin to oxymyoglobin, and development of appropriate color. Measurements were performed in five replicates per sample for each variant, and the mean value was reported as the final result. A MINOLTA® CR-400 colorimeter (Minolta, Tokyo, Japan) was used with the following settings: illuminant D65, 10° standard observer, and an 8 mm aperture. The instrument was calibrated prior to measurement using a white standard ($Y = 95.2$, $x = 0.3159$, $y = 0.3326$). The L* parameter represents lightness (0 = black, 100 = white), a* indicates the degree of greenness (−a*) to redness (+a*), and b* denotes the degree of blueness (−b*) to yellowness (+b*).

2.3.4. pH Level

The pH was determined using a Testo 206 pH meter (Testo SE & Co. KGaA, Titisee-Neustadt, Germany). Measurements were performed by inserting the combined electrode and temperature probe directly into the ground beef samples. Prior to analysis, the instrument was calibrated using standard buffer solutions at pH 4.0 and 7.0.

2.3.5. Water-Holding Capacity (WHC)

Water-holding capacity was determined using the filter-paper press method according to the method described by Jaworska et al. [27]. Approximately 0.3 g of meat was placed on Whatman No. 1 filter paper that had been conditioned in a saturated KCl solution for 24 h. The sample was positioned between two glass plates and subjected to a 2 kg load for 5 min. After compression, the areas of the pressed meat sample and the exudate ring were outlined and scanned. Surface areas were measured using ImageJ ver 1.53e software, and WHC was expressed as cm²/g.

2.3.6. Thermal Drip

The percentage of thermal drip was determined based on the difference in meat weight before and after heating. The meat (approx. 30 g) was placed in a 150 cm³ beaker, compacted to remove air spaces, and the beaker was covered with cling film before being placed in the water bath. The heat treatment was carried out at 75 °C for 30 min.

2.3.7. TBARS Index

Thiobarbituric acid reactive substances (TBARS) were determined according to the method described by Shahidi [28]. Briefly, 2 g (± 0.01 g) of ground beef was weighed into a centrifuge tube, followed by the addition of 5 mL of 10% trichloroacetic acid (TCA). The sample was rubbed with a rod for 2 min. Then, 5 mL of 2-thiobarbituric acid (TBA) solution was added, and the mixture was shaken for 2 min. The samples were centrifuged at 4000 rpm for 10 min, and the supernatant was filtered into glass tubes. The filtrate was heated in a boiling water bath for 35 min, then immediately cooled to room temperature. Absorbance was measured at 532 nm using a spectrophotometer (CampSpec M501, CampSpec Ltd., Leeds, UK) against a blank containing 5 mL of TBA solution and 5 mL of 10% TCA. TBARS values were calculated using a conversion factor of 2.34 and expressed as mg of malondialdehyde (MDA) per kg of product.

2.3.8. Fat Extraction

Fat extraction was performed using the Folch method. For this purpose, 75 g of meat was weighed and placed in a Schott bottle, followed by the addition of 125 mL of a chloroform:methanol mixture (1:1, *v/v*). The contents were vigorously mixed for 3 min, after which the sealed bottles were incubated at 60 °C for 20 min. After 10 min, the bottles were briefly opened to release gas and then resealed. Following incubation, the samples were cooled to room temperature, 125 mL of chloroform was added, and the solution was mixed and filtered into a clean bottle. Next, 70 mL of 1 N KCl was added, and the samples were stored at 4 °C for 12 h.

After refrigeration, the samples were conditioned to achieve room temperature and transferred to separatory funnels. Once phase separation occurred, the lower layer was collected into an Erlenmeyer flask, and anhydrous magnesium sulfate was added. The samples were left for 30 min, with mixing every 10 min. The contents of the Erlenmeyer flask were then filtered into pre-weighed round-bottom flasks, and the solvent was evaporated using a vacuum rotary evaporator (Büchi R-215 Rotavapor, Büchi Labortechnik AG, Flawil, Switzerland) at 45 °C and a minimum pressure of 70 mbar. Any remaining solvent residues were removed under a nitrogen atmosphere. Finally, the flasks containing the oil were weighed again to determine the fat content in the meat samples [29,30].

2.3.9. Gas Chromatography

To determine the fatty acid profile, fatty acids were converted to fatty acid methyl esters (FAMES) according to PN-EN ISO 5509:2001 [31] using a 1 M KOH solution in methanol. The analysis of FAMES was conducted using a YL6100 (Young Lin Instrument Co., Ltd., Anyang, Republic of Korea) gas chromatograph (GC) equipped with a BPX-70 (SGE Analytical Science, Milton Keynes, UK) capillary column (60 m length, 0.25 mm internal diameter, 0.25 μ m film thickness) and a flame ionization detector (FID). Nitrogen was used as the carrier gas. The fatty acids were identified by comparing their retention times with a reference FAME standard mixture. The peak areas on the chromatogram were used to calculate the percentage share of individual fatty acids in the oil samples [20].

2.3.10. Oxidation Kinetics

To assess oxidation kinetics, including the activation energy (E_a), pre-exponential factor (Z), and reaction rate constant (k), a non-isothermal pressure differential scanning calorimetry (PDSC) method was applied [21]. Oil samples (3–4 mg) were heated at rates (β) of 2.5, 5.0, 7.5, 10.0, and 12.5 °C/min over a temperature range of 40–300 °C. The experiments were conducted using DSC Q20 instrument (TA Instruments, New Castle,

DE, USA) under an oxygen atmosphere with a gas flow rate of 50 mL/min and an initial pressure of 100 kPa.

The onset oxidation temperature (T_{on}) was determined by identifying the intersection point of the leading edge (tangent line) of the recorded curve with the extrapolated baseline. The experimental T_{on} values, as a function of heating rate (β), were converted into absolute initial oxidation temperatures (T_{on}). A plot of the logarithm of the heating rate versus oxidation temperature was constructed, and the relationship was described using the following regression equation (Equation (1)):

Equation (1):

$$\log \beta = a \left(\frac{1}{T_{on}} \right) + b \quad (1)$$

where

β —heating rate;

T_{on} —absolute initial oxidation temperature (K).

The activation energy (E_a) and pre-exponential factor (Z) were calculated using Equations (2)–(4), based on the Ozawa–Flynn–Wall method:

Equation (2):

$$E_a = -2.19R \cdot \frac{d \log \beta}{d \frac{1}{T}} \quad (2)$$

where

E_a —activation energy;

R —gas constant.

Equation (3):

$$Z = \frac{\beta E_a e^{\frac{E_a}{RT}}}{RT^2} \quad (3)$$

Equation (4):

$$k = Z \exp \frac{-E_a}{RT} \quad (4)$$

where

k —reaction rate constant;

Z —pre-exponential factor.

2.3.11. Melting Characteristics

The melting characteristics of fat were determined using differential scanning calorimetry (DSC) with a DSC Q200 instrument (TA Instruments, New Castle, DE, USA). Hermetically sealed aluminum pans containing 3–4 mg of oil were cooled to -80 °C and then heated at a rate of 10 °C per minute up to 80 °C. The results were recorded as DSC curves, illustrating the relationship between temperature and heat flow [32].

2.3.12. Acid Value Determination

The acid value (AV) was determined according to AOCS Cs 3d-63 Method [33]. A weighed oil sample was dissolved in 50 mL of an ethanol/diethyl ether mixture (1:1, v/v). The solution was placed on a magnetic stirrer, and titration was performed using an ethanolic potassium hydroxide (KOH) solution (0.1 mol/L) as the titrant. A TitraLab AT100 automatic titrator (HACH LANGE, Wrocław, Poland) was used for titration. The acid value was expressed as the mass of KOH (mg) required to neutralize the free fatty acids in 1 g of oil.

2.3.13. Statistical Analysis

For each combination of packaging method and storage time, results were calculated from three independent packages, each originating from a separate production batch. Instrumental or analytical repetitions performed within the same package were treated as technical replicates and averaged before statistical analysis. The results are presented as mean $\pm$ standard deviation. Statistical processing was conducted using Statistica v. 13.3 software (v. 13.3, TIBCO Software Inc., Palo Alto, CA, USA). Prior to ANOVA, data distribution was checked for normality using the Shapiro–Wilk test, and homogeneity of variance was assessed using Levene’s test. A two-way ANOVA was applied to evaluate the effects of packaging method and storage time, both considered fixed factors, as well as their interaction. Tukey’s post hoc test was used to compare means when significant effects were detected. A one-way ANOVA was applied to compare packaging variants within the same storage day. The significance level was set at $\alpha = 0.05$.

3. Results and Discussion

3.1. Changes in Gas Composition in MAP Packages

Figure 1 shows changes in O₂ and CO₂ contents during refrigerated storage of ground beef packed under MAP 80/20 and MAP 50/50. As defined in the experimental design, on day 0 the O₂ content in MAP 80/20 packages was significantly ($p \leq 0.05$) higher than in MAP 50/50, whereas the CO₂ content was significantly ($p \leq 0.05$) lower. These differences between MAP variants remained significant throughout the entire storage time (Figure 1).

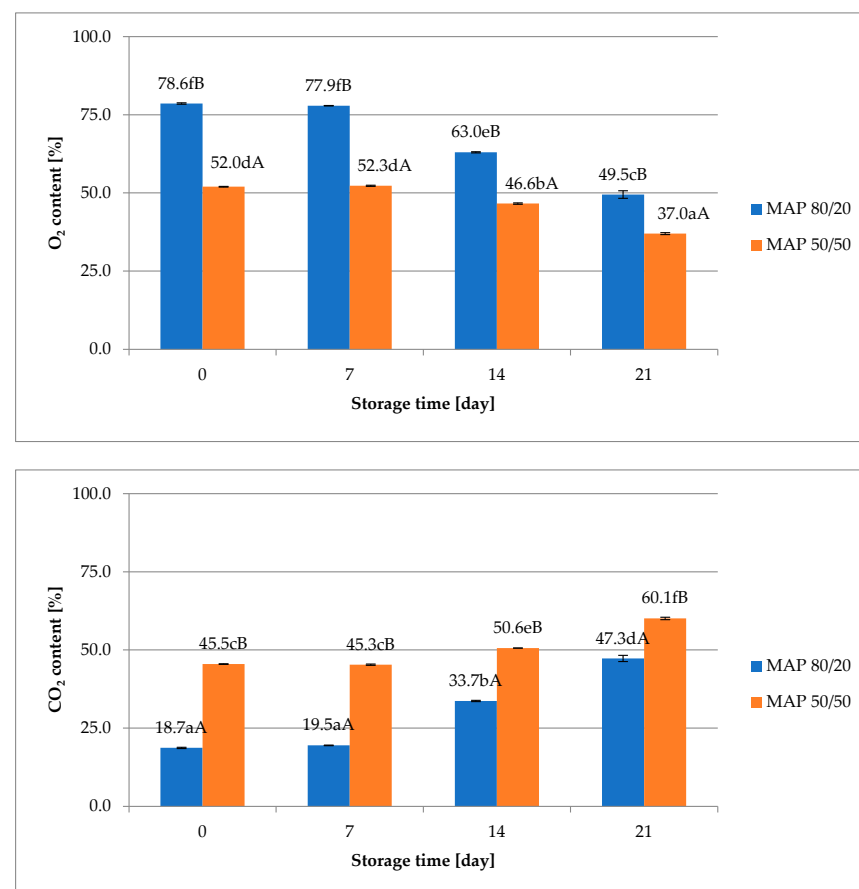


Figure 1. Changes in MAP gas mixture composition during ground beef storage. Different lowercase letters (a–f) indicate significant differences between all means determined by two-way analysis of variance ($p \leq 0.05$), while different uppercase letters (A,B) indicate differences between means on a given day of designation determined by one-way analysis of variance ($p \leq 0.05$).

Both the initial oxygen concentration and its subsequent changes during storage are particularly important in the context of lipid oxidation and meat color stability [10]. Significant modifications in headspace gas composition were observed during refrigerated storage of ground beef. A gradual and significant ($p \leq 0.05$) decrease in O_2 content in both MAP variants was observed with storage time extension (Figure 1). The decrease in O_2 content was more visible in MAP with higher oxygen content in the gas mixture. In contrast, CO_2 concentration significantly ($p \leq 0.05$) increased during storage in both MAP variants. Similar trends were reported by Conte-Junior et al. [13], who observed a significant decrease in O_2 and an increase in CO_2 contents during storage of ground beef in MAP gas mixtures consisting of 80% O_2 and 20% CO_2 and 60% O_2 and 40% CO_2 . Esmer et al. [4] demonstrated that varying O_2/CO_2 ratios significantly influenced the stability and quality of minced beef during refrigerated storage. According to Conte-Junior et al. [13] and Yang et al. [34], the reduction in O_2 content in MAP packages may be attributed to oxygen consumption resulting from oxidative reactions occurring in the meat matrix, including lipid oxidation and myoglobin oxidation. In addition, these authors suggested that microbial activity during refrigerated storage may also contribute to O_2 consumption and CO_2 production in MAP packages. Such changes may also be influenced by shifts in the headspace gas balance and gas exchange between the package atmosphere and the meat matrix during storage.

3.2. Quality Characteristic of Ground Beef

Table 1 presents the effects of packaging method and storage time on selected quality parameters of ground beef. Drip loss was significantly ($p \leq 0.05$) affected by the packaging method only at the beginning and end of storage time. On day 0, VP meat was characterised by significantly higher drip loss compared to MAP variants. However, this tendency was not maintained throughout storage.

On day 21, VP meat was characterised by significantly lower drip loss than MAP variants. The higher initial drip loss observed in VP may be explained by mechanical compression and rapid pressure changes occurring during vacuum packaging, which promote fluid release from muscle tissue [34]. During storage, the tight adhesion of the packaging material to the meat surface in VP likely limited further fluid accumulation inside the package, resulting in comparatively lower drip loss at the end of storage. In contrast, meat packed under MAP with high oxygen content may undergo protein oxidation, reducing the ability of proteins to bind water and, consequently, increasing drip loss [35]. Regardless of the packaging method, drip loss increased progressively during refrigerated storage, reaching its highest values on day 21. Excessive drip loss is undesirable because it negatively affects meat appearance, may reduce consumer acceptance, and can compromise microbiological stability, especially when the volume of exudate exceeds the absorbent pad capacity [16]. An increase in drip loss during storage was observed by Wang et al. [36].

The initial pH of the ground beef was 5.7 (Table 1). Significant differences in pH between packaging methods were observed at the end of storage time, where MAP 80/20 beef was characterized by the highest pH. The lower pH of meat packed in MAP with a higher CO_2 content (MAP 50/50) in the gas mixture could be attributed to increased solubility of CO_2 in ground beef at higher concentrations. Greater dissolution of CO_2 in the meat may lead to enhanced formation of carbonic acid, which consequently results in a reduction in pH [37]. Throughout storage, the pH of MAP 80/20 meat remained relatively stable, increasing only slightly on day 21. In contrast, MAP 50/50 and VP samples showed a gradual decrease in pH, reaching 5.5 and 5.4, respectively, at the end of storage time. According to Hur et al. [38], a decrease in meat pH during refrigerated storage may be associated with microbial metabolic activity and the production of acidic metabolites. A similar decline in

pH during storage of beef packed under modified atmospheres with different gas compositions was reported by Yang et al. [34] and Conte-Junior [13] for ground beef stored under different MAP and VP for 20 days.

Table 1. Quality characteristics of ground beef packed under various methods.

Quality Characteristic	Packaging Variant	Storage Time [Day]			
		0	7	14	21
Drip loss [%]	MAP 80/20	1.5 ^{aA} ± 0.2	3.5 ^{cA} ± 0.1	4.2 ^{cdA} ± 0.7	5.3 ^{eB} ± 0.4
	MAP 50/50	1.3 ^{aA} ± 0.3	3.5 ^{cA} ± 0.2	4.3 ^{cdA} ± 0.2	4.6 ^{deAB} ± 0.5
	VP	2.5 ^{bB} ± 0.2	3.8 ^{cdA} ± 0.1	4.2 ^{cdA} ± 0.4	4.0 ^{cdA} ± 0.1
pH	MAP 80/20	5.7 ^{cdA} ± 0.1	5.8 ^{cdA} ± 0.1	5.7 ^{cdB} ± 0.1	5.9 ^{dB} ± 0.1
	MAP 50/50	5.7 ^{cdA} ± 0.1	5.8 ^{cdA} ± 0.1	5.6 ^{bcAB} ± 0.1	5.5 ^{abA} ± 0.1
	VP	5.7 ^{cdA} ± 0.1	5.7 ^{cdA} ± 0.1	5.5 ^{abA} ± 0.1	5.4 ^{aA} ± 0.1
WHC [cm ² /g]	MAP 80/20	14.2 ^{abcA} ± 0.8	15.7 ^{bcdA} ± 0.3	16.3 ^{cdA} ± 0.8	17.8 ^{deA} ± 0.3
	MAP 50/50	12.8 ^{abA} ± 0.3	16.8 ^{cdeA} ± 0.7	16.1 ^{bcdA} ± 0.1	17.6 ^{deA} ± 0.5
	VP	12.4 ^{aA} ± 1.4	14.6 ^{abcdA} ± 2.1	16.1 ^{bcdA} ± 1.7	19.8 ^{eA} ± 1.9
Thermal drip [%]	MAP 80/20	22.3 ^{eA} ± 1.3	19.6 ^{cdA} ± 1.1	16.2 ^{abA} ± 0.8	14.5 ^{aA} ± 0.6
	MAP 50/50	20.6 ^{deA} ± 0.7	17.7 ^{bcA} ± 1.7	17.2 ^{bcA} ± 0.7	16.7 ^{abB} ± 0.9
	VP	22.1 ^{deA} ± 1.2	22.4 ^{eA} ± 1.2	21.6 ^{deB} ± 1.4	20.8 ^{deC} ± 0.7
TBARS [mg MDA/kg of product]	MAP 80/20	0.22 ^{aA} ± 0.02	0.82 ^{dB} ± 0.14	1.15 ^{eC} ± 0.06	3.46 ^{gC} ± 0.21
	MAP 50/50	0.24 ^{aA} ± 0.01	0.72 ^{cdB} ± 0.06	0.73 ^{cdB} ± 0.03	1.50 ^{fB} ± 0.12
	VP	0.19 ^{aA} ± 0.04	0.43 ^{abA} ± 0.01	0.26 ^{abA} ± 0.04	0.45 ^{bcA} ± 0.1
L*	MAP 80/20	48.3 ^{abcA} ± 1.4	48.8 ^{abcdA} ± 1.1	49.3 ^{bcdA} ± 1.4	50.9 ^{cdB} ± 0.1
	MAP 50/50	47.3 ^{abA} ± 0.4	49.8 ^{bcdA} ± 0.1	51.4 ^{dA} ± 1.1	51.0 ^{cdB} ± 0.9
	VP	46.2 ^{aA} ± 0.5	48.3 ^{abcA} ± 1.1	48.6 ^{abcdA} ± 2.0	46.7 ^{abA} ± 1.4
a*	MAP 80/20	19.4 ^{deA} ± 1.4	17.5 ^{cdB} ± 1.3	9.0 ^{bA} ± 0.3	7.1 ^{abA} ± 1.3
	MAP 50/50	18.9 ^{deA} ± 0.5	15.3 ^{cA} ± 0.2	6.9 ^{abA} ± 0.2	5.3 ^{aA} ± 0.8
	VP	18.8 ^{deA} ± 0.2	19.5 ^{deB} ± 0.8	20.7 ^{eB} ± 2.3	20.1 ^{deB} ± 0.3
b*	MAP 80/20	11.6 ^{abcA} ± 0.3	12.8 ^{cdeB} ± 0.4	11.0 ^{aA} ± 0.9	10.4 ^{aA} ± 0.9
	MAP 50/50	11.6 ^{abcA} ± 0.4	11.4 ^{abA} ± 0.7	10.6 ^{aA} ± 0.1	10.6 ^{aA} ± 0.3
	VP	11.0 ^{aA} ± 0.3	12.3 ^{bcdB} ± 0.3	13.5 ^{eB} ± 0.3	12.8 ^{cdeB} ± 0.4

Different lowercase letters (^{a–g}) indicate significant differences between all means determined by two-way analysis of variance ($p \leq 0.05$), while different uppercase letters (^{A–C}) indicate differences between means on a given day of designation determined by one-way analysis of variance ($p \leq 0.05$).

Water-holding capacity (WHC) and thermal drip are parameters that describe the ability of muscle proteins to retain water under different physical conditions, such as compression and heat treatment, respectively [39]. There were no significant differences ($p > 0.05$) in the WHC of ground beef packed under various methods. However, WHC values changed significantly ($p \leq 0.05$) during storage, regardless of the packaging method. The increase in WHC values over time indicates a deterioration in water-binding properties, as a greater surface area of exudate reflects reduced water retention within the muscle structure. These results indicate a deterioration in water-holding capacity (Table 1). These changes may be associated with progressive structural modifications of myofibrillar proteins and weakening of the muscle matrix, which alter water distribution within the meat system [39,40].

The effect of packaging method on thermal drip was observed only on days 14 and 21 of storage (Table 1). Ground beef stored under VP was characterized by significantly higher ($p \leq 0.05$) thermal drip than meat stored in MAP. Moreover, the thermal drip decreased during meat storage in MAP variants, whereas VP samples remained relatively stable. This tendency may be linked to the greater drip accumulation observed in MAP-

packaged meat during storage, so water released as purge was no longer available to be lost during subsequent heat treatment (Table 1).

At day 0, no significant differences ($p > 0.05$) in TBARS index values were observed among packaging variants (Table 1). However, during storage, TBARS index values increased significantly ($p \leq 0.05$) in ground beef stored under MAP. From day 7 VP beef was characterized by significantly lower TBARS index values compared to MAP variants, and from day 14, differences between MAP variants were also observed. The higher oxygen content in the gas mixture composition, the higher TBARS index values were observed.

With the extension of storage time, TBARS index values increased in beef from all packaging variants. On day 21, TBARS index values were the highest in MAP 80/20 samples and lower in MAP 50/50 samples, whereas VP samples maintained at low and relatively stable levels throughout storage. These indicate various dynamics of the production of MDA during storage depending on oxygen availability in the packaging system. Previous studies have shown that vacuum packaging effectively limits lipid oxidation; for example, Li et al. [41] reported that TBARS index values in vacuum-packed meat after 14 days were comparable to those of fresh meat at day 0. In contrast, meat stored in MAP with elevated oxygen levels was characterized by significantly higher TBARS values, confirming that oxygen availability promotes MDA formation. Peng et al. [42] reported that panelists first detected rancid odor at TBARS values of 0.5–1.0 mg MDA/kg, although MDA represents only part of the compounds responsible for off-odors. In our study TBARS index values in VP samples remained below this threshold level throughout storage, whereas MAP samples exceeded this range by day 14–21. Moreover, lipid oxidation processes promote myoglobin oxidation and a decrease in meat redness [42]. As oxidative processes intensify under high-oxygen MAP conditions, increased metmyoglobin formation may occur, contributing to discoloration, an effect also observed in the present study (Table 1). These oxidative changes were accompanied by corresponding changes in instrumental color parameters (L^* , a^* , and b^*), particularly a progressive decline in redness.

VP samples maintained relatively stable L^* values throughout storage time, whereas an increase in L^* was observed for MAP beef, particularly MAP 50/50. Similar trends have been previously reported [37]. Yang et al. [34] also demonstrated that steaks stored under VP maintained relatively stable L^* values over 14 days of refrigerated storage. Redness (a^* color component) was significantly lower in MAP beef variants on days 14 and 21 compared to VP meat, indicating progressive discoloration during storage. In contrast, VP samples maintained higher and more stable a^* values, suggesting that limited oxygen availability effectively slowed down myoglobin oxidation. The yellowness (b^* color component) showed a slight decreasing tendency in MAP variants. Significant differences ($p \leq 0.05$) between VP and MAP beef were observed on days 14 and 21. Changes in meat color were presented in Figure 2. Yang et al. [26] reported greater color stability in VP beef compared to meat stored under MAP. The observed changes in the color components of ground beef packed under different methods confirm that VP more effectively stabilizes color of meat during refrigerated storage compared to MAP.

Taken together, the increase in TBARS values and the decrease in a^* values suggest that lipid oxidation and color deterioration occurred simultaneously during storage, particularly in MAP 80/20 samples. According to Zhu et al. [43] and Uhlig et al. [44] microbial activity should also be considered as a potential additional factor affecting rancidity perception and color deterioration during refrigerated storage. Spoilage microorganisms may contribute to the formation of volatile metabolites, including aldehydes, ketones, sulfur compounds, and other off-odor compounds, which can intensify rancid or spoiled flavor perception. In addition, microorganisms such as *Pseudomonas* spp. may contribute to beef discoloration and browning. From a practical perspective, our results indicate that high-oxygen MAP

may support the desirable initial appearance of ground beef, but it can also accelerate oxidative discoloration and lipid deterioration during extended refrigerated storage.



Figure 2. Changes in color of ground beef during storage under MAP and VP.

3.3. Fat Content and Fatty Acids Profile of Ground Beef

The fat content of the ground beef studied is shown in Figure 3. The values ranged from 16.17 to 20.46% with a mean fat content of 17.89%. Differences in fat content most likely reflected natural variation among production batches rather than the effects of packaging or storage. According to Ramadan et al. [11], the typical composition of ground beef is about 18% lipids, and its fatty acid content is divided into 46% saturated, 51% mono-unsaturated, and 3% polyunsaturated.

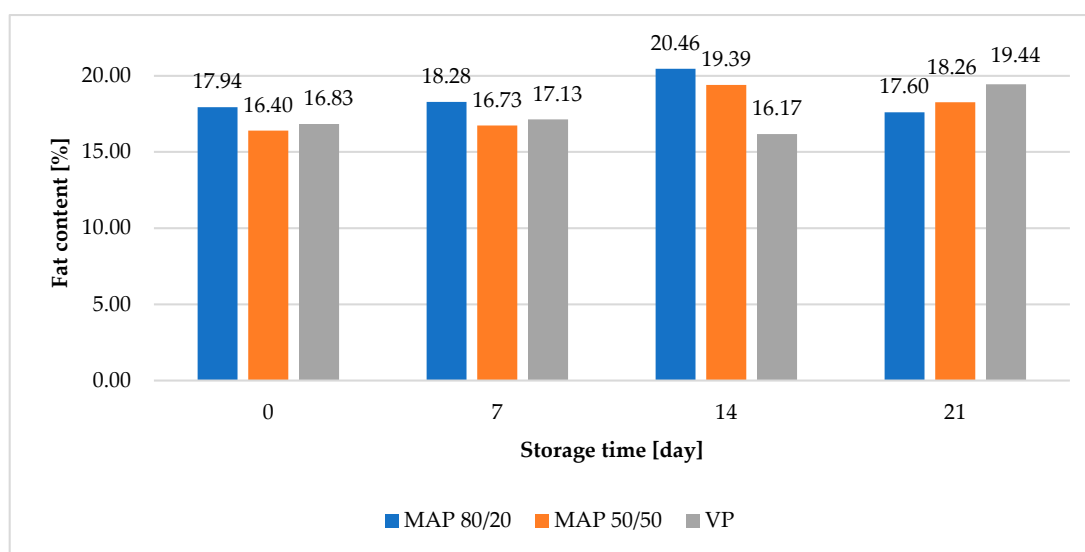


Figure 3. Fat content in the studied ground beef.

Storage conditions and packaging atmosphere may influence the fatty acid composition of meat and consequently affect the oxidative stability of its lipid fraction [45,46]. Therefore, fat extracted from ground beef stored under VP and MAP was analyzed by gas chromatography at defined storage times to determine potential changes in its fatty acid profile.

Table 2 presents the fatty acid composition of ground beef fat stored under different packaging systems. Regardless of packaging method of meat, oleic acid (C18:1n-9) was the predominant fatty acid, followed by palmitic (C16:0) and stearic acids (C18:0). Minor fatty acids included palmitoleic (C16:1) and myristic acids (C14:0). In MAP 80/20 samples, the fatty acid profile was primarily composed of oleic acid, palmitic acid, and stearic acid. In MAP 50/50 samples, the highest oleic acid levels were observed, while maintaining comparable proportions of palmitic and stearic acids. In VP samples, oleic acid was the predominant fatty acid, followed by palmitic and stearic acids (Table 2). Regardless of packaging variant, saturated fatty acids (SFA; 52–56%) represented the largest fraction of total fatty acids, followed by monounsaturated (MUFA; 42–46%) and polyunsaturated fatty acids (PUFA; 2%). This profile is consistent with previously reported data describing the dominance of oleic, palmitic, and stearic acids in beef lipids [17,47]. Also, Chmiel et al. [46] reported similar dominance of oleic, palmitic, and stearic acids in chicken fat.

Both storage time and packaging method affected the proportions of selected fatty acids in ground beef fat. Across all packaging variants, only minor fluctuations in individual fatty acids were observed, without a clear directional trend indicating extensive degradation. VP-packed samples generally maintained a relatively consistent fatty acid profile throughout storage time, suggesting limited oxidative modification under reduced oxygen availability. During storage, minor fluctuations in SFA proportions were observed, including a decrease on day 7, particularly in MAP 80/20 samples. The observed variation may reflect proportional shifts among lipid fractions, or natural batch-related variability. These observations are consistent with those reported by Vatansever et al. [48] and Vahmani et al. [49], who also found that beef fat rich in SFA exhibited higher oxidative stability compared with unsaturated fatty acids.

Interestingly, despite the significant increase in TBARS values during storage (Table 1), particularly in high-oxygen MAP samples, the proportional fatty acid composition remained relatively stable (Table 2). This suggests that the formation of secondary lipid oxidation products, reflected by MDA accumulation, may occur without marked changes in the overall fatty acid distribution. Oxidative reactions were sufficient to generate secondary oxidation products, but not extensive enough to markedly alter the relative proportions of major fatty acids within the studied storage period. Moreover, because fatty acids were expressed as relative percentages rather than absolute concentrations, possible decreases in individual fatty acids may have been masked if oxidation occurred proportionally across lipid fractions. From a nutritional perspective, the limited changes in SFA, MUFA, and PUFA proportions suggest that the overall fatty acid composition of ground beef was largely preserved. However, the increase in oxidation markers, particularly under high-oxygen MAP, indicates that lipid quality may deteriorate even when the proportional fatty acid profile remains relatively stable.

Table 2. The fatty acid profile of ground beef packed under various methods.

Compound [%]	Packaging Variant	Storage Time [Day]			
		0	7	14	21
C14:0	MAP 80/20	4.81 ± 0.70	3.49 ± 0.06	3.41 ± 0.10	3.41 ± 0.11
	MAP 50/50	3.68 ± 0.25	3.69 ± 0.08	3.43 ± 0.03	3.65 ± 0.11
	VP	4.13 ± 0.17	3.88 ± 0.23	3.53 ± 0.03	3.86 ± 0.50

Table 2. Cont.

Compound [%]	Packaging Variant	Storage Time [Day]			
		0	7	14	21
C14:1	MAP 80/20	2.23 ± 0.28	1.68 ± 0.03	1.62 ± 0.05	1.63 ± 0.05
	MAP 50/50	1.73 ± 0.11	1.77 ± 0.05	1.61 ± 0.03	1.78 ± 0.07
	VP	1.92 ± 0.11	1.81 ± 0.12	1.61 ± 0.01	1.78 ± 0.22
C16:0	MAP 80/20	30.64 ± 2.77	26.02 ± 0.04	26.41 ± 0.17	26.14 ± 0.28
	MAP 50/50	26.54 ± 0.84	26.50 ± 0.18	25.87 ± 0.03	26.35 ± 0.33
	VP	29.37 ± 0.10	27.45 ± 0.79	26.34 ± 0.11	27.00 ± 0.95
C16:1	MAP 80/20	4.60 ± 0.52	3.93 ± 0.05	4.03 ± 0.09	3.87 ± 0.04
	MAP 50/50	4.50 ± 0.37	3.97 ± 0.04	3.86 ± 0.03	3.98 ± 0.08
	VP	4.46 ± 0.05	4.08 ± 0.18	3.93 ± 0.01	3.94 ± 0.18
C17:0	MAP 80/20	1.51 ± 0.03	1.49 ± 0.01	1.34 ± 0.01	1.42 ± 0.04
	MAP 50/50	1.51 ± 0.03	1.41 ± 0.01	1.35 ± 0.01	1.45 ± 0.04
	VP	1.62 ± 0.01	1.54 ± 0.04	1.36 ± 0.01	1.49 ± 0.02
C18:0	MAP 80/20	17.12 ± 1.16	19.43 ± 0.12	19.31 ± 0.05	19.63 ± 0.02
	MAP 50/50	19.13 ± 0.38	18.82 ± 0.38	19.41 ± 0.02	19.19 ± 0.10
	VP	18.92 ± 0.04	20.02 ± 0.42	19.81 ± 0.13	19.67 ± 0.55
C18:1 n9	MAP 80/20	33.85 ± 3.16	38.62 ± 0.04	38.99 ± 0.46	38.38 ± 0.26
	MAP 50/50	37.57 ± 0.18	38.24 ± 0.59	38.50 ± 0.25	38.33 ± 0.18
	VP	33.86 ± 0.05	36.39 ± 0.86	38.24 ± 0.29	37.38 ± 1.50
Other	MAP 80/20	5.25 ± 0.14	5.38 ± 0.04	4.91 ± 0.08	5.55 ± 0.18
	MAP 50/50	5.38 ± 0.30	5.64 ± 0.19	5.98 ± 0.09	5.27 ± 0.22
	VP	5.74 ± 0.06	4.87 ± 0.04	5.19 ± 0.25	4.89 ± 0.16
ΣSFA	MAP 80/20	56.09 ^{cA} ± 4.93	52.35 ^{abA} ± 0.25	52.33 ^{abA} ± 0.38	52.47 ^{abA} ± 0.56
	MAP 50/50	52.73 ^{abA} ± 1.61	52.44 ^{abA} ± 0.68	51.90 ^{aA} ± 0.22	52.56 ^{abA} ± 0.68
	VP	56.17 ^{cA} ± 0.39	54.75 ^{bcB} ± 1.59	52.91 ^{abB} ± 0.40	53.94 ^{abcA} ± 2.19
ΣMUFA	MAP 80/20	42.05 ^{abA} ± 4.03	45.57 ^{cB} ± 0.16	45.74 ^{cB} ± 0.68	45.09 ^{cA} ± 0.39
	MAP 50/50	45.14 ^{cA} ± 0.78	45.17 ^{cB} ± 0.72	45.14 ^{cA} ± 0.36	45.28 ^{cA} ± 0.36
	VP	41.79 ^{aA} ± 0.67	43.56 ^{abcA} ± 1.20	44.85 ^{cA} ± 0.38	44.20 ^{bcA} ± 1.95
ΣPUFA	MAP 80/20	1.87 ^{abA} ± 0.13	2.09 ^{abcAB} ± 0.25	1.94 ^{abcA} ± 0.08	2.45 ^{cdB} ± 0.25
	MAP 50/50	2.15 ^{abcA} ± 0.35	2.42 ^{bcdB} ± 0.22	2.96 ^{dB} ± 0.16	2.15 ^{abcAB} ± 0.26
	VP	2.03 ^{abcA} ± 0.05	1.71 ^{aA} ± 0.10	2.24 ^{abcA} ± 0.31	1.87 ^{abA} ± 0.18

Different lowercase letters (^{a–d}) indicate significant differences between all means determined by two-way analysis of variance ($p \leq 0.05$), while different uppercase letters (^{A,B}) indicate differences between means on a given day of designation determined by one-way analysis of variance ($p \leq 0.05$).

3.4. Oxidation Kinetics and Melting Characteristics of Ground Beef

The fat in meat is prone to oxidation during storage. The kinetics of oxidation of lipids depend on the packaging method, fatty acid profile of the fat and accessibility to oxygen. Oxidation leads to product spoilage, deterioration of sensory attributes, and a reduction in nutritional value [3]. In the present study, oxidation kinetic parameters were evaluated at 7-day intervals over 21 days of storage (Table 3). The activation energy (E_a) derived from PDSC reflects the energy barrier that must be overcome for oxidation to proceed. Therefore, higher E_a values indicate greater resistance of lipids to oxidative degradation and are commonly used as an indicator of oxidative stability [50]. Initial E_a was measured at approximately 81 kJ/mol for all meat samples, indicating comparable baseline oxidative stability. On day 7, a slight decrease was observed, with the lowest E_a recorded for samples stored under MAP 80/20 and the highest under MAP 50/50.

Table 3. Oxidation kinetic parameters of ground beef fat.

Parameter	Packaging Variant	Storage Time [Day]			
		0	7	14	21
a	MAP 80/20	4.472	4.163	4.781	4.784
	MAP 50/50	4.46	4.37	4.414	4.459
	VP	4.467	4.305	4.375	4.629
b	MAP 80/20	10.551	9.915	11.296	11.361
	MAP 50/50	10.601	10.332	10.475	10.651
	VP	10.547	10.238	10.436	10.99
R ²	MAP 80/20	0.9952	0.9978	0.9977	0.9926
	MAP 50/50	0.9921	0.9931	0.9924	0.9812
	VP	0.9937	0.98	0.9938	0.9942
<i>E_a</i> [kJ/mol]	MAP 80/20	81.52	75.79	87.05	87.1
	MAP 50/50	81.26	79.56	80.36	81.18
	VP	81.32	78.37	79.65	84.26
logZ	MAP 80/20	8.88	8.27	9.59	9.66
	MAP 50/50	8.83	8.67	8.8	8.98
	VP	8.87	8.58	8.77	9.3
Z	MAP 80/20	7.47×10^8	1.86×10^8	3.90×10^9	4.53×10^9
	MAP 50/50	7.40×10^8	4.64×10^8	6.38×10^8	9.47×10^8
	VP	7.44×10^8	3.79×10^8	5.88×10^8	1.99×10^9
k at 100 °C	MAP 80/20	3.20×10^{-3}	4.83×10^{-3}	2.71×10^{-3}	3.09×10^{-3}
	MAP 50/50	3.30×10^{-3}	3.59×10^{-3}	3.81×10^{-3}	4.34×10^{-3}
	VP	3.26×10^{-3}	4.91×10^{-3}	4.42×10^{-3}	3.39×10^{-3}
k at 110 °C	MAP 80/20	6.48×10^{-3}	9.11×10^{-3}	5.62×10^{-3}	6.41×10^{-3}
	MAP 50/50	6.37×10^{-3}	6.98×10^{-3}	7.47×10^{-3}	8.56×10^{-3}
	VP	6.44×10^{-3}	8.28×10^{-3}	8.61×10^{-3}	6.86×10^{-3}
k at 120 °C	MAP 80/20	1.26×10^{-2}	1.66×10^{-2}	1.12×10^{-2}	1.28×10^{-2}
	MAP 50/50	1.21×10^{-2}	1.31×10^{-2}	1.42×10^{-2}	1.63×10^{-2}
	VP	1.23×10^{-2}	1.54×10^{-2}	1.62×10^{-2}	1.34×10^{-2}
k at 130 °C	MAP 80/20	2.28×10^{-2}	2.95×10^{-2}	2.17×10^{-2}	2.48×10^{-2}
	MAP 50/50	2.24×10^{-2}	2.40×10^{-2}	2.60×10^{-2}	3.02×10^{-2}
	VP	2.27×10^{-2}	2.79×10^{-2}	2.96×10^{-2}	2.53×10^{-2}
k at 140 °C	MAP 80/20	4.11×10^{-2}	5.09×10^{-2}	4.06×10^{-2}	4.63×10^{-2}
	MAP 50/50	4.06×10^{-2}	4.25×10^{-2}	4.63×10^{-2}	5.41×10^{-2}
	VP	4.08×10^{-2}	4.90×10^{-2}	5.25×10^{-2}	4.65×10^{-2}
k at 150 °C	MAP 80/20	7.18×10^{-2}	8.56×10^{-2}	7.36×10^{-2}	8.41×10^{-2}
	MAP 50/50	7.21×10^{-2}	7.33×10^{-2}	8.03×10^{-2}	9.43×10^{-2}
	VP	7.12×10^{-2}	8.39×10^{-2}	9.06×10^{-2}	8.28×10^{-2}

As storage progressed, *E_a* increased in all samples, reaching the highest value on day 21 in MAP 80/20, whereas MAP 50/50 exhibited the lowest. The initial decrease in *E_a* observed in MAP 80/20 corresponds with an increase in TBARS values (Table 1), indicating accelerated primary lipid oxidation under high-oxygen conditions during later storage stages may reflect depletion of highly oxidizable lipid fractions and a shift toward oxidation of more stable substrates. The higher *E_a* values observed in MAP 80/20 at later storage stages suggest increased resistance of the remaining lipid fraction to further oxidation. In general, increased activation energy corresponds to slower reaction rates and greater oxidative stability of the residual lipid matrix [50]. The increase in *E_a* during

prolonged storage may suggest changes in the oxidative susceptibility of the lipid fraction. One possible explanation is that the most reactive lipid components were preferentially involved in oxidation during the earlier stages of storage, whereas the remaining lipid matrix required greater energy input to undergo further oxidative reactions. However, because the fatty acid profile was expressed as relative percentages and showed only minor proportional changes over time, this mechanism cannot be directly confirmed from the present fatty acid data. In addition, the accumulation of secondary oxidation products (e.g., aldehydes, ketones, hydroperoxide breakdown compounds) can also contribute to increased E_a values. A similar trend was also observed for the olive oil samples [51].

The melting behavior of beef fat was evaluated using differential scanning calorimetry (DSC) to evaluate whether packaging atmosphere and storage time influenced thermal transitions of the lipid fraction. The DSC graphs (Figure 4) reflecting melting characteristics of fat show four main thermal events in the temperature range approximately between -0.9 °C to 43.5 °C. The courses of the DSC curves of the studied beef fat do not differ significantly among packaging variants and storage time. The melting curves of fats reflect their triacylglycerol (TAG) profiles, and their registration is a method of material authentication [22]; thus, packaging method or storage time does not influence their course significantly. Zhang et al. [23] studied the melting characteristics of different mutton tallows and beef tallow. All the fat samples had a similar course of the DSC curve, with thermal events occurring between -20 °C and 55 °C. Authors explained occurrence of the peaks in higher temperatures by earlier melting of some unstable crystal structures and the recrystallization of the remaining TAGs fractions to form more stable crystal structures.

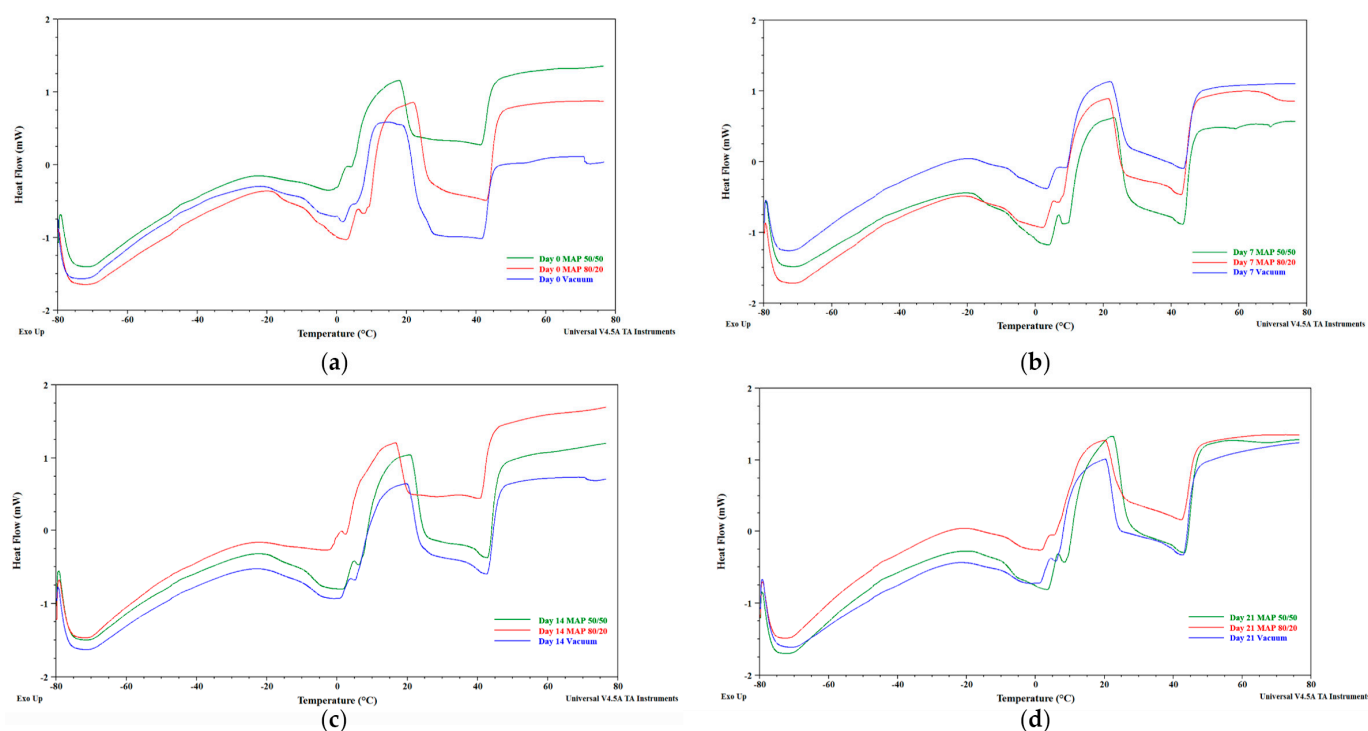


Figure 4. The examples of DSC curves obtained for ground beef fat: (a) day 0, (b) day 7, (c) day 14 and (d) day 21 of storage.

Comparison with plant oils further emphasises the influence of fatty acid composition on melting behavior. Oils rich in unsaturated triacylglycerols exhibit melting transitions at substantially lower temperatures (-47 to -21 °C), as reported for apricot and peach kernel oils [52] and berry seed oils [53]. In contrast, the higher melting temperatures observed in ground beef fat (40 – 45 °C) are associated with its greater proportion of saturated and long-

chain triacylglycerols. The minor thermal variations detected during storage are therefore more likely related to oxidative or hydrolytic modifications within existing lipid fractions rather than to alterations in overall lipid class composition. The stability of melting curves is consistent with the relatively unchanged fatty acid composition observed during storage, confirming that oxidative processes did not substantially modify the triacylglycerol matrix over the studied storage period.

From an applied research perspective, DSC and PDSC analyses provide additional information that may help explain why packaging systems differ in their effect on lipid stability. These techniques allow a deeper characterization of the lipid fraction by showing whether oxidative changes are accompanied by alterations in oxidative resistance or melting behavior. Such information may be useful for developing evidence-based recommendations for packaging selection and for designing storage strategies that balance color stability, lipid quality, and expected shelf life of ground beef.

3.5. Acid Value

The acid value is one of the key indicators of fat quality, reflecting the extent of lipid degradation resulting primarily from hydrolytic reactions. This parameter expresses the concentration of free fatty acids (FFAs) released due to lipolytic enzyme activity and autoxidative lipid breakdown [54]. Packaging methods can influence the rate of these transformations and, consequently, the oxidative stability of meat fat [12].

The packaging method had a significant ($p < 0.05$) effect on the acid value (AV). The highest AV were observed for VP samples. Moreover, the acid value increased progressively during refrigerated storage, regardless of packaging method (Table 4). Most differences between storage days were significant ($p \leq 0.05$). The slowest increase in acid value was observed in samples packed under MAP 50/50, whereas VP samples showed the most pronounced increase by the end of storage.

Table 4. Acid values of ground beef fat.

Packaging Variant	Storage Time [Day]			
	0	7	14	21
MAP 80/20	0.2986 ^{aA} $\pm$ 0.0043	2.2445 ^{dB} $\pm$ 0.0035	2.9580 ^{gB} $\pm$ 0.0050	4.0513 ^{jB} $\pm$ 0.0015
MAP 50/50	0.3399 ^{bB} $\pm$ 0.0028	2.1378 ^{cA} $\pm$ 0.0030	2.7837 ^{fA} $\pm$ 0.0047	3.6239 ^{iA} $\pm$ 0.0040
VP	0.3524 ^{bC} $\pm$ 0.0006	2.4294 ^{eC} $\pm$ 0.0075	3.3237 ^{hC} $\pm$ 0.0007	4.3505 ^{kC} $\pm$ 0.0074

Different lowercase letters (^{a-k}) indicate significant differences between all means determined by two-way analysis of variance ($p \leq 0.05$), while different uppercase letters (^{A-C}) indicate differences between means on a given day of designation determined by one-way analysis of variance ($p \leq 0.05$).

These findings indicate that modified atmosphere packaging, particularly with a 50% O₂ and 50% CO₂ gas mixture, more effectively slowed the increase in acid value compared to vacuum packaging. This effect may be attributed to carbon dioxide, which can inhibit lipolytic and oxidative processes by reducing oxygen availability [55]. Similar trends have been reported in the literature. Wang et al. [56] observed a consistent increase in acid value during storage of pork under both VP and MAP, with VP samples showing the greatest increase (approximately 6 mg KOH/g fat after 14 days) compared to MAP (5.5 mg KOH/g fat). Likewise, Karpińska-Tymoszczyk [57] found that after 30 days of refrigerated storage of turkey meat in MAP, a lower acid value (4.6 mg KOH/g fat) than in VP (5.8 mg KOH/g fat) was observed. The author attributed this effect to the presence of CO₂ in MAP, which limited hydrolytic degradation more efficiently than the anaerobic conditions of VP. The observed gradual increase in acid value across all packaging types reflects the ongoing hydrolytic and oxidative decomposition of lipids during storage. However, the slower rate of change under MAP confirms that oxygen concentration plays a decisive role in

modulating lipid stability. The simultaneous increase in acid value and TBARS indicates that hydrolytic and oxidative degradation proceeded in parallel.

From a practical perspective, the choice of packaging system for ground beef should be guided by the intended storage period, target quality attributes, and market requirements. High-oxygen modified atmosphere packaging may support the attractive bright-red appearance of fresh beef during the early stages of storage; however, prolonged oxygen exposure accelerates lipid oxidation, leading to increased TBARS values and progressive color deterioration. In contrast, vacuum packaging more effectively limited lipid oxidation expressed as TBARS and maintained color stability during storage, although higher acid values indicated that hydrolytic changes may occur independently of oxidative deterioration. Therefore, selecting an appropriate packaging system requires balancing retail visual appeal, oxidative stability, and the expected shelf life of the product.

4. Conclusions

Packaging method and storage time affected the quality parameters of ground beef containing approximately 18–20% fat, including oxidative stability. Lipid oxidation progressed during storage; however, its intensity depended on the packaging type. The MAP with high oxygen content (80% O₂ and 20% CO₂) promoted the fastest oxidative changes, as evidenced by increased TBARS values and a decrease in redness (a*), whereas VP most effectively limited TBARS increase and maintained color stability throughout the 21 days of storage. Despite the increase in oxidation markers, the overall fatty acid composition and DSC melting characteristics remained relatively stable, suggesting that oxidative changes did not substantially modify the proportional fatty acid profile or the triacylglycerol matrix under the conditions applied in this study.

A limitation of the present study is that microbiological quality was not evaluated. Consequently, the mechanisms responsible for changes in pH and package gas composition could not be directly related to microbial activity. Future studies should combine microbiological analyses with physicochemical, lipid oxidation, and thermal measurements to provide a more comprehensive understanding of quality changes occurring in ground beef during refrigerated storage under different packaging systems.

From a practical perspective, packaging selection for ground beef should balance retail color attractiveness with oxidative stability and the expected storage period. High-oxygen MAP may be suitable for short-term retail display, whereas VP offers greater protection against secondary lipid oxidation during extended refrigerated storage. MAP 50/50 may represent an intermediate option by reducing oxidative changes compared with MAP 80/20. These results may support the development of packaging strategies aimed at shelf-life optimization and quality preservation of ground beef.

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