

Effect of high-oxygen and oxygen-free modified atmosphere packaging on the spoilage process of poultry breast fillets

Sonja Rossaint,¹ Sonja Klausmann, and Judith Kreyenschmidt

University of Bonn, Faculty of Agriculture, Institute of Animal Science, Cold-Chain Management Group, Katzenburgweg 7-9, 53115 Bonn, Germany

ABSTRACT A comparison was made of the effect of atmospheres containing high oxygen (70% O₂ and 30% CO₂) or high nitrogen (70% N₂ and 30% CO₂) on the spoilage process during storage (at 4°C) of poultry fillets. Four samples of each gas atmosphere were analyzed at 7 sample points during storage. For this analysis, the growth of typical spoilage organisms (*Brochothrix thermosphacta*, *Pseudomonas* spp., *Enterobacteriaceae*, and *Lactobacilli* spp.) and total viable count (TVC) were analyzed and modeled by using the Gompertz function. Sensory analyses of the poultry samples were carried out by trained sensory panelists to analyze color, odor, texture, drip loss, and general appearance.

The composition of the spoilage flora differed between the oxygen-free atmosphere and the high-oxygen atmosphere. Anaerobic conditions favored the growth of *Lactobacilli* spp., whereas aerobic gas composition favored the growth of *B. thermosphacta*. However, no significant difference ($P < 0.05$) in TVC and sensory parameters were observed for poultry samples stored under a high-oxygen atmosphere in comparison to a high-nitrogen atmosphere.

These results indicate that high-oxygen packaging has no additional beneficial effect on the quality maintenance and shelf life of fresh poultry fillets.

Key words: high-oxygen packaging, modified atmosphere packaging, chicken breast fillets, spoilage flora, shelf life

2015 Poultry Science 94:96–103
<http://dx.doi.org/10.3382/ps/peu001>

INTRODUCTION

During recent years, the application of modified atmosphere packaging (MAP) has increased in the poultry industry. The commonly used gases for MAP poultry are oxygen, carbon dioxide, and nitrogen as filling gas (Dangel, 2006). Despite the recommendation of several gas manufacturers in Europe to pack light poultry under an atmosphere composed of carbon dioxide and nitrogen, different kinds of atmospheres are also used for poultry. Several producers in the German poultry industry are using high concentrations of oxygen to pack fresh poultry (unpublished data IQ-Freshlabel project).

The main reason for high-oxygen packaging is to preserve the red color in red meats, which is caused by the muscle pigments myoglobin and hemoglobin (Phillips, 1996; Totosaus et al., 2007). The pigments can occur in different forms: the desired bright red oxymyoglobin, the purple deoxymyoglobin, and the undesirable grey-brown metmyoglobin (Mullan and McDowell, 2003). For fresh meat, the required oxymyoglobin is stable in an oxygen-rich environment, and therefore high percentages of oxygen are used for MA packing

of red meat (Buchner, 1999). The high oxygen levels saturate the meat pigments with oxygen, thus slowing the formation of metmyoglobin (Cornforth and Hunt, 2008). Poultry breast muscles are less-used muscles with a low quantity of myoglobin and are considered to be white meat (McKee, 2007). The amount of myoglobin in chicken breast muscle varies between 0.15 and 0.31 mg/g, depending on the extractability from muscle tissue (Kranen et al., 1999). Therefore, the positive effect of high oxygen concentrations for poultry packaging is discussed here (Löwenadler, 1994).

Millar et al. (1994) recommended in their study that chicken breast samples had a limited capacity to form oxymyoglobin. Moreover, the authors considered that the high-oxygen packaging method for beef should be adopted by poultry packagers with caution because the color of poultry meat is not as significant to the consumer as that of beef. Saucier et al. (2000) determined that the color of ground chicken and turkey meat remained more stable in an oxygen-free atmosphere. This is also confirmed by the investigations of Dhananjayan et al. (2006), who found that the surface color of ground turkey breast patties in an 80% O₂ atmosphere is less stable compared with patties in a 97% CO₂ atmosphere. Moreover, the high-carbon dioxide atmosphere inhibited the growth of microorganisms. Also, Sante et al. (1994) found that poultry packed in a 100% CO₂

© 2014 Poultry Science Association Inc.

Received June 13, 2013.

Accepted October 2, 2014.

¹Corresponding author: rossaint@uni-bonn.de

atmosphere shows the best color stability and lowest microbial counts, in comparison to 100% O₂, 100% N₂, or a mixture of 25% CO₂, 66% O₂, and 9% N₂.

In addition to the effect on the product's color, different gas concentrations also influence the composition of the spoilage flora. The use of CO₂ and N₂ extends the lag phase of aerobic microorganisms and favors the growth of facultative and anaerobic microorganisms. This causes a shift in the microbial flora from aerobic bacteria, such as *Pseudomonas* spp., to facultative and anaerobic bacteria such as lactic acid bacteria. As a consequence, the spoilage characteristics also change (McKee, 2007). The facultative anaerobic microorganism *Brochothrix thermosphacta* is one of the main spoilage organisms of MAP meat (Kakauri and Nychas, 1994; Ordóñez et al., 1991). Pin et al. (2002) reported that CO₂ and O₂ content affects the metabolites resulting from the consumption of glucose by *B. thermosphacta*. Because anaerobic metabolism produces less intense odors than aerobic metabolism, the authors recommend the use of a low oxygen concentration in MA packaging. Jayasingh et al. (2002) indicated that a high O₂ content of 80% leads to significant development of rancid off-flavor in MAP ground beef.

Based on the above, it is debatable whether the use of high-oxygen packaging for poultry is beneficial when compared to an oxygen-free nitrogen-containing atmosphere. At present, there is no poultry breast meat study that compares the commonly used gas atmosphere of 70% O₂ and 30% CO₂ (e.g., as is done in Germany) with the recommended oxygen-free high-nitrogen atmosphere (70% N₂ and 30% CO₂). Most of the existing studies compare extreme gas compositions, such as 100% CO₂ (Sante et al., 1994), that are not used in practice. Therefore, the aim of this study is to compare the spoilage process of MA-packaged poultry meat under the usual high-oxygen atmosphere and the recommended N₂-containing oxygen-deficient atmosphere stored at 4°C.

MATERIALS AND METHODS

Sample Preparation

Fresh boneless and skinless broiler chicken breast fillets were used as test samples. The fillets from unisex 42-d-old broiler chickens (Ross 308 and 708) were obtained as double breast fillets from a German slaughtering and processing plant. For transportation, the fillets were wrapped in polypropylene (PP) foil and packed in a cardboard box. Samples were transported to a German wholesaler and forwarded to a local retailer. The fillets were then transported to the laboratory under temperature-controlled conditions within 24 hours after slaughtering.

Before repackaging at the laboratory, a sterile scalpel was used to divide the double breasts into two single breast fillets. To achieve a head-to-product ratio of

nearly 3:1, the inner fillet was removed, resulting in a weight of approx. 230 g for each fillet.

Packaging and Storage Conditions

The chicken fillets were packed in the laboratory in polypropylene trays (680 mL, R. Fearch Plast A/s, Holstebro, Denmark) using a tray sealer packaging machine (Traysealer T200 Multivac Sepp Haggemüller GmbH & Co. KG, Wolfertschwenden, Germany). As lidding film, a low-gas and water vapor-permeable polypropylene foil was used (Top Tray 50 LAF, SÜDPACK Verpackungen GmbH & Co. KG, Ochsenhausen, Germany) with an oxygen transmission rate of $</ = 1,5 \text{ cm}^3/\text{m}^2 \text{ d bar}$.

The gas mixtures 70% N₂ and 30% CO₂, and 70% O₂ and 30% CO₂ were adjusted by a 4-component gas blender machine (WITT-GASETECHNIK GmbH & Co KG, Witten, Germany) (hereinafter referred to as a nitrogen [70% N₂] or an oxygen [70% O₂] atmosphere). For technical reasons, the N₂ atmosphere contained residual oxygen (0.4–0.6%).

Packaged samples were stored at 4°C under controlled temperature conditions in a low-temperature high-precision incubator (Sanyo MIR-254, Sanyo Electric Co., Ora-Gun, Gumma, Japan).

Air temperature was recorded every 5 min by data loggers (ESCORT JUNIOR Temperature Recorder, Escort, New Zealand).

Gas composition, sensory, and microbial parameters were determined after 0, 3, 6, 9, 12, 15 and 20 d. In total, 56 poultry fillets were investigated. For each test day, 2 samples per gas atmosphere were prepared, and the storage test was repeated twice. Thus, at one investigation point for each scenario, four samples were tested.

Microbiological Analyses

For microbiological analyses, 25 g of the sample surface were separated under sterile conditions with a scalpel and transferred to a filtered Stomacher bag with 225 mL saline peptone diluent (0.85% NaCl with 0.1% peptone Saline-Tablets, Oxoid Br0053G, Cambridge, England) and homogenized for 60 s in a Stomacher (Stomacher BagMixer Interscience, Saint Nom, France). Serial decimal dilutions of the homogenates were prepared using saline peptone diluent. Total viable count (TVC) was determined on plate count agar (PCA, Merck, Darmstadt, Germany), and plates were incubated at 30°C for 72 h.

Presumptive *Pseudomonas* spp. were determined by spread plate technique on *Pseudomonas* agar with cetrinide fucidin cephaloridine (CFC) selective supplement (Oxoid, Cambridge, England). The incubation period was 48 h at 25°C.

Presumptive *Brochothrix thermosphacta* were detected on streptomycin inositol toluylene red agar

(SIN agar) referring to the method of Hechelmann (1981), using the drop plate technique (Sheep Blood Agar Base, Oxoid, Cambridge, England). Plates were incubated at 25°C for 48 h. Presumptive *Enterobacteriaceae* were identified by overlay treatment on violet red bile dextrose agar (VRBD, Merck, Darmstadt, Germany). Petri dishes were incubated for 48 h at 30°C. De Man, Rogosa, Sharpe agar (MRS, Oxoid, Cambridge, England) was used to presumptively identify *Lactobacillus* spp. (LAB) by pour plate technique. Plates were incubated aerobically at 37°C for 72 h. All amounts of colony-forming units were expressed as log₁₀ cfu/g. Two samples per gas atmosphere were examined on each test day. The storage test was repeated twice. Therefore, the number of colony-forming units is the average of four samples.

Sensory Analysis

Sensory analysis of the chicken breast fillets was completed by a trained sensory panel of 5 people. All sensory test personnel were recruited from the Institute of Animal Science (University of Bonn) and were experienced in poultry evaluation. Before the test trials started, the panelists completed an intensive training session that provided descriptions and definitions of typical sensory attributes at different stages of spoilage during storage. During the test series, after opening the tray, each sample was evaluated directly via the developed sensory scheme the panelists learned about in their training (Table 1). The scheme included the predefined detail descriptions of the sensory attributes. For optical evaluation, a picture of a fresh chicken breast fillet was used as reference. The texture was assessed by cutting and pressing the sample. General appearance (G), odor (O), color (C), texture (T), drip loss (D), and cut (Z) were rated using a 5-point scoring system (1 = highest quality; 5 = unacceptable quality). A weighted sensory quality index (QI) was calculated (Kreyenschmidt et al., 2010; Herbert et al., 2013) (Eq. 1.1). The end of shelf life was achieved at a QI of 2.5 or if a parameter was evaluated with 5 points.

$$QI = \frac{2 * G + 2 * C + T + 2 * O + D + 0.5Z}{8.5} \quad (1.1)$$

Gas Analysis

The CO₂ and O₂ concentrations were measured with a handheld gas analyzer (OXYBABY O₂/CO₂ WITTE-GASETECHNIK GmbH & Co KG, Witten, Germany). Before starting the gas measurement inside the trays, the composition of air was analyzed to control the accuracy of the gas analyzer. Headspace gas concentration was measured by penetration with a syringe needle into the lidding film. The oxygen concentration was detected by an electrochemical sensor, and the carbon

dioxide concentration was detected by infrared (IR) spectrophotometer.

Gas concentrations were recorded as volume percentages of the total packaging atmosphere. Reference samples without products were stored, and gas compositions were measured parallel to the atmosphere inside the sample packages.

Data Analysis

The growth data of TVC, *Pseudomonas* spp., *Brochothrix thermosphacta*, *Enterobacteriaceae*, and *Lactobacillus* spp. were analyzed by the statistical software Origin 8.0G (OriginLab Corporation, Northampton, MA). The Gompertz model (Eq. 1.2) was used as the primary model to describe the growth of microorganisms with time (Gibson et al., 1987):

$$N(t) = A + C \cdot e^{-e^{-B \cdot (t-M)}} \quad (1.2)$$

with N(t): microbial count [log₁₀ cfu/g] at time t; A: lower asymptotic line of the growth curve (N₀ = initial bacterial count [log₁₀ cfu/g]); C: difference between upper asymptotic line of the growth curve (N_{max} = maximum population level [log₁₀ cfu/g]) and the lower asymptotic line (A [log₁₀ cfu/g]); B: relative growth rate at time M [h⁻¹]; M: time at which maximum growth rate is obtained (reversal point); t: time [h].

Statistical Analysis

For each scenario, 4 samples were tested at 1 investigation point. For data analysis, the mean value of the four samples was calculated.

The Mann–Whitney U test was used to compare the measured counts of colony-forming units and sensory evaluation with a level of significance of 0.05. SPSS Statistics 20 for Windows was used.

RESULTS AND DISCUSSION

Gas Composition Development on Packed Poultry Breast Fillets

The starting oxygen concentration of the nitrogen-containing packs varied between 0.4 and 0.6% due to technical limitations (n = 4). At the beginning of storage, a decrease of CO₂ could be measured in both atmospheres (O₂/CO₂: approx. 5%; N₂/CO₂: approx. 10%; data not shown). This is due to the high solubility of carbon dioxide in fat tissue and water on the meat surface (Betts, 1995; Gill, 1988). Parra et al. (2010) and Dhananjayan et al. (2006) reported similar results. Throughout the entire storage period, the O₂ concentration inside the trays showed a small decrease. This was caused by microbiological consumption of O₂, the respiration of meat enzymes, and gaseous exchanges

Table 1. Sensory scheme.

Sensory attribute	Detail description of the sensory attribute	Score
General appearance	Fresh, bright pink color, no or very slight drip loss, no discoloration, glossy and smooth surface, succulent, white fat	1
	Fresh, bright pink color, slight drip loss, slight discoloration, glossy, white fat	2
	Less fresh, drip loss, slight discoloration, little or no glossiness, dry spots (at the sites), white to yellowish fat	3
	Grey to yellowish color, obvious drip loss, dark dry spots, soft and dull surface, forming threads, yellowish fat	4
	Yellowish to brownish color, strong drip loss, sticky, slimy, dappled surface, yellowish to brownish fat	5
Color	Fresh, bright pink color, no discoloration, glossy, white fat	1
	Bright pink to red color, pale, slight discoloration, glossy, white fat	2
	Pale, grayish to yellowish color, less glossy to dull, slight discoloration (especially at the sides and edges), white to yellowish fat	3
	Dirty brownish to yellowish color, dry spots, discolorations, dull surface, yellowish fat	4
	Yellowish to brownish color, white colonies, dappled surface, yellowish to brownish fat	5
Drip loss	No drip loss	1
	Very slight drip loss, limpid to slightly pink	2
	Slight drip loss, minor discoloration (pink, cloudy)	3
	Drip loss, light brownish to yellowish, grayish, cloudy	4
	Clear drip loss, brownish, yellowish, dirty and cloudy	5
Cutting	Double breast fillet	1
	Single breast fillet	2
	Fresh, characteristic for meat, neutral	1
	Slightly sour, characteristic for meat, neutral	2
	No longer fresh, slightly changed odor (sweet, sour), atypical	3
Odor	Fruity or musty, slightly sour, sharp	4
	Old, musty, sweet, rancid, sharp, cheesy	5
	Flexible, no loss of structure, smooth, solid	1
	Less flexible, slight loss of structure	2
	Little flexibility, loss of structure, dry spots	3
Texture	No flexibility, soft, slushy consistency, strong loss of structure, forming threads	4
	Soft, loosely, slushy, sticky to slimy, complete loss of structure	5

between the gas inside the trays and the environment (Mullan and McDowell, 2003).

Microbial Development on Packed Poultry Breast Fillets

Development of TVC values for poultry fillets packaged under a nitrogen and under an oxygen atmosphere are shown in Figure 1. The initial TVC are nearly the same for the samples packed under oxygen (3.2 log₁₀ cfu/g) in comparison to the nitrogen samples (3.3 log₁₀ cfu/g). The growth of TVC under an oxygen or under a nitrogen atmosphere is not significantly different ($P > 0.05$). Under both atmospheres, TVC reached the microbial limit defined by the International Commission on Microbiological Specifications for Foods (ICMSF) of 7 log₁₀ cfu/g after approx. 10 d. Also, the maximum number of TVC at the end of storage showed no relevant differences (Table 2). After 20 d, the samples packed in the high-oxygen atmosphere reached a maximum TVC level of 8.4 log₁₀ cfu/g. Samples packaged in nitrogen reached a value of 8.3 log₁₀ cfu/g. Also, the calculated growth parameters showed no relevant difference between gas atmospheres. The calculated growth rate for the O₂-containing atmosphere is 0.021 [1/h] in comparison to 0.022 [1/h] for the N₂ atmosphere (Table 2). These results are in agreement with

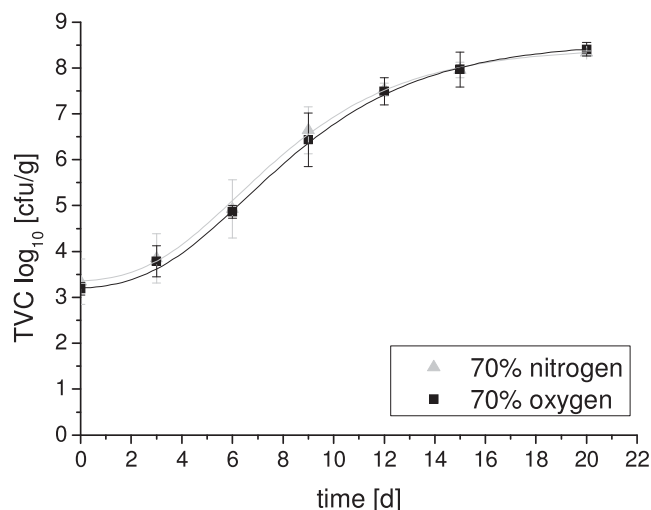


Figure 1. Comparison of total viable count packaged under two different gas mixtures: 70% O₂ and 30% CO₂, or 70% N₂ and 30% CO₂; T = 4°C (mean values ± SD of 4 analyses per sample point)

those of Gallas et al. (2010), who reported no statistical differences during storage in psychotropic bacteria counts between samples of 75% O₂ and 25% CO₂, and 75% N₂ and 25% CO₂.

Figure 2 shows the development of the spoilage microflora in high nitrogen concentration and high oxygen concentration. The results show that microbial growth is not significantly influenced by gas composition ($P > 0.05$).

Lactobacillus spp. grows more quickly under anaerobic conditions. With high oxygen concentration, the difference between the initial count of *Lactobacillus* spp. and the count at the end of storage is 1 log₁₀ level. LAB remains relatively constant in oxygen MAP and plays a minor role in the spoilage flora (Table 2). Therefore, the growth cannot be described by the Gompertz model. With high nitrogen concentration, the difference between the initial count and the count at the end is 2.4 log level. The maximal bacterial count between intact oxygen and intact nitrogen atmospheres differs significantly ($P < 0.05$) by 2.1 log cfu/g. Lactic acid bacteria are anaerobic aerotolerant organisms that usually dominate the flora of meat stored anaerobically (Saucier et al., 2000).

B. thermosphacta showed similar growth in the first 6 d under both atmospheres. From d 7 on, there was faster growth under the high-oxygen atmosphere, and *B. thermosphacta* became the predominant microorganism ($P < 0.05$). This is also reflected by the higher maximum growth rate with oxygen (Table 1). Our findings of the favored growth of *B. thermosphacta* in the O₂-containing atmosphere agrees with other studies (Herbert et al., 2013; Gallas et al., 2010; Skandamis and Nychas, 2002). Moreover, *B. thermosphacta* grows better when oxygen is available for aerobic metabolism (Gill, 1986). The growth reduction in the nitrogen atmosphere could be due to the interaction between different microorganisms, particularly LAB. Russo et al. (2006) also report that in vitro, the counts of *B. thermosphacta* were 2 log levels lower in the presence of LAB than when there was not co-inoculation with LAB.

Pseudomonas spp. are strictly aerobic gram-negative bacteria, but they are able to grow under near oxygen-free conditions (Saucier et al., 2000). Chouliara et al. (2008) detected *Pseudomonas* under a 30% CO₂ and 70% N₂ modified atmosphere. Similar results were shown by Herbert et al. (2013) under a near oxygen-free atmosphere. In both atmospheres, the growth of

Table 2. Development of growth parameters during storage of poultry under different atmospheres calculated with the Gompertz function

	Growth parameters		Duration lag phase [h]		Nmax [log ₁₀ cfu/g]		N(0) [log ₁₀ cfu/g]	
	O ₂	N ₂	O ₂	N ₂	O ₂	N ₂	O ₂	N ₂
TVC	0.021	0.022	60.5	69.5	8.4	8.3	3.2	3.3
<i>B. thermosphacta</i>	0.021	0.017	70.2	63.7	8.0	6.3	2.2	2.2
<i>Lactobacillus</i> spp.	—	0.024	—	136.2	3.9	6.0	2.9	2.6
<i>Enterobacteriaceae</i>	0.013	0.019	48.1	93.3	5.6	7.0	1.5	2.5
<i>Pseudomonas</i> spp.	0.013	0.018	80.7	118.0	6.8	7.6	2.7	3.0

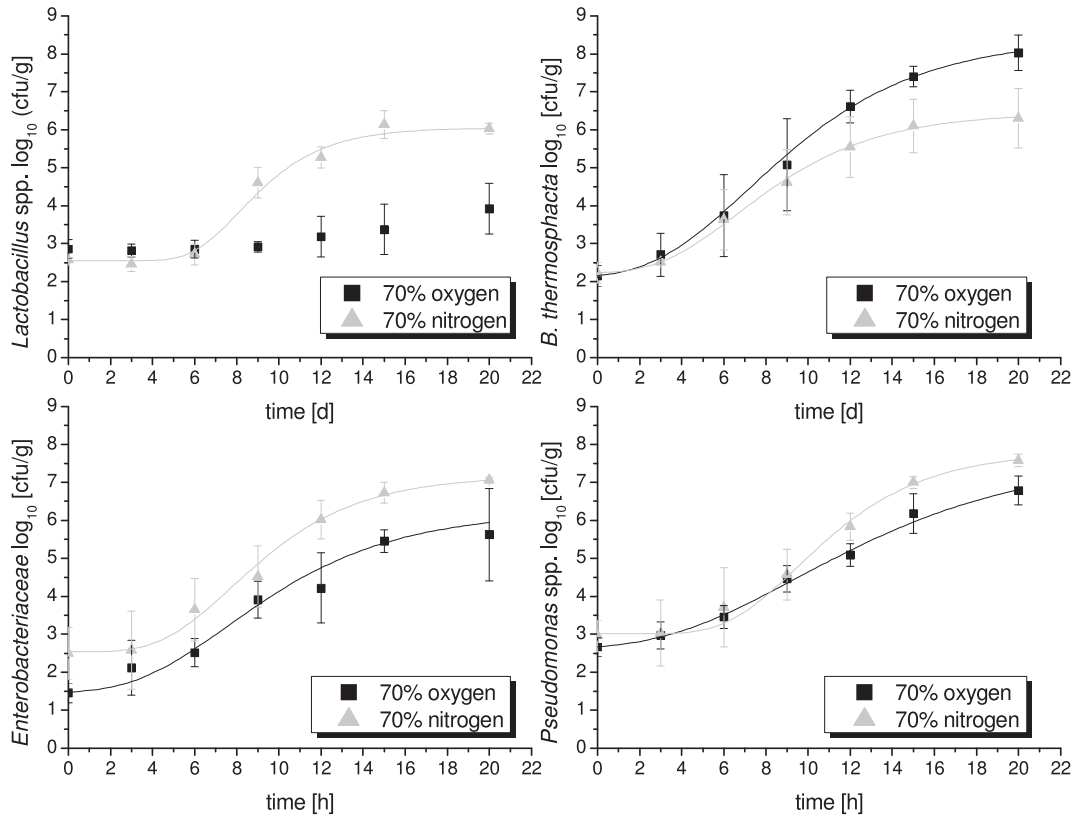


Figure 2. Growth of *Lactobacillus* spp., *B. thermosphacta*, *Enterobacteriaceae*, and *Pseudomonas* spp. under high-nitrogen and high-oxygen atmospheres (mean value \pm SD of 4 analyses per sample point)

Pseudomonas spp. was comparable up to d 9. After that, *Pseudomonas* spp. grew in an oxygen-containing atmosphere at a slower rate than in a nitrogen atmosphere ($P > 0.05$). At the end of storage, the nitrogen atmosphere resulted in an insignificant increase of 0.8 log cfu/g in comparison with samples stored in high oxygen concentrations ($P > 0.05$). A possible explanation is the inhibition of *Pseudomonas* spp. due to high oxygen concentration of the packaging, as described by Lee et al. (2008). Another reason is substrate competition, as *B. thermosphacta* and *Pseudomonas* preferentially use glucose as the main substrate (Russo et al., 2006).

Enterobacteriaceae are facultative anaerobic bacteria, which grow preferably under aerobic conditions. The maximum number of *Enterobacteriaceae* at the end of storage was higher for the nitrogen atmosphere than the oxygen atmosphere ($P < 0.05$), but the maximum growth rate was in the same range (Table 1). Thus, this difference is because initial counts of *Enterobacteriaceae* were with 1 log₁₀ level ($P < 0.05$) significantly higher for the nitrogen atmosphere than for the oxygen atmosphere (Table 1).

Sensory Evaluation

Figure 3 illustrates the development of the quality index (QI) during storage. The QI increases linearly for both atmospheres with increasing storage time. There is

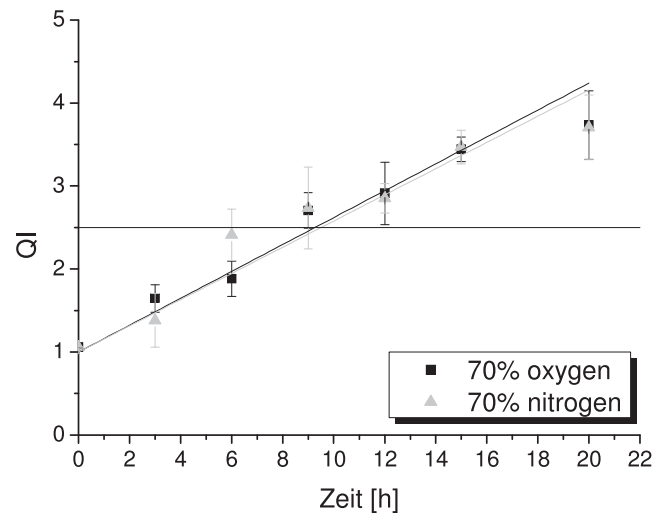


Figure 3. Development of sensory parameters of chicken breast fillets (mean values \pm SD of 4 poultry samples per sample point)

no significant difference ($P > 0.05$) in the development of the sensory quality index with and without oxygen. The end of shelf life (calculated from time point zero of the laboratory investigations, which means 24 h after slaughtering) is reached after approx. 10 d (236 h for oxygen and 233 h for nitrogen). At this point, TVC reaches an N₂ value of 6.8 log₁₀ cfu/g and an O₂ value of 6.7 log₁₀ cfu/g. Chouliara et al. (2007) reported a comparable value of 7 log₁₀ cfu/g for fresh chicken meat,

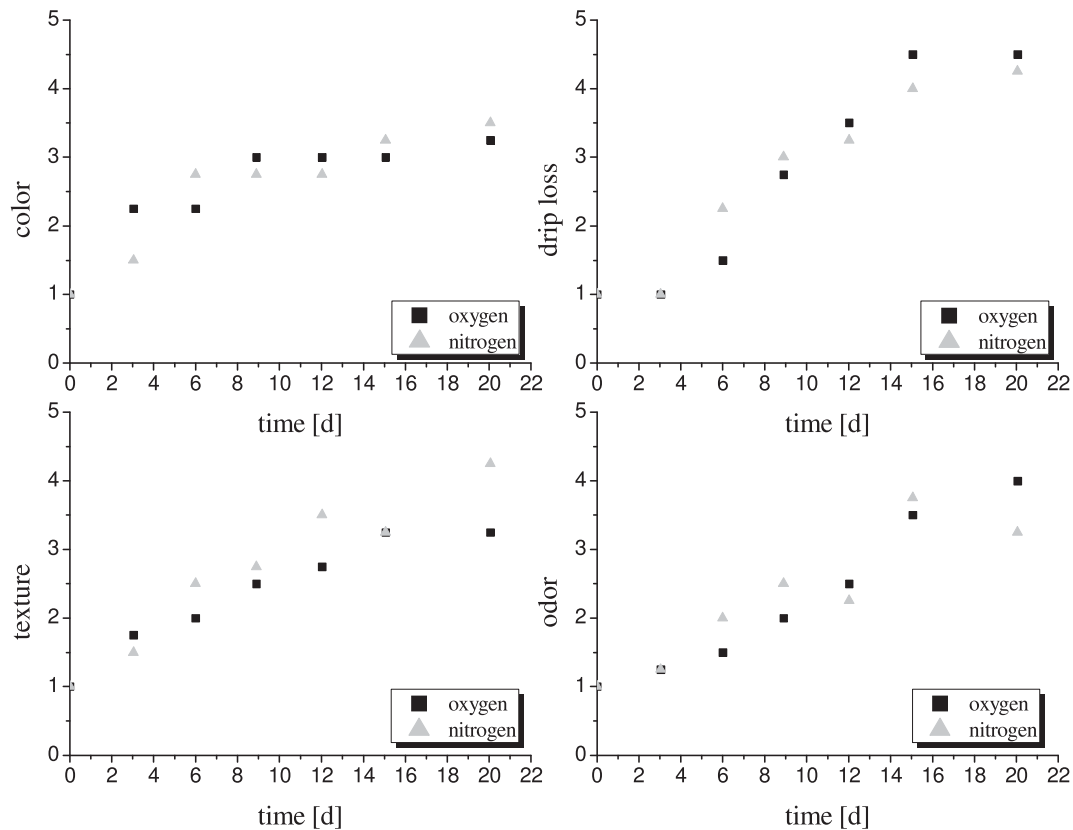


Figure 4. Development of texture, drip loss, color, and odor during storage of chicken breast fillets ($n = 4$)

reached after 11–12 d in a modified atmosphere composed of 30% CO₂ and 70% N₂.

The development of meat texture, drip loss, and odor during storage in oxygen- and in nitrogen-containing atmospheres is illustrated in Figure 4. No beneficial effect of oxygen is noticeable on color development ($P > 0.05$). This is presumably due to the limited ability of poultry, as compared to pork or beef, to form oxymyoglobin (Millar et al., 1994). This confirms the assumption that high-oxygen packaging is not necessary to preserve the color of white meat (Löwenadler, 1994). However, individual differences between the samples were noticeable because the color of poultry is influenced by several factors in addition to packaging conditions.

The color is influenced by animal-specific differences such as age, sex, meat moisture content, preslaughter conditions, and processing variables (Faustmann, 1990; Totosaus et al., 2007). There is no significant difference ($P > 0.05$) in the development of texture and drip loss between the oxygen- and nitrogen-containing atmospheres. Comparing the sensory criteria between oxygen with nitrogen, neither of the two gas atmospheres has a better effect on odor scoring ($P > 0.05$). In both atmospheres, odor was the worst-rated sensory parameter.

Conclusion

The comparison between a high-oxygen and a high-nitrogen atmosphere showed no relevant differences

between the two atmospheres. Based on the sensory data, the shelf life of MA-packaged poultry was approx. 10 d under both atmospheres. However, the composition of the spoilage flora differed between the oxygen-free and the high-oxygen atmospheres. *Lactobacillus* spp. grew more quickly under the nitrogen-containing atmosphere, whereas *B. thermosphacta* grew better under the high-oxygen atmosphere than it did under the high-nitrogen atmosphere.

Based on these results, it could be observed that high-oxygen packaging has no additional beneficial effect on microbial control and sensory quality loss and thus on the shelf life of MAP poultry fillets.

ACKNOWLEDGMENTS

This work was financed by the EU project IQ-Freshlabel (FP7-243423).

REFERENCES

- Betts, G. The microbiological consequences of MAP and vacuum packaging. International Conference on Modified Atmosphere Packaging and Related Technologies. Campden & Chorleywood Research Association, Chipping Campden, England; 1995.
- Buchner, N. Verpackung von Lebensmitteln, lebensmitteltechnologische, verpackungstechnologische und mikrobiologische Grundlagen. Berlin-Heidelberg: Springer Verlag; 1999.
- Chouliara, E., A.Karatapanis, I. N. Savvaidis, and M. G. Kontominas. Combined effect of oregano essential oil and modified atmosphere packaging on shelf-life extension of fresh chicken breast meat, stored at 4°C. Food Microbiol. 2007;24:607–617.

- Cornforth, D., and M. Hunt. Low-oxygen packaging of fresh meat with carbon monoxide: meat quality, microbiology, and safety. AMSA white paper series no. 2 Savoy, IL: American Meat Science Association; 2008.
- Dangel, S. MAP-Verfahren bei Frischgeflügel casa Blanca Communication PR-Artikel Sealppac "MAP." 2006. http://www.verpackungslinks.de/fileadmin/user_upload/nh_verpackungen/dokumente/plattform/Neuigkeiten/map-verfahren.gefluegel_04-07-06.pdf.
- Dhananjayan, R., I. Y. Han, J. C. Acton, and P. L. Dawson. Growth depth effects of bacteria in ground turkey meat patties subjected to high carbon dioxide or high oxygen atmospheres. *Poult. Sci.* 2006;85:1821–1828.
- Faustmann, C. The biochemical basis for discoloration in fresh meat: a review. *J. Muscle Foods.* 1990;1:217–243.
- Gallas, L., E. Standarová, I. Steinhauserová, L. Steinhauser, and L. Vorlová. Formation of biogenic amines in chicken meat stored under modified atmosphere. *ACTA VETERINARIA BRNO* 2010;79:107–116.
- Gill, C. O. The control of microbial spoilage in fresh meats. In: A. M. Pearson, and T. R. Dutson, eds. *Advances in meat research*. Westport: AVI Publishing Co. Inc. 1986:49–81.
- Gibson, A., N. Bratchell, and T. Roberts. The effect of sodium chloride and temperature on rate and extent of growth of *Clostridium botulinum* type A in pasteurized pork slurry. *J. Appl. Bacteriol.* 1987;62:479–490.
- Gill, C. O. The solubility of carbon dioxide in meat. *Meat Sci.* 1988;22:65–71.
- Hechelmann, H. Vorkommen und Bedeutung von *Brochothrix thermosphacta* bei Kühlagerung von Fleisch und Fleischerzeugnissen. *Mitteilungsblatt der Bundesanstalt für Fleischforschung, Kulmbach*; 1981:4435–4437.
- Herbert, U., S. Rossaint, M.-A., Khanna, and J. Kreyenschmidt. Comparison of argon-based and nitrogen-based modified atmosphere packaging (MAP) on bacterial growth and product quality of chicken breast fillets. *Poult. Sci.* 2013;92(5): 1348–1356.
- Jayasingh, P., D. P. Cornforth, C. P. Brennan, C. E. Carpenter, and D. R. Whittier. Sensory evaluation of ground beef stored in high-oxygen modified atmosphere packaging. *J. Food Sci.* 2002;67(9):3493–3496.
- Lee, D. S., K. L. Yam, and L. Piergiovanni. *Food packaging science and technology*. Boca Raton, Florida: CRC Press Taylor & Francis Group; 2008.
- Löwenadler, J. Modified atmosphere packaging carbon dioxide, its interaction with micro-organisms and application as food preservative: a review. Göteborg: SIK; 1994.
- Kakauri, A., and G. J. E. Nychas. Storage of poultry meat under modified atmosphere or vacuum packs: possible role of microbial metabolites as indicator of spoilage. *J. Appl. Bacteriol.* 1994;76:163–172.
- Kranen, R. W., T. H. van Kuppevelt, H. A. Goedhart, C. H. Veerkamp, E. Lambooy, and J. H. Veerkamp. Hemoglobin and myoglobin content in muscles of broiler chickens. *Poult. Sci.* 1999;78:467–476.
- Kreyenschmidt, J., A. Hübner, E. Beierle, L. Chonsch, A. Scherer, and B. Petersen. Determination of the shelf life of sliced cooked ham based on the growth of lactic acid bacteria in different steps of the chain. *J. Appl. Microbiol.* 2010;108(2):510–520.
- McKee, L. Microbiological and sensory properties of fresh and frozen poultry. In: L. M. L. Nollet, ed. *Handbook of meat, poultry and seafood quality*. Blackwell; 2007:487–498.
- Millar, S., R. Wilson, B. W. Moss, and D. A. Ledward. Oxymyoglobin formation in meat and poultry. *Meat Sci.* 1994;36:397–406.
- Mullan, M., and D. McDowell. Modified atmosphere packaging. In: R. Coles, D. McDowell, and M. J. Kirwan, eds. *Food packaging technology*. London: Blackwell; 2003:303–339.
- Ordóñez, J. A., B. de Pablo, B. P. de Castro, M. A. Asensio, and B. Sanz. Selected chemical and microbiological changes in refrigerated pork stored in carbon dioxide and oxygen enriched atmosphere. *J. Agric. Food Chem.* 1991;39:668–72.
- Parra, V., J. Viguera, J. Sanchez, J. Peinado, F. Esparrago, J. I. Gutierrez, and A. I. Andrés. Modified atmosphere packaging and vacuum packaging for long period chilled storage of dry-cured Iberian ham. *Meat Sci.* 2010;84:760–768.
- Pin, C., G. D. Garcia de Fernando, and J. A. Ordonez. Effect of modified atmosphere composition on the metabolism of glucose by *Brochothrix thermosphacta*. *Appl. Environ. Microbiol.* 2002;68:4441–4447.
- Phillips, C. A. Review: modified atmosphere packaging and its effects on the microbiological quality and safety of produce. *Int. J. Food Sci. Tech.* 1996;31:463–479.
- Russo, F., D. Ercolini, G. Mauriello, and F. Villani. Behaviour of *Brochothrix thermosphacta* in presence of other meat spoilage microbial groups. *Food Microbiol.* 2006;23:797–802.
- Saucier, L., C. Gendron, and C. Gariépy. Shelf life of ground poultry meat stored under modified atmosphere. *Poultry Sci.* 2000;79:1851–1856.
- Sante, V., M. Rennerre, and A. Lacourt. Effect of modified atmosphere packaging on color stability and on microbiology of turkey breast meat. *J. Food Qual.* 1994;17:177–195.
- Skandamis, P. N., and G.-J. E. Nychas. Preservation of fresh meat with active and modified atmosphere packaging conditions. *Intl J. Food Microbiol.* 2002;79(1):35–45.
- Totosaus, A., M. L. Pérez-Chabela, and I. Guerrero. Color of fresh and frozen poultry. In: L. M. L. Nollet, ed. *Handbook of meat, poultry and seafood quality*. 1st ed. Oxford: Blackwell; 2007:455–465.