

## Research Article

# Distribution of Thiobarbituric Acid Reactive Species in Conventional and Biodegradable Modified Atmosphere Packaging in Various Pork Meat Products

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## Abstract

Biodegradable packaging materials are of increasing interest to the food packaging industry, as well as to the end consumers, as awareness of the environmental damage of conventional packaging materials has grown. Up to this point not many studies have been performed investigating the applicability of biodegradable packaging materials in fresh pork meat. Lipid oxidation is considered to be one major factor in meat spoilage and reduction of quality and acceptability overall. This study was performed to determine the lipid oxidation in conventional and biodegradable modified atmosphere packaging in various pork meat products. Over the course of up to 52 days, lipid oxidation, fat content, and gas composition were assessed and compared between the packaging materials. The meat matrices used were ground pork meat and pork loin. The biodegradable packaging was based on polylactic acid and cellulose. No significant differences were found in the thiobarbituric acid reactive species values. This study suggests that biodegradable modified atmosphere packaging might be a suitable alternative to conventional materials during the minimum storage life usually applied in the meat retail sector.

**Keywords:** MAP; Biodegradable packaging; Pork; TBARS; Lipid oxidation; Fat content

## Introduction

Oxidation is one of the most important mechanisms behind the non-microbial degradation of meat [1] and a major factor in reducing meat quality and acceptability of the end consumer [2]. It is the result of radical chain reactions with resulting products depending on the substrate, which are generally unsaturated fatty acids. The fat oxidation in meat products is mainly influenced by the oxygen (O<sub>2</sub>) available in the packaging. Disruption of the integrity of muscle membranes by mechanical processes like mincing or deboning can alter the cellular

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compartmentalization and facilitate interaction of pro-oxidants with unsaturated fatty acids, which results in the generation of free radicals and propagation of the oxidative reaction [3]. In the first two phases of oxidation radicals are formed, which are then transformed into non-radical compounds and considered the primary products of lipid oxidation. These non-radical compounds decompose further and give rise to the secondary products of lipid oxidation [4].

Lipid oxidation in meat can result in sensorial degradations in color, producing off-flavors and odors, reducing polyunsaturated fatty acids, fat-soluble vitamins and pigments and producing of potentially toxic compounds, such as peroxides and aldehydes [5-7]. Aldehydes are key compounds of the secondary lipid oxidation as they react readily with proteins, leading to modifications of their organoleptic and nutritional characteristics. Assessing the extent of lipid oxidation in meat is thus of importance [5]. The measurement of Thiobarbituric Acid Reactive Substances (TBARS) is widely used to measure lipid oxidation [8], which produces off-odors and off-colors typically associated with spoiled meat products, due to the conversion of oxymyoglobin to metmyoglobin [9]. The determination of TBARS content is one of the most widely used methods to analyze the fat oxidation in meat products. By means of the method of Ulu, 2004, it is possible to compare the fat oxidation of various meat products in different packaging systems and materials. With the aforementioned

method, a product of the secondary fat oxidation reaction, malonaldehyde (MDA), can be measured by photometric means. The results are then generally expressed in terms of milligrams MDA per kilogram of meat [5]. Despite the limitations of this method it was preferred because of its simplicity, as well as the recent suggestion that the method is a more accurate and sensitive parameter in the assessment of oxidative deterioration than other tests [10-12].

Food packaging as means of protection against product deterioration through damage to physical, chemical, and biological properties has led to advancements in the choice of materials and packaging modifications throughout the last decades. It is the ongoing aim to create packaging systems that increase shelf-life of meat products while retaining, or even increase, consumer acceptance. While overwrap packaging systems have been historically used for short-term chilled storage, a diversity of Modified Atmosphere Packaging (MAP) systems have emerged on the market and are commonly being used for long-term chilled storage [13]. MAP with high atmospheric oxygen content is used to increase shelf-life and color, though, high oxygen content also leads to faster deterioration of some quality attributes [14]. Nevertheless, MAP has established itself as a commonly used packaging system for fresh meats and meat products at the retail level.

As of lately, awareness of the environmental damage associated with conventional packaging has been growing [15] and has put an additional focus on bioplastics, which can be biobased, biodegradable or both, as shown in Figure 1 [16].

Biodegradable materials are, for example, being used for packaging of various foods, with the aim to reduce the use of packaging materials derived from fossil fuels, which are commonly used for the various food packaging systems. Bioplastics play a key role in this transition by replacing the aforementioned fossil-fuel based packaging materials. This is shown by the recently adopted revised EU waste package law, which encourages Member States to support the use of bio-based materials for the production of packaging and improving the market conditions for such products [17].

There has been significant progress in the development of bioplastics and biodegradable plastics, largely produced from renewable natural sources, with similar functionalities compared to oil-based polymers [18]. One material being on the rise, and being seen as most promising in the group of bioplastics is polylactic acid (PLA). PLA plastics are lactic acid based, bio-degradable polymers, produced by fermenting various renewable resources or agricultural byproducts such as starch-rich substances like corn, wheat, sugarcane, tapioca, as a raw material [19-21]. A general overview of the lifecycle of PLA can be found in Figure 2 [22].

The global market for PLA is expected to show significant growth over the upcoming years, also due to a growing consumer awareness regarding the aspects of sustainability, recyclability and green packaging [23]. Despite the promising characteristics of PLA, the study of literature shows that only a limited amount of biopolymers in general, are used for food packaging applications, though the use of biodegradable polymers represents a real step in the direction of reducing environmental pollution [24] from the manufacturing of conventional, oil-based materials. While there is a positive outlook for further growth of the PLA-market and governmental support expressed, not many studies have been performed investigating the effect of PLA packaging on fresh pork meat products.

## Referring to

Figure 2 and regarding the recyclability of PLA, Henton et al. 2005, described that PLA will degrade quickly and disintegrate within weeks to months under conditions of high temperature and humidity, such as in active compost for example. However, they also state that PLA is very stable under typical conditions and will retain its physical properties for years [25].

The objective of this study was to determine whether differences in meat storage quality could be observed between various fresh pork meat products, namely ground pork meat and boneless pork loin, in conventional MAP and MAP using PLA and cellulose. Since muscle foods contain variable amounts of pro- and antioxidant species, processes such as mincing can favor contact between pro-oxidant agents and their targets and therefore, affect the quality of the final product [5]. The assessment of any potential differences was performed by means of invasive methods, notably by comparison of TBARS, via the aqueous method by Ulu, 2004, and total fat content via the Weibull-Stoldt method, as described by Matissek et al. [26]. Storage length was based on the acceptability of the meat products, as laid out per EU regulations [27] and differed between ground pork meat and pork loin due to the nature of the meat matrices. While lipid oxidation, in contrast to total viable count for example, is not regulated at this point, it is one of the main factors limiting the quality and acceptability of meat and meat products [2]. The focus of this study was thus to establish the analysis of TBARS in pork meat products as quality characteristic besides regulated and other established methods to determine meat quality.

To the best of our knowledge, only few studies have been published that analyzed the suitability of bioplastics to store fresh meat products, especially pork meat products, in comparison with conventional packaging materials. In this study, we thus want to determine the suitability of bioplastics for storage of pork meat products when compared to established, conventional packaging materials.

## Materials and Methods

### Raw materials and storage conditions

For this study, ground pork meat and boneless pork loin (longissimus dorsi) with subcutaneous fat and rind, from both male and female pigs of the two highest meat classifications in terms of lean-meat and muscle development [28], was used to determine differences

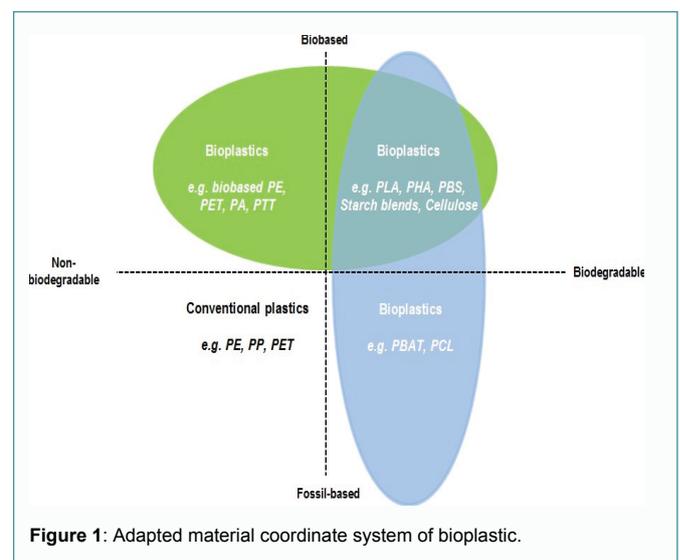


Figure 1: Adapted material coordinate system of bioplastic.

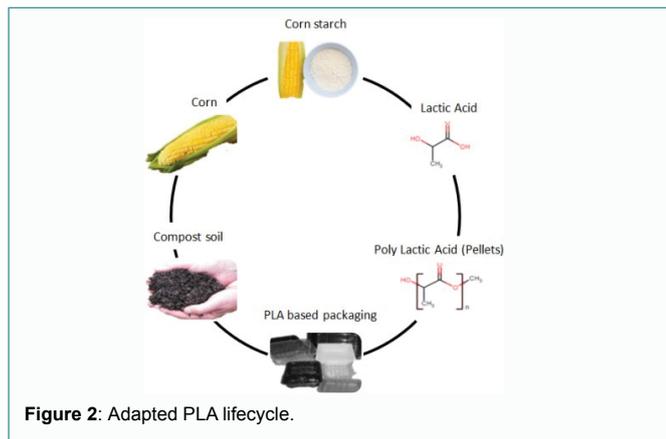


Figure 2: Adapted PLA lifecycle.

in packaging materials. The used pork meat for all experiments showed a lean meat content of above 55%.

The animals were slaughtered at a slaughter plant according to standard routines and regulations. The ground meat samples were subsequently ground on site, using a hole-plate with 5 millimeters diameter. Both, the ground meat and the pork loin were packaged in vacuum bags and transported at less than 4°C to the packaging site of MULTIVAC Sepp Haggenmüller SE & Co. KG in Wolfertschwenden, DE. The bulk bags were opened on site and repackaged in equally sized portions, while keeping direct human interaction with the meat to a minimum in order to avoid microbiological contaminations. The meat was split equally between the two packaging types, conventional modified atmospheric packaging and modified atmospheric packaging using bioplastics. After packaging, the samples were transported at less than 4°C to the Management Center Innsbruck for final storage. Samples were immediately transferred to a humidity-controlled 4°C fridge and stored unstacked on shelves for the entire experimental duration. For ground pork meat samples the total storage time was 32 days, for boneless pork loin samples it was 48 days. On the days of analysis samples were removed accordingly from the fridge while ensuring that the overall temperature of the fridge was not affected.

For the conventional MAP, the trays were made out of mono amorphous polyethylene terephthalate (PET; MAPET®II) (Færch Plast Group, Holstebro, Denmark) and the sealing top film of a polyethylene terephthalate (PET), laminate adhesive, EVEP (Polyethylene/Ethylene- Vinyl alcohol-Copolymer (EVOH)/ Polyethylene Peel) layer combination (Südpack, Ochsenhausen, Germany). For the biodegradable MAP (BioMAP), the trays were made out of polylactic acid (PLA) resin (NatureWorks, Minnetonka, MN, USA), the sealing top film was made of a cellulose/polylactic acid layer combination (NATURABIOMAT GmbH, Schwaz, Austria). The trays for the MAP were fitted with sucker pads, as is standard in retail-packaging of meats. The BioMAP were split into trays fitted with a paper insert to remain fully biodegradable, as well as trays fitted with the conventional sucker pads. Gas composition for both packaging types was a mixture of 70% O<sub>2</sub> and 30% CO<sub>2</sub>. Oxygen permeability and water vapor transmission were tested beforehand for the BioMAP, for the MAP the manufacturer provided values were used. For oxygen transmission rates (OTR) assessment in all packaging materials, the DIN 53380 was used for assessment. The Water Vapor Transmission Rates (WVTR) in biodegradable packaging materials was assessed by using DIN 53122-1, for the MAP materials ASTM E-96 and ASTM F 1249 were used, as per the manufacturers. The OTR and WVTR for the conventional

MAP were manufacturer-provided; the biodegradable MAP was tested beforehand. The OTRs and WVTRs were as described in Table 1 in the Supplemental Data Section.

Besides the OTR and WVTR, the heat resistance of all used packaging materials was investigated, either by consulting manufacture-provided documentation or by literature research on the topic [29,30]. Addressing the potential impact of temperature and humidity on the material durability of PLA, details regarding the heat resistance of used packaging materials can be found in Table 1 and 2 in the Supplemental Data Section. The heat resistances of the used materials are comparable with each other and no decrease in material durability is expected in either material due to the used temperatures. The same applies to moisture and its influence on material resistance. The humidity and temperature during transport and storage of the samples cannot be compared to conditions of active compost, and thus no impact on the used materials, namely the BioMAP, can be expected.

### Lipid oxidation

The sample preparation was performed according to the aqueous extraction method by Ulu, 2004, which is a modified method of Pikul et al. [31]. TBARS values were calculated according to Pikul et al. [31].

All chemicals used in this study were reagent grade. The standard curve was done using Tetramethoxypropane (TMP). The calibration points of the standard curve were chosen, such as that the absorption at 532 nm lies within 0.1 and 0.8 for the chosen TMP-concentrations of  $2.5 \times 10^{-9}$  to  $2.0 \times 10^{-8}$  mol in 5 mL of filtrate. The recovery rate was assessed by weighing out a pre-set amount of meat and mixing it with an equivalent amount of TMP-solution – the amount of trichloroacetic acid (TCA) used was reduced accordingly. The absorbance of the TMP-meat mixture was subtracted from the absorbance of the meat and divided through the absorbance of the TMP-solution. This calculation was done according to Pikul et al. [31] using the K-factor, which converts the absorbance in mg MDA per kg of meat. The K-factor is calculated by the slope of the standard curve, the recovery rate and the molecular weight of MDA, as shown below:

$$K_{extract} = \frac{S}{A} \times 72.063 \times \frac{10^6}{E} \times \frac{100}{P}$$

In the above formula, S stands for the standard concentration (range from  $2.5 \times 10^{-9}$  to  $2.0 \times 10^{-8}$  mol) of TMP in 5 mL of filtrate, A for the absorbance of the standard curve, 72.063 is the molecular weight of TMP, E stands for the sample weight equivalent, and P for the percent recovery. Absorbance was measured at 532 nm. In this study the sample equivalent for 10 g of meat in 10 mL of filtrate was 1. The average recovery rate in ground pork meat was 62.97% and the average K<sub>e</sub> was 3.46. In pork loin the average recovery rate was 65.03% and the average K<sub>e</sub> was 2.94.

For each packaging type and type of meat matrix at any individual time-point, three measurements were performed. The series of each packaging type were ultimately seen as one packaging type to compare the conventional MAP with the BioMAP. The results were expressed as MDA in mg per kg of meat.

### Total fat content

The total fat content in the various pork meat samples was assessed by Weibull-Stoldt digestion with subsequent Soxhlet extraction, described by Matissek et al. [26]. The method was chosen

due to universal availability of materials, as well as to avoid laborious calibrations required for fast measuring techniques [32], for example via spectrophotometry. All chemicals used in this study were reagent grade. The method was adapted by using n-hexane as extraction solvent and reducing the extraction time to three hours. For each packaging type and at each time-point a mixed sample was taken from the individual series and analyzed for the overall total fat content.

The assessments of total fat contents for the ground pork meats were performed on the same days as the TBARS assessments, while the assessments of total contents in pork loin were performed delayed from the TBARS assessments. An adequate amount of meat samples were taken from each measurement time-point, vacuum packaged, and subsequently kept at -20°C until analyses were performed. Freezing of samples with the purpose of being used for total fat content analyses does not influence the overall fat content.

### Gas composition

Samples used for the assessment of gas composition and partial oxygen pressure were stored at  $6^{\circ}\text{C} \pm 1^{\circ}\text{C}$  for up to four weeks. The oxygen partial pressure and gas composition were measured invasively by using the Microx 4 Trace (PrecisionSensing GmbH, Regensburg, Germany) and the MAT 1500 (A. KRUESS Optronic GmbH, Hamburg, Germany), respectively. The Microx 4 Trace uses PSt 7 sensors, with a measurement range of 0-100%  $\text{O}_2$  and a detection limit of 15 ppb. The MAT 1500 uses zirconium dioxide sensors ( $\text{ZrO}_2$ -sensors) to measure the  $\text{O}_2$  content, and non-dispersive infrared sensors (NDIR sensors) to assess the  $\text{CO}_2$  content. The  $\text{N}_2$  content is calculated arithmetically based on the measurements for  $\text{O}_2$  and  $\text{CO}_2$  content. Technical parameters for the MAT 1500 can be found in Table 3 in the Supplemental Data. The invasive partial oxygen pressure measurement was done by inserting a hollow needle through a self-adhesive septum into the headspace of the packaging. The measuring tip was then inserted into the packaging through the needle opening. To keep gas exchange between the packaging and the environment at a minimum while using the septum, the gas composition was measured immediately following the partial oxygen pressure measurement.

### Data analysis

Analysis of variance (ANOVA) was performed to assess differences between the investigated TBARS values, fat content and gas composition of various pork meat samples stored in the two different packaging materials. A P-value of less than 0.05 was considered to be statistical significant. Statistical analysis was conducted with SPSS software (Version 24, SPSS, Chicago, IL, USA), graphic processing was done in GraphPad Prism (Version 7.04, GraphPad Software, San Diego, CA, USA).

## Results and Discussion

### Total fat content

Average fat content in ground pork meat was 16.93% in MAP and 15.90% in BioMAP, which is in compliance with EU regulation [33], stating the ground meat containing pork should have a fat content of equal or less than 30%. Average fat content in pork loin was 25.87% in MAP and 23.93% in BioMAP (Figure 3), which is also in compliance with EU regulations, stating that meat from porcine has to have a maximum fat content of 30% [33].

No significant differences were found in the average fat contents between the packaging types, neither in ground pork meat nor in pork loin. If lipid oxidation was influenced by the fat content, this would

not be visible in this study, as fat contents did not differ significantly between the various meat matrices. Rather, it can be assumed that lipid oxidation is driven by the amount of oxygen available, rather than the fat content of the meat samples, as shown by others [34,35].

### Lipid oxidation

In this study, ground pork meat stored in BioMAP showed slightly lower TBARS values than ground pork meat stored in MAP for up to 21 days meat age. For the remaining experimental duration, the ground meat stored in MAP showed lower TBARS values than the ground meat stored in BioMAP. However, the measured values were not significantly different between the packaging types over the whole duration of the experiment or at any time-point. The trends in TBARS-value increase over the experimental duration appear to be similar between the two packaging materials (Figure 4A).

Pork loins, which were stored in MAP and BioMAP for this study, showed similar TBARS for up to 10 days of meat age. There were no significant differences in TBARS values between the packaging materials when comparing them over the entire storage length (Figure 4B).

However, starting at day 17 of meat age, the TBARS values in pork loins stored in BioMAP were significantly higher than in those stored in MAP for the remainder of the experimental duration. For the remaining time points, day 24 through day 52, TBARS values for pork loins stored in BioMAP are significantly higher than for pork loins stored in MAP, as it can be seen in Figure 4B. This difference could be explained by the commercial grades of the used pork loin samples. As mentioned prior, pork loin from the two highest meat classifications were used. However, loins stored in conventional MAP were exclusively from the highest grade, while loins stored in BioMAP were from the second highest grade. This (minimal) difference in fat and muscle content might explain the development of TBARS in the packaging types over an elongated time period, and might point to TBARS development differences due to the meat quality rather than the packaging materials used.

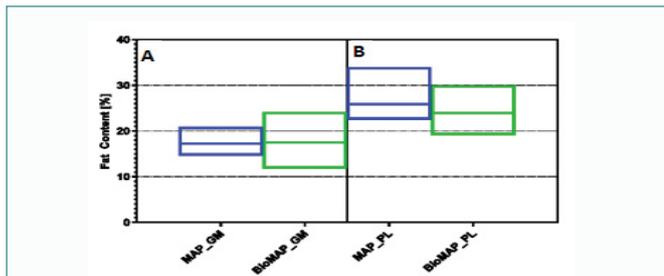
When comparing TBARS values and trends of ground pork meat and pork loins stored in MAP and BioMAP over the course of up to 38 days of meat age differences between the meat types can be seen (Figure 5). The measured TBARS values indicate an influence of the meat matrices, rather than the used packaging materials. When keeping the average retail shelf-life of the various pork meat products in mind, no significant differences between the packaging types can be seen.

Generally, it was seen that TBARS values did not change significantly throughout the first two weeks of storage in either of the packaging types and for either of the pork meat products. It can be seen that after two weeks of storage, TBARS values in ground pork meat increase in comparison to pork loin. This can be explained by the increased surface area of ground pork meat due to the meat grinding process and thus an increase in lipid oxidation. It can be assumed that differences in TBARS values in pork loin will differ between MAP and BioMAP over extended storage times (>38 days), however, these differences most likely arise from the meat and its quality itself rather than the packaging materials used.

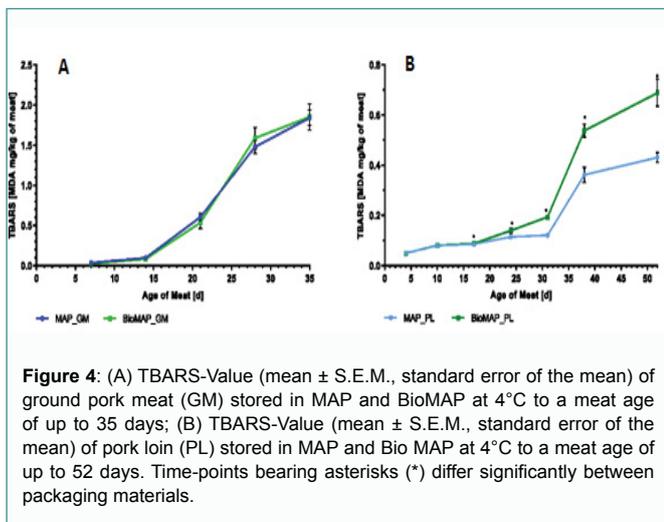
### Gas composition trends

No significant difference was found throughout the experimental duration or on any specific measurement day for the evolution of gases

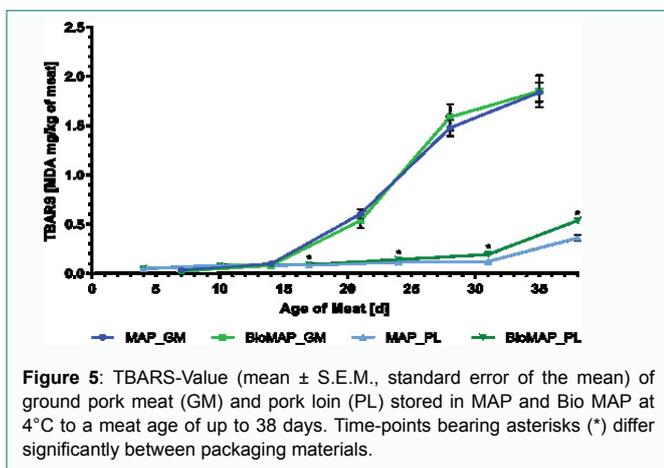
or the partial oxygen pressure in the packaging materials. While the OTR and WVTR are different between the packaging materials, it is difficult to compare the values directly due to the use of different methods to assess the permeability. However, in this study they do not appear to influence the gas composition or evolution throughout the storage period. It can be assumed that in this study the meat matrices stored, rather than the packaging materials, were the cause for any differences in the gas composition. PLA, the main packaging material in BioMAP, is comparable to PET, the main packaging material in MAP, except for PLA being biodegradable and biobased (Figure 6).



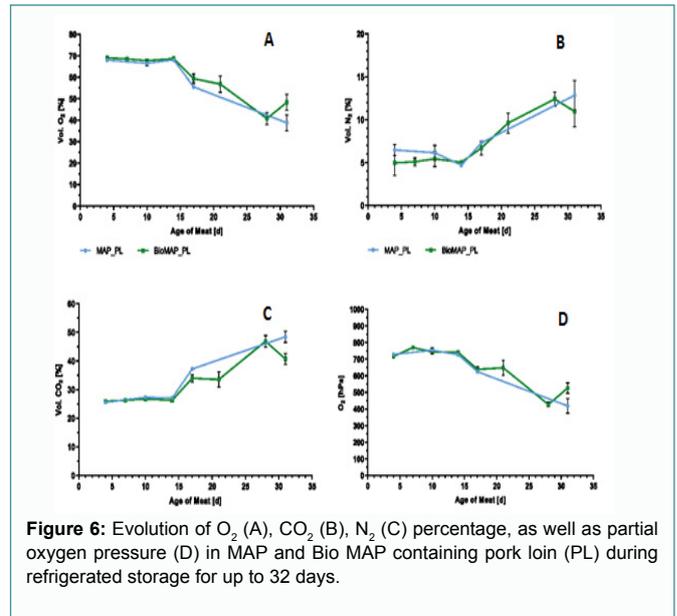
**Figure 3:** (A) Fat Content of ground meat (GM) stored in MAP and BioMAP throughout the experimental duration. (B) Fat Content of pork loin (PL) stored in MAP and BioMAP throughout the experimental duration. The lines within the different boxes represent the average fat contents within the specific meat matrix and packaging material.



**Figure 4:** (A) TBARS-Value (mean  $\pm$  S.E.M., standard error of the mean) of ground pork meat (GM) stored in MAP and BioMAP at 4°C to a meat age of up to 35 days; (B) TBARS-Value (mean  $\pm$  S.E.M., standard error of the mean) of pork loin (PL) stored in MAP and Bio MAP at 4°C to a meat age of up to 52 days. Time-points bearing asterisks (\*) differ significantly between packaging materials.



**Figure 5:** TBARS-Value (mean  $\pm$  S.E.M., standard error of the mean) of ground pork meat (GM) and pork loin (PL) stored in MAP and Bio MAP at 4°C to a meat age of up to 38 days. Time-points bearing asterisks (\*) differ significantly between packaging materials.



**Figure 6:** Evolution of O<sub>2</sub> (A), CO<sub>2</sub> (B), N<sub>2</sub> (C) percentage, as well as partial oxygen pressure (D) in MAP and Bio MAP containing pork loin (PL) during refrigerated storage for up to 32 days.

A decrease in O<sub>2</sub> content can be seen in both packaging types and the trend appears to be similar between them. This reduction over the storage period was seen by others [36,37] in conventional MAP. In this study, however, no difference could be seen between the packaging materials. The barrier properties of the PLA materials used could be the differentiating factor leading to the differences in O<sub>2</sub> percentage trends described above. The CO<sub>2</sub> contents in both packaging types increased throughout the storage period, however, the trends for both gas contents appeared to be similar between packaging materials. The measured percentages of CO<sub>2</sub> and nitrogen remained relatively constant during the first 14 days of storage in either of the packaging materials - a trend that was also seen by others [36-38]. The nitrogen content remained stable as well during the initial first two weeks of storage, as described also by Esmer et al. [37]. Both gases increase within both packaging types after the 14<sup>th</sup> day of storage. Bingol et al. [39] described similar trends in O<sub>2</sub> and CO<sub>2</sub> composition when using polystyrene/EVOH/polyethylene trays and oriented polypropylene top film to package ostrich meat. They compared different headspace compositions, of which the 80:20 O<sub>2</sub>:CO<sub>2</sub> and 60:40 O<sub>2</sub>:CO<sub>2</sub> headspaces were most similar to the headspace used in this study. When comparing the gas composition trends, it can be seen that their measured O<sub>2</sub> content decreased more strongly, while their measured N<sub>2</sub> content increased more strongly over a time period of 10 days when compared with this study. The measured CO<sub>2</sub> composition in the packaging with an 80:20 O<sub>2</sub>:CO<sub>2</sub> headspace of Bingol, et al. [39] appeared to be comparable to this study, while the packages with a 60:40 O<sub>2</sub>:CO<sub>2</sub> headspace appeared to have decreasing CO<sub>2</sub> contents between days 5 and 7 [39]. Production and removal of the dominant gases O<sub>2</sub> and CO<sub>2</sub> through respiration, oxidation, solubilization and permeation processes can change the headspace gas composition in packaged meat dynamically [40]. Headspace composition can also be influenced by microbial growth and permeability of the used packaging materials [37].

A reduction of O<sub>2</sub> and increase in CO<sub>2</sub> could generally be explained by muscle respiration and microbial growth in the meat samples [41]. An increase in CO<sub>2</sub> could also be explained by an increase in microbial growth of microorganisms producing CO<sub>2</sub> such as *B. thermospecta* and lactic acid bacteria [42]. The microbiological

data indicates no significant difference ( $p>0.05$ ) in the total aerobic count (TAC) of MAP and BioMAP, independent of the meat matrix used. For further details see Table 4 and Table 5 in the Supplemental Data Section.

## Outlook

While the TBARS assay gives a good insight into the lipid oxidation in meat matrices, additional methods should be incorporated to describe the fat oxidation and its profile more complete. Overall, a goal could be to establish sensory analysis and TBARS analysis further, while incorporating the analysis of hexane content, or other volatile compounds, into the pool of methods. Since the original work of Turner et al. [43] in the 1950s, a plethora of assay variations has resulted out of the continuous and wide use of the TBARS assay. The extraction method chosen for this study may be considered most suitable for the matrix chosen due to the omission of heat application, as well as simplicity and speed of the method, allowing a higher sample throughput than alternative methods. The omission of heat potentially leads to reduced TBARS values due to the reduction of auto-oxidation within the sample during the extraction. Nonetheless, some limitations are also present when utilizing this method, notably impurities being caused by water soluble proteins, peptides and other aldehydes, which might cause interferences with the red pigment formation upon which the method is based [44]. These limitations could be alleviated by using alternative methods to determine TBARS, which have been developed more recently. The utilization of high performance liquid chromatography (HPLC), which is able to measure lipid oxidation in meat, even when only trace amounts are present, would be a more current example of an alternative to the method used in this study. Alternatively, chemical and physical methods, like gas chromatography, NMR spectroscopy, mass spectrometry and reductive ozonolysis have been found to be suitable to identify MDA in biological samples [45]. However, in conclusion it can be said that while alternative methods are continuously being developed and adapted to detect and quantify MDA, in most cases these methods are lengthy and the assays complex. They also often require expensive instrumentation and employ time consuming procedures, which are not suitable for larger amounts of samples being screened [46].

As feed can influence the amount of polyunsaturated fatty acids [47], the incorporation of analysis of the fatty acid composition, in addition to the TBARS analysis, especially when working with pork loin as meat matrix, might be beneficial for future studies. The MDA, measured with the TBARS assay, is the most important oxidative degradation product of polyunsaturated fatty acids. This also explains why MDA values in salmon and chicken are higher at similar amounts of total fat content measured, when compared to MDA values in red meat [48]. This fact might also come into play when investigating meat samples of different quality grades, i.e. higher graded meat has a higher ratio of muscle to fat than lower graded meat. An incorporation of analyses of fatty acids, followed by investigation of potential correlations with TBARS values might be beneficial in further studies and in determining any potential differences between packaging types.

Another aspect to consider in further studies is the establishing of non-invasive methods for the assessment of meat quality, specifically in relation to the lipid oxidation. The application of Raman and NIR-spectroscopy are showing potential for future use in assessing meat quality non-invasively. However, at this point some considerations need to be kept in mind, especially when trying to achieve a completely

non-invasive alternative to the current methods to assess meat quality [49]. While there might be a certain potential of handheld Raman and NIR spectrometers being used in meat-sector relevant applications, the current reference methods might have to be improved or new methods established overall, in order to achieve dependable results. There might be the need to establish assessments of meat quality based on an overall categorization of quality traits, rather than a focus on specific parameters, like pH or drip loss [50].

Generally, it can be said that fresh meat products, comparable to those used in this study, are complex and inhomogeneous matrices. This fact can lead to complications with several aspects of a study. The comparability of measured values between experiments is only given to a limited degree, which in turn leads to alternative ways of data analysis in order to produce reliable results. Additionally, to establish methods further, be it non-invasive or invasive, a larger number of samples over a long period of time need to be collected and analyzed, which in turn leads to the issue of biological variability, as mentioned prior.

In conclusion, it was seen that TBARS values did not change significantly throughout the first two weeks of storage in either of the packaging types and for either of the pork meat products. This might be influenced by the initial headspace composition of 30% CO<sub>2</sub> and 70% O<sub>2</sub>. This specific make-up of headspace gas composition might be beneficial to delay lipid oxidation, as described by Muhlisin et al. [38], due to reduced bacterial counts in the samples. While this study did not focus on the production of packaging materials, an aspect of PLA and PLA-based packaging might be its sustainability and efficiency in production thereof. As of 2017, Asia is the major production hub with over 50% of bioplastics being produced there. As of 2017, 0.02% of the global agricultural area is being used to grow renewable feedstock for the production of bioplastics. It is projected, that this area will not increase by the year 2021. Thus, a competition between land-use for bioplastic production and traditional agriculture (e.g. pasture, feed, food) is not expected in the near future [51].

However, while holding the claim to be a biodegradable, and thus environmental friendly alternative to plastics, not all aspects of sustainability, efficiency, and efficacy in the supply chain have been optimized yet. If the production and use of bioplastics increases globally beyond the current projections, further research and solutions will be needed. Further research into the use of PLA-based and other materials from renewable sources as alternative to crude oil based plastic packaging in meat packaging, and food packaging generally, should be done.

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## Supplemental Data

**Table 1:** OTRs and WVTRs for conventional and biodegradable MAP trays and top films.

	Trays	Top Film
<b>MAP</b>		
OTR	$100 - 160 \frac{cm^2 \times 25 \mu m}{m^2 \times d \times bar}$	$< 2.5 \frac{cm^3}{m^2 \times d \times bar}$
WVTR	$10 - 30 \frac{g \times 25 \mu m}{24 h \times m^2}$	$< 6.0 \frac{g}{24 h \times m^2}$
<b>BioMAP</b>		
OTR	$32.77 \frac{cm^3}{m^2 \times d \times bar}$	$1.44 \frac{cm^3}{m^2 \times d \times bar}$
WVTR	$37.60 \frac{g}{24 h \times m^2}$	$11.33 \frac{g}{24 h \times m^2}$

**Table 2:** Heat resistances for conventional and biodegradable MAP trays and top films.

	Trays	Top Film
<b>MAP</b>		
Heat resistance	55°C - 80°C	10°C - 30°C
<b>BioMAP</b>		
Heat resistance	40°C - 80°C	15°C - 30°C

**Table 3:** Technical parameters for MAT 1500 (according to A. KRUESS Optronic GmbH, 2016)

	O <sub>2</sub> [ Vol.% ]	CO <sub>2</sub> [ Vol.% ]	N <sub>2</sub> [ Vol.% ]
Measurement Range	0-100	0-50	
Accuracy	±0.001 (<1 Vol.%)	±0.5	Calculated arithmetically
	±0.01 (<6 Vol.%)		
	±0.1 (<35 Vol.%)		
	±0.4 (>35 Vol.%)		
Resolution	0.001	0.1	0.1

**Table 4:** Total aerobic count (TAC) in pork loin in both MAP and BioMAP packaging over the course of 49 days in meat age.

Storage	MAP		BioMAP	
	Mean	S.E.M.	Mean	S.E.M.
Day	[log10 CFU/g]		[log10 CFU/g]	
D1	0.00	± 0.00	0.65	± 0.65
D4	1.43	± 0.72	1.63	± 0.81
D7	1.88	± 1.07	2.06	± 0.19
D11	3.52	± 0.14	4.58	± 0.25
D14	4.48	± 0.54	5.57	± 0.37
D18	5.68	± 0.74	5.92	± 0.50
D21	5.92	± 0.78	6.31	± 0.38
D25	5.76	± 0.01	6.57	± 0.33
D28	6.66	± 0.90	6.90	± 0.31
D35	6.07	± 0.33	6.28	± 0.41
D49	6.47	± 0.45	4.59	± 2.30

**Table 5:** Total aerobic count (TAC) in ground pork meat in both MAP and BioMAP packaging over the course of 34 days in meat age.

Storage	MAP		BioMAP	
	Mean	S.E.M.	Mean	S.E.M.
Day	[log10 CFU/g]		[log10 CFU/g]	
D3	2.24	± 0.13	2.00	± 0.01
D6	4.86	± 0.68	4.77	± 0.72
D10	7.10	± 0.77	7.02	± 0.73
D13	7.62	± 0.63	7.56	± 0.62
D17	6.64	± 0.08	6.06	± 0.41
D20	8.36	± 0.63	8.33	± 0.62
D34	12.22	± 0.01	12.14	± 0.23