Co-extruded alginate as an alternative to collagen casings in the production of dry-fermented sausages: Impact of coating composition

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Abstract

The performance of co-extruded alginate coatings containing no extra additives (A), polyglycerol esters of fatty acids (EA), or pea protein (PA) was assessed as an alternative to collagen casings (C) for the manufacturing of dry-fermented sausages (fuet) with no inoculation of moulds and without a fermentation step (NMNF) and fuet inoculated with *Penicillium candidum* and fermented (MF).

Stuffing into collagen casings resulted in slower sausage drying kinetics compared with alginate coating. No significant differences in a_w were observed among the studied casing types for NMNF and MF fuets and for the evolution of the technological and spoilage microorganisms. Fuets coated with A, EA, and PA showed lower pH values than fuets stuffed in collagen casings. No significant differences on sensory properties between casing types were observed. Therefore, alginate coatings would be a feasible alternative to collagen casing from a technological and safety point of view.

1. Introduction

Dry-fermented sausage manufacturing involves grinding of meat and back fat, mixing with salt, spices and other ingredients and additives, and stuffing into casings. After stuffing, sausages are fermented to the desired pH and dried to the target water content, at the appropriate temperature and air humidity. Traditionally, dry-fermented sausages have been stuffed into natural casings made from animal intestine (sheep, pork, and beef) and into artificial casings mainly consisting of collagen, cellulose, or plastic. Natural casings are still a very popular choice all over the world. However, they can be contaminated by enteric bacteria, as well as exogenous microorganisms, mainly due to the lack of hygiene during slaughter, post-processing handling and due to high storage temperatures (Trigo & Fraqueza, 1998). Artificial casings offer several advantages over their natural counterparts including a more uniform size, strength and flexibility for varying processing conditions, a lower variability in the product weight, and a cleaner, more hygienic product (Kutas, 1987). However, like natural casings, artificial casings are of a finite length and thus sausage stuffing remains a batch process.

The sausage casings sector has a global market share of more than €4.2 billion per year, with continuous growth of artificial casings (Adzaly, Jackson, Villalobos-Carvajal, Kang, & Almenar, 2015). The importance of the sector has led to innovations in the sector, such as new highly productive casing technology: co-extrusion. A co-extrusion system is a fully automated system that simultaneously extrudes a continuous flow of meat batter and a thin layer of casing material. The most commonly used co-extruded casing materials are composed of calcium alginate. The principle of the co-extrusion process takes advantage of the solubility of alginates in cold water and the ability of sodium alginate to develop strong and elastic gels on exposure to calcium ions. Higher productivity, and lower raw material and production costs in comparison with traditional processes are the main advantages highlighted by the suppliers of this technology (Kamenik, 2014). Additionally, alginate coatings are a vegetable-based alternative to animal-based and artificial casings. They are edible, and suitable for vegetarian, halal and kosher products.

Alginates are polysaccharides obtained from the cell walls of brown seaweed, from which they are extracted in the form of alginic acid (Lamkey, 2009). They are composed of β-D-mannuronic acid (M) and α-L-guluronic acid (G) in varying proportions, sequence, and molecular weight. Alginate gellation takes place when divalent or multivalent ions (usually Ca^{2+}) interact ionically with blocks of guluronic acid residues from two different chains resulting in a three-dimensional network (Braccini & Perez, 2001; King, 1983). The performance of alginate films is highly dependent on the processing conditions (e.g. mixing speed), as well as on the alginate coating composition (e.g. presence of ions, pH) (Comaposada, Gou, Marcos, & Arnau, 2015; Harper, Barbut, Smith, & Marcone, 2015; Marcos, Gou, Arnau, & Comaposada, 2016; Senturk Parreidt, Schott, Schmid, & Müller, 2018). The application of alginate co-extrusion for the manufacture of dry fermented sausages has focused on the prevention of surface efflorescence formation (Hilbig, Hartlieb, Gibis, Herrmann, & Weiss, 2020; Hilbig, Murugesan, Gibis, Herrmann, & Weiss, 2019; Walz et al., 2018). However, to the knowledge of the authors, the impact of alginate coatings on the drying process and final quality of dry fermented sausages hasn’t been studied. In a previous study, Comaposada et al. (2018) reported modifications of water and oxygen transfer in composite films consisting of alginate, protein and surfactant compared to alginate films with no additives in *in vitro* tests. The authors concluded that there is a need to evaluate the industrial performance of composite coatings to improve the properties of standard casings. Thus, the objective of the present work was to fill the gap of knowledge about the impact of co-extruded composite alginate coatings on the manufacture of dry-fermented sausages. With this purpose, the performance of different compositions of alginate coatings as an alternative to artificial casings for the manufacture of small calibre dry-fermented sausages (fuet) was evaluated.

2. Materials and methods

2.1. Dry sausage (fuet) manufacturing

Two types of dry sausages (fuet type) were produced: non-mould non-fermented fuet (NMNF) produced without addition of starter culture nor mould to surface, and mould-fermented fuet (MF) produced with addition of starter culture and surface inoculation of mould.

Fuets were manufactured with 70% of pork shoulder and 30% of pork belly using the following formula (g/kg of shoulder and belly blend): sodium chloride (18), sodium nitrite (0.15), potassium nitrate (0.15), sodium ascorbate (0.5), dextrose (2), lactose (20) (all additives from Merck KGaA, Darmstadt, Germany) and black pepper (3). Formula of MF fuet also included 0.1 g/kg of starter culture TEXEL® SA 306 (Danisco® DuPont™, Copenhagen, Denmark).

Lean pork meat and fat were minced in a mincer with an adjustable plate set at a hole diameter of 5 mm. The minced meat was mixed using a vacuum mixer model 35P (Tecnotrip S.A., Terrassa, Spain) with the ingredients at 0 °C for 3 minutes in a vacuum mixer. At this point, the meat batter was either stuffed into collagen casings using a vacuum stuffer or co-extruded with an alginate coating using the vacuum stuffer with a co-extruding unit developed in a mechanical workshop nearby for this specific activity (Figure 1). Four different casings were used for each type of fuet (NMNF and MF): Collagen (C), stuffed in 40 mm diameter collagen casings (Fibran S.A., Sant Joan de les Abadesses, Spain); Alginate (A), co-extruded with a coating containing 2 % of sodium alginate (Alcogel 6061, Cargill France S.A.S, Saint-Germain-en-Laye, France); E 475 alginate (EA), co-extruded with a coating containing 2 % of sodium alginate and 1% of polyglycerol esters of fatty acids (E 475, Lasenor Emul, S.L., Olesa de Montserrat, Spain); and pea protein alginate (PA), co-extruded with a coating containing 2 % of sodium alginate and 1 % of pea protein (Provital Group, Barcelona, Spain). The concentrations of A, EA and PA were selected according to the results obtained in Comaposada et al. (2018). One percent of EA reduced mass transfer properties, and PA was limited to 1% due to its negative effect to the mechanical properties of the film. After the co-extrusion, the sausages coated with alginate solutions (A, EA, and PA) were cross-linked by immersion in a 30 % calcium chloride (Cargill Inc., Minneapolis, MN, USA) solution.

After stuff casing/coating MF fuets were surface inoculated by immersion into a solution of *Penicillium candidum* spores (CHOOZIT™ Cheese Cultures, Danisco) and subjected to a fermentation process (36 h at 21.5 ± 0.1 °C and 86.9 ± 3.2 % RH). Afterwards, the sausages were hung in a drying chamber until an average weight loss of 40 % was achieved. Average drying conditions were: 12.7 ± 1.0 °C and 74.5 ± 2.6 % air relative humidity (RH) for NMNF fuets and 13.1 ± 0.5 °C and 71.6 ± 6.3 % RH for MF fuets. The dryer needed about 20 % of the daily time to maintain the drying conditions with an air velocity of 0.15 ± 0.08 m/s.

A minimum of 25 sausages per casing type (C, A, EA, PA) were produced for each fuet type (NMNF, MF). Two independent manufacturing batches were carried on.

2.2. Drying process monitoring

During the drying process, five sausages per casing type (C, A, EA, PA) for each fuet type (NMNF, MF) were monitored for weight control until an average weight loss of 40 % was achieved. Weight loss (%), weight loss rate (% weight loss/day) and drying time (days) were calculated at the end of the drying process. The calibre of sausages were measured using a Vernier caliper.

Temperature, relative humidity and velocity of air were monitored in each batch with a data logger Testo 400 (Testo SE & Co. KGaA, Lenzkirch, Germany).

2.3. Effective diffusivity

Effective diffusivity (D_e) was determined using IRTAsim (IRTAsim, 2018), an online tool developed on Matlab, which implements mass transfer equations and heat transfer equations (Trigo & Fraqueza, 1998). Mass and heat transfer is modelled approximating stuffed products to a porous infinite vertical cylinder.

IRTAsim tool allows to estimate the D_e coefficients as a function of water content when the drying curve of a product is given together with the drying air conditions (temperature, relative humidity, air speed and time in which air is in forced movement), sausage initial water content and size(diameter, length) (http://irtasim.irta.cat).

The D_e was calculated considering the sausage water content changes during the drying process (Equation 1):

$$De = \exp\left(ax + b - \frac{53467}{RT}\right) \quad (1)$$

where D_e is the effective diffusivity (m^2/s), ?? and b are the D_e equation coefficients, x is the water content (kg/kg dry mater), R is the gas constant ($J{\cdot}K^{-1}{\cdot}mol^{-1}$) and T is temperature (K). For comparative purposes, D_e was calculated for each sausage by Equation 1 and it was averaged in a water content range between 0.5 and 1.5 kg water / kg dm.

2.4. Physico-chemical analysis

Three sausages per casing type (C, A, EA, PA) for each fuet type (NMNF, MF) were sampled for physico-chemical analysis before drying and at the end of the drying process. The fat content of meat paste before drying was determined by triplicate using a FoodScan™ Lab (Foss Analytical, Hillerød, Denmark) device. The water content of fuets was determined in duplicate by drying the minced samples at 103 ± 2°C until reaching a constant weight (AOAC, 1990). The pH values were measured in triplicate using a portable Crison penetration electrode connected to a Crison pH meter PH25 (Crison Instruments S.A., Alella Spain). Water activity (a_w) was measured in duplicate at 25°C with an Aqualab equipment (Decagon Devices, Inc. Pullaman, Washington, USA). The average of replicates were recorded for statistical analysis.

2.5. Instrumental colour analysis

Colour was measured using a Minolta CR-410 Chroma Meter (Minolta, Co., Ltd., Japan), with illuminant D65, 2° standard observer angle, and 50 mm port size. Colour measurements were taken on the surface and interior (transversal section) of fuets and averaged over three zones (upper, middle, and bottom). Colour coordinates were determined using the 1976 CIEAB system and the results expressed as L^* (lightness), a^* (redness), and b^* (yellowness). Five sausages per casing type (C, A, EA, PA) for each fuet type (NMNF, MF) were used for surface colour measurements and three sausages for internal colour measurements at the end of the drying process. The average of three readings was used for analysis.

2.6. Microbiological analysis

Sampling was performed at days 0 (after stuff casing/coating), 3, 7, and 15 of the drying process. At each selected time, 25 g of fuet were 10-fold diluted in sterile BHI broth (Brain heart infusion, DB, NJ, USA). The solution was homogenised for 1 minute in a Masticator Classic (IUL S.A., Barcelona, Spain). After appropriate dilutions, the following determinations were carried out: lactic acid bacteria (LAB) were enumerated by pour plating in MRS agar (Merck KGaA, Darmstadt, Germany) incubated anaerobically at 30°C for 72 h; *Enterobacteriaceae* were enumerated by pour plating in violet red bile glucose agar (Merck) at 30°C for 24 h. Three sausages per casing type (C, A, EA, PA) for each fuet type (NMNF, MF) were measured. Two replicates per sausage were performed.

2.7. Sensory analysis

Quantitative Descriptive Analysis (Stone, Sidel, Oliver, Wooley, & Singleton, 1974) was carried out to assess the appearance, taste/ flavour and texture of fuet. The panel consisted of six trained assessors (ISO 8586-1, 1993; ISO 8586-2, 1994). The generation and selection of descriptors was carried out by open discussion in three sessions prior to the experiments. The descriptors retained for the sensory profile are described in Table 1. As detailed in Table 1, some descriptors were assessed on the whole fuet piece and others on 5 mm-thick slices. In addition, some attributes (odour: mould and ripened; flavour: ripened) were only evaluated in mould fermented (MF) fuets because they were not present in non-mould non-fermented (NMNF) fuets. A non-structured scoring scale (Amerine, Pangborn, & Roessler, 1965) was used, where 0 and 10 meant absence and the highest intensity of the descriptor, respectively. Sensory evaluation was undertaken in 6 sessions for each fuet type (3 sessions for each manufacturing batch) using a complete block design (Steel, Torrie, & Dickey, 1997), where each assessor evaluated one fuet from each casing type in each session. Samples were presented to the assessors balancing the first order and the carry over effects according to MacFie, Bratchell, Greenhoff, & Vallis (1989).

2.8. Statistical analysis

Data obtained from non-mould non-fermented (NMNF) fuet and mould fermented (MF) fuet were analysed separately with the General Linear Models procedure in the SAS program, version 9.4 (SAS Institute Inc., Cary, NC, USA). The linear model included the casing type as a fixed effect and the manufacturing batch as a block effect. The model also included as fixed effects, the sampling time and its interaction with the casing type for the microbiological indicators, and the assessor and the tasting session (nested to manufacturing batch and assessor) for the sensory data. Least square means were calculated and the differences were tested with the Tukey test ($p<0.05$).

3. Results and discussion

3.1. Drying parameters

The drying parameters measured during the manufacturing process of non-mould non-fermented (NMNF) and mould-fermented (MF) fuets are summarized in Tables 2 and 3. Weight losses in a range of 39.6% to 42.7% were obtained among the different casing types in both fuet types (NMNF and MF). Stuffing into collagen casings (C) resulted in slower drying of NMNF fuets ($p<0.05$) compared to coating with alginate solutions. The D_e of NMNF fuets with C casings also tended to be lower than the ones with alginate coatings. These results confirm in real production conditions those obtained by Comaposada, Marcos, Bou, & Gou (2018) using *in vitro* conditions where non fermented salami slices covered with collagen films without moulds showed lower weight loss rate than those covered with alginate films. As suggested by Walz et al. (2018), differences observed in sausages stuffed in collagen and alginate casings could be related to differences in the pore size of the casings. The pore size of collagen casings have been reported to be around 5 nm (Gong et al., 2016), while the pore size of alginate films (1.5-3.5% alginate) have been found to be in a range of 158-243 µm. This fact could explain the lower weight loss rate observed in C fuets. The weight loss rate of MF fuets with C casing was also lower, while the D_e became similar among the fuets with the different coatings. This is because the calculation of D_e integrates the effect of the initial diameter, which is bigger with the C casing fuets. Moreover, the presence of moulds can influence the water vapour transmission through the casing/coatings making it more uniform. In agreement with this results, Comaposada et al. (2018) reported a significant decrease of weight loss rates of salami slices covered with alginate films containing surfactant E 475. Senturk Parreidt et al.(2018) related the decreased rate of moisture loss in alginate coatings containing surfactants with the reduced superficial water activity. However, no significant differences in weight loss rate between the different alginate coating types used (A, EA, and PA) were observed. The present study showed that in real production conditions, the addition of 1% of polyglycol esters of fatty acids (E 475) was not enough to significantly modify water transfer through alginate coatings.

Although NMNF and MF fuets achieved a similar weigth loss they had differences in the moisture content due to the differences in fat content of the meat paste before drying: 16.7 ± 2.6 % in NMNF and 21.3 ± 4.1 % in MF. Similarly, the lower weight loss rates and D_e of MF fuets were also attributed to their higher fat content. Palumbo et al. (1977) and Mulet et al. (1992) also reported lower D_e coefficients in their meat products when fat content increased.

NMNF fuets coated with alginate presented higher moisture ($p<0.05$) than fuets stuffed in collagen casings at the beginning and at the end of processing (Table 2). Walz et al. (2018) also reported higher moisture content on sausages coated with alginate compared to those stuffed in collagen casings, mainly due to the high moisture content of the alginate coating itself. Comaposada et al. (2018) described similar differences in moisture content between both casing types, which were attributed to the different type and concentration of salt present in alginate coatings (calcium chloride) and in the collagen casings (sodium chloride). No significant differences in moisture content at the end of the drying process were detected (Table 3).

No significant differences in the a_w of fuets were observed among the studied casing types for any of the fuet types (NMNF and MF). It is important to highlight that all the studied samples of fuet presented a_w values lower than 0.92. Thus, according to Regulation (EC) 2073/2005 these type of fuets are considered ready-to-eat foods unable to support the growth of *Listeria monocytogenes* (European Commission, 2005). These results indicate that the use of co-extruded alginate as an alternative casing system to commercial collagen casings would not compromise the food safety of these products with regard to *L. monocytogenes*.

3.3. Colour parameters

The colour of the product is a very important quality factor for dry-cured meat products (Morales, Guerrero, Claret, Guàrdia, & Gou, 2008). Instrumental colour measurements revealed significant differences among the studied casing types (Tables 2 & 3) on the product surface, but not in the internal part (transversal section).

NMNF fuets coated with alginate (A, EA and PA) showed a slight increase of the superficial a* value compared to those stuffed in collagen casings (C). A fuets also showed a slight decrease of the superficial b* value. MF fuets, coated with A and EA showed a slight decrease of the superficial a* values with respect to C and PA fuets. A and EA fuets also showed higher superficial L* values ($p<0.05$), mainly due to the higher growth of white mould on the surface of those fuets (Figures 2 & 3). Except for the L* value at the surface in MF, the rest of the differences between C fuets and those coated with alginates were not important, including the internal colour. Therefore, the obtained results confirm that colour would not be a drawback for the use of alginate coatings as an alternative to traditional casings for this type of product.

3.4. Evolution of microbiological indicators and pH values

The statistical analysis revealed that the interaction between the sampling time and the casing type was not significant. The type of casing effect was not significant for the selected microbial indicators (LAB and *Enterobacteriaceae*), but the sampling time effect was significant.

The evolution of LAB, *Enterobacteriaceae* and the pH values was very different depending on the product type (Figures 4 and 5). NMNF fuets presented initial LAB counts of 2.0-2.3 log CFU/g. Endogenous LAB population increased gradually throughout the drying process, with a maximum increase of 3.3-3.4 log units detected at the end of the process (day 15). MF fuets, inoculated with a starter culture of LAB at levels of 5.4-5.5 log CFU/g, showed similar increases (3.2-3.5 log units), but the maximum growth was achieved much earlier, at the 3rd day of drying. MF fuet showed higher LAB counts ($p<0.05$) than NMNF fuet throughout the drying process, resulting in significantly lower pH values in MF fuets, as previously reported. No significant growth of *Enterobacteriaceae* was observed in NMNF fuets, while a decrease of 1 log unit ($p<0.05$) was observed in MF fuets (Figures 4 and 5). The control of *Enterobacteriaceae* growth is essential to prevent quality and safety defects such as the formation of off-flavours and biogenic amines (Garriga et al 1996; Maijalaet al, 1995). The pH drop within the first days of the process contributed to reduce endogenous *Enterobacteriaceae* population in fuets inoculated with starter culture (MF).

Although no significant differences among casing types were observed on the evolution of the technological (LAB) and spoilage (*Enterobacteriaceae*) microorganisms, fuets stuffed in A, EA, and PA coatings showed lower pH values than the ones stuffed in collagen casings (C) for both fuet types (NMNF and MF) which could contribute to improve the food safety of these type of products. These results confirm that the use of alginate coatings would be a feasible alternative to the use of collagen casing from a technological and safety point of view.

3.5. Sensory analysis

Visual assessment of NMNF revealed that alginate coated fuets showed significantly lower brightness and colour intensity than C fuets (Table 4). While in MF fuets no colour differences were detected between A and C fuets (Table 5).

No significant differences in global odour or flavour intensities between casing types were detected for NMNF and MF fuets. However, some specific odour and flavour differences were detected in MF fuets. Mould and ripened odour, and flavour were more intense in alginate coated MF fuets than in C fuets, probably due to the higher presence of white mould on their surface (Figure 2). Moulds are known to provide a pleasant appearance and contribute to the development of the taste and aroma of fermented meat products (Cook, 1995).

Calcium chloride used to cross-link alginate coatings can produce bitter taste (Frye, Hand, Calkins, & Mandigo, 1986; Hand, Terrell, & Smith, 1982; Lawless, Rapacki, Horne, & Hayes, 2003). However, no bitterness was noticed in any A fuets.

Collagen casings were removed before the sensory analysis, while alginate coated fuets were evaluated with the coating. Consequently, the sensory analysis revealed that the alginate coating was clearly perceived by the assessors (data not shown).

Both NMNF and MF fuets stuffed in collagen casings showed lower values of hardness and tactile waxy feeling than alginate coated fuets. Similarly, the assessors found fuets stuffed in collagen casings to be less hard and more crumbly in the mouth. NMNF fuets stuffed in collagen casings also showed lower elasticity and gumminess than those coated with alginate.

The higher pH in C fuets (Tables 2 and 3) could partly explain the differences in texture. The consistency of fermented sausages increases due to acidification and drying, as the pH decline during fermentation results in myofibrillar protein aggregation to form a gel (Arnau, Serra, Comaposada, Gou, & Garriga, 2007).

4. Conclusions

The reported results have shown that the differences observed during the drying process of alginate coated and collagen stuffed fuets did not affect the product stability (a_w and pH). Moreover, no remarkable differences on the internal colour and sensory properties of A fuets compared to C ones would support the use of co-extruded alginate as an alternative to artificial casings. These results confirm that the use of alginate coatings would be a feasible alternative to collagen casing for the production of fuet type small-calibre dry-fermented sausages from a technological and safety point of view. The potential of producing other types of dry-fermented meat products should be explored.

However, the additives used to produce composite coatings (polyglycerol esters of fatty acids and pea protein) did not improve the properties of alginate coatings. Further research in order to improve alginate based composite coatings for the production of dry-fermented meat products should be performed.

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Figure 1. Pilot equipment for co-extrusion of the meat batter with the alginate coatings.

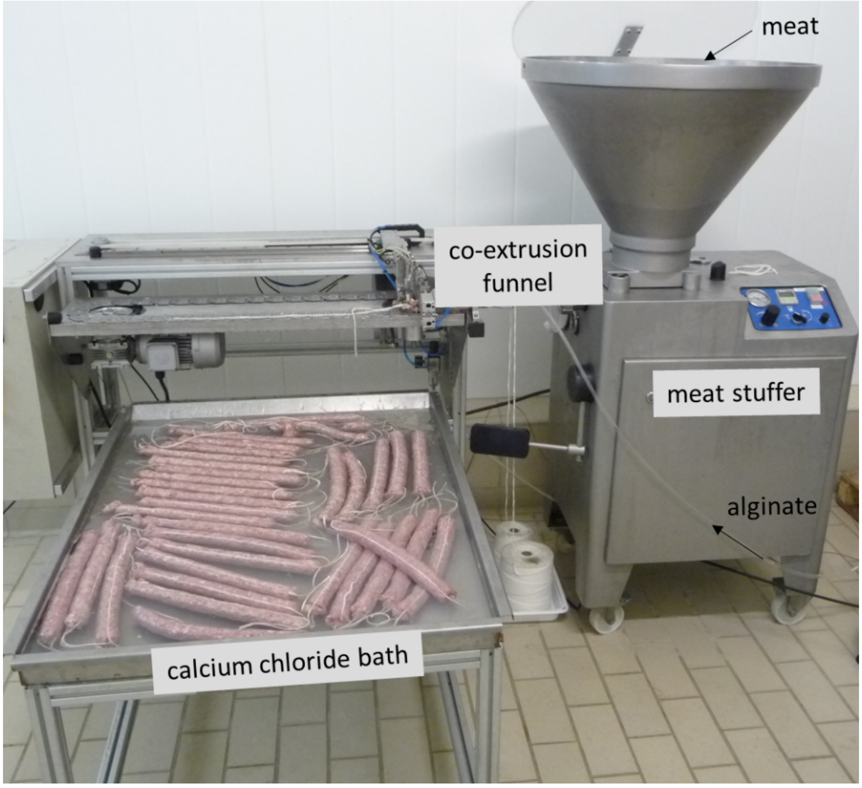

Figure 2. Image of fuets MF at the beginning of the drying process (day 3). From left to right C, A, EA, PA.

Figure 3. Image of fuets MF at the end of the drying process. From left to right C, A, EA, PA.

Figure 4. LAB (a), *Enterobacteriacea* (b) levels, and pH values (c) during the drying process of non-mould non-fermented fuet (NMNF). C: Colllagen; A: Alginate; EA: E 475 alginate; PA: pea protein alginate.

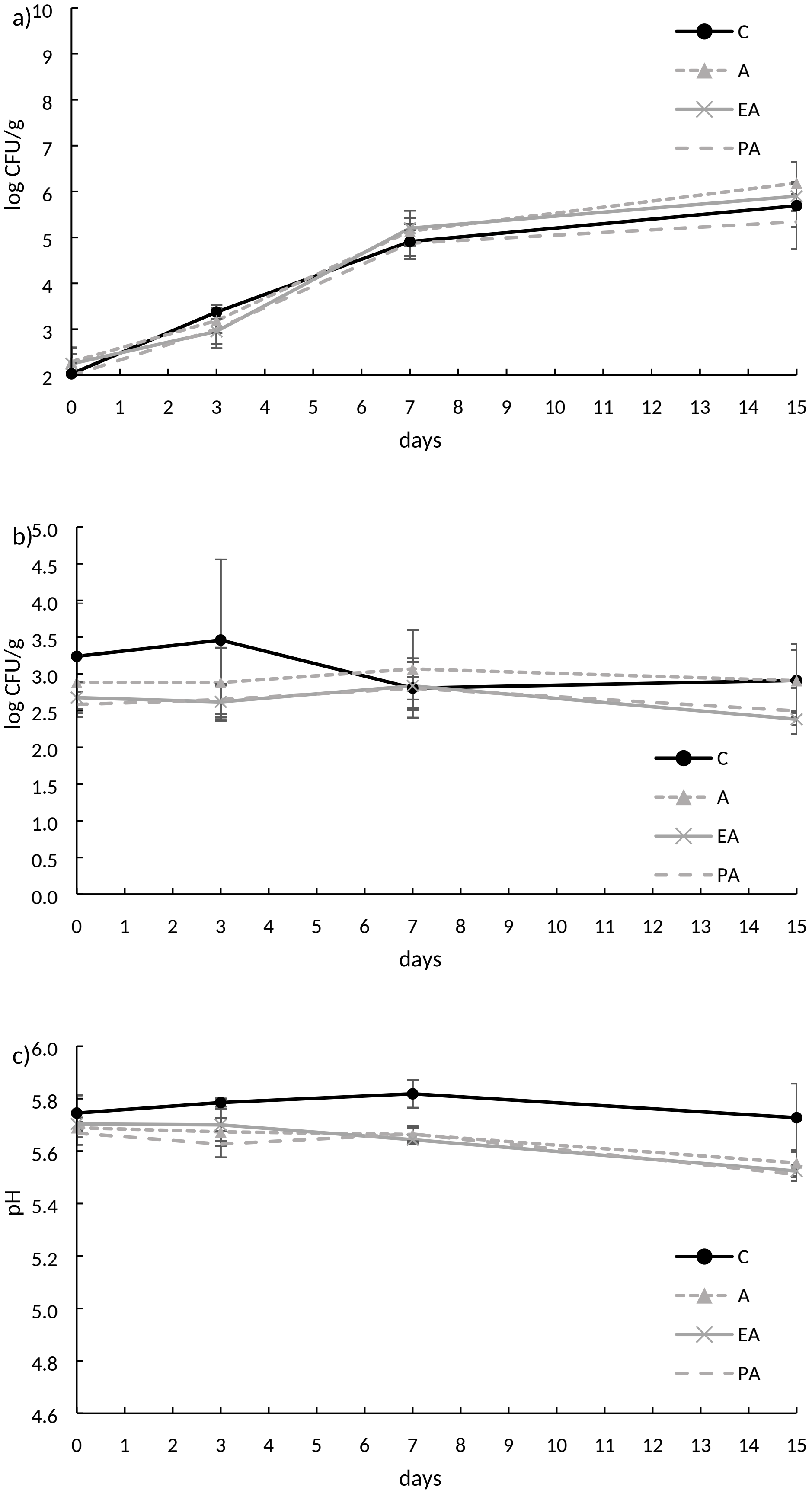

Figure 5. LAB (a), *Enterobacteriacea* (b) levels, and pH values (c) during the drying process of mould-fermented fuet (MF). C: Colllagen; A: Alginate; EA: E 475 alginate; PA: pea protein alginate.

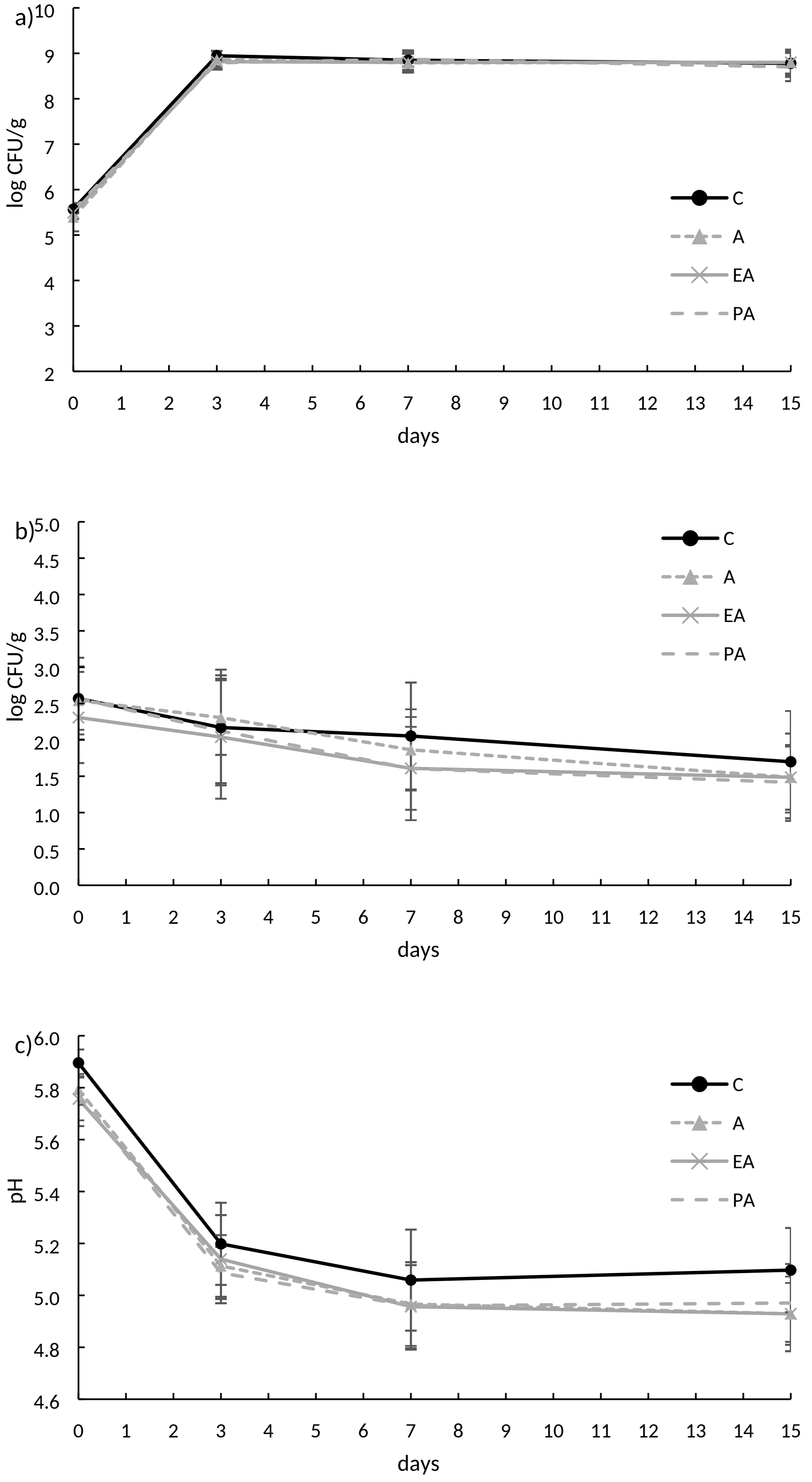

Table 1. Definition of sensory parameters used in the Quantitative Descriptive Analysis of fuets.

Descriptors[1]	**Definition**
Appearance (slice)	
Colour intensity	Red colour intensity on a transversal section (on a freshly cut)
Brightness	Brightness intensity evaluated on a transversal section (on a freshly cut)
Odour (slice)	
Intensity	Overall odour intensity of fuet
Mould	Intensity of mould odour
Ripened	Pleasant odour characteristic of dry-fermented sausages
Taste and flavour (slice)	
Flavour Intensity	Overall flavour intensity of fuet
Sourness	Basic flavour sensation elicited by lactic acid
Bitterness	Basic taste sensation elicited by L-Tryptophan
Ripened	Pleasant flavour characteristic of dry-fermented sausages
Texture (tactile; whole piece)	
Hardness	Amount of pressure required to completely compress the sample
Waxy	Resembling wax when touching
Texture (slice)	
Hardness	Force required to bite through the sample
Elasticity	Degree of return to the original position of the sample when a compression force is applied between molars
Crumbliness	Texture property characterized by the ease with which the product can be separated into smaller particles during chewing
Gumminess	Texture property of a sample which resembles or of the consistency of gum

Table 2. Drying, physico-chemical, and colour parameters of non-mould non-fermented (NMNF) fuet.

Parameters	**C**	**A**	**EA**	**PA**	**RMSE**
Weight loss (%)[1]	39.6^{b}	41.0^{a}	40.4^{ab}	40.0^{ab}	1.2
Drying time (day)[1]	17.8^{a}	17.3^{b}	17.3^{b}	17.3^{b}	0.2
Weight loss rate (% weight loss/day)[1]	2.25^{b}	2.41^{a}	2.38^{a}	2.36^{a}	0.06
D_e (x10^{-11})	2.42	3.03	2.33	2.28	0.87
Calibre$_0$ (mm)[1]	36.5	36.1	36.4	36.0	0.6
Calibre$_f$ (mm)[1]	33.4	33.1	33.5	34.3	1.1
Moisture$_0$ (%)[2]	62.2^{b}	63.6^{a}	63.7^{a}	63.7^{a}	0.7
Moisture$_f$ (%)[2]	36.9^{b}	39.5^{a}	39.0^{a}	38.9^{a}	1.0
$a_{w,0}$[2]	0.975	0.975	0.977	0.975	0.001
$a_{w,f}$[2]	0.912	0.919	0.918	0.915	0.004
pH$_0$[2]	5.75^{a}	5.69^{ab}	5.68^{b}	5.67^{b}	0.04
pH$_f$[2]	5.73^{a}	5.56^{b}	5.52^{c}	5.51^{c}	0.07
$L^*_{f,\ surface}$[2]	41.8^{a}	38.4^{b}	41.0^{ab}	40.7^{ab}	2.4
$a^*_{f,\ surface}$[2]	6.4^{b}	8.1^{a}	7.9^{a}	8.7^{a}	1.0
$b^*_{f,\ surface}$[2]	1.3^{a}	0.3^{b}	1.0^{ab}	1.0^{ab}	0.8
$L^*_{f,\ internal}$[2]	45.0	46.1	45.1	46.7	2.3
$a^*_{f,\ internal}$[2]	9.9	9.8	9.7	9.5	0.8
$b^*_{f,\ internal}$[2]	3.0	2.8	2.4	2.7	0.7

C: Collagen; A: Alginate; EA: E 475 alginate; PA: pea protein alginate; RMSE: root mean square error; [1]n=5; [2]n=3; $_0$: day 0 (before drying); $_f$: end of drying process; surface: colour measured on the surface of fuet; interior: colour measured on the transversal section of fuet. Different letters within a row indicate significant differences between batches ($p < 0.05$).

Table 3. Drying, physico-chemical, and colour parameters of mould-fermented (MF) fuet.

Parameters	**C**	**A**	**EA**	**PA**	**RMSE**
Weight loss (%)^1	39.9^c	41.7^b	42.4^{ab}	42.7^a	0.8
Drying time (day)^1	20.3^a	19.8^b	19.8^b	19.8^b	0.2
Weight loss rate (% weight loss/day)^1	2.03^c	2.16^b	2.20^{ab}	2.21^a	0.04
D_e (x10^{-11})	2.14	2.02	1.97	1.97	0.34
Calibre$_0$ (mm)^1	36.6^a	34.1^c	35.2^b	35.2^b	0.8
Calibre$_f$ (mm)^1	31.2	29.9	29.8	29.6	1.6
Moisture$_0$ (%)^2	58.6^b	58.9^b	60.9^a	60.7^a	0.8
Moisture$_f$ (%)^2	33.0	32.8	32.2	32.5	1.1
$a_{w,0}{}^2$	0.974^{ab}	0.973^b	0.974^{ab}	0.975^a	0.001
$a_{w,f}{}^2$	0.900	0.887	0.888	0.863	0.027
$pH_0{}^2$	5.89^a	5.79^{ab}	5.77^b	5.76^b	0.07
$pH_f{}^2$	5.10^a	4.93^c	4.98^b	4.97^{bc}	0.03
$L^*_{f,\ surface}{}^2$	58.9^b	70.8^a	69.6^a	61.2^b	5.8
$a^*_{f,\ surface}{}^2$	2.6^a	0.6^b	0.7^b	3.2^a	1.5
$b^*_{f,\ surface}{}^2$	3.7	4.5	4.1	3.7	0.8
$L^*_{f,\ internal}{}^2$	49.7	50.2	48.4	48.2	1.6
$a^*_{f,\ internal}{}^2$	8.5	9.1	9.1	9.1	0.6
$b^*_{f,\ internal}{}^2$	2.6	2.7	2.1	2.1	0.5

C: Collagen; A: Alginate; EA: E 475 alginate; PA: pea protein alginate; RMSE: root mean square error; ^{1}n=5; ^{2}n=3; $_0$: day 0 (before drying); $_f$: end of drying process; surface: colour measured on the surface of fuet; interior: colour measured on the transversal section of fuet. Different letters within a row indicate significant differences between batches ($p < 0.05$).

Table 4. Sensory analysis of non-mould non-fermented (NMNF) fuet.

Descriptors	**C**	**A**	**EA**	**PA**	**RMSE**
Appearance					
Colour intensity	6.3^{a}	5.4^{b}	5.0^{b}	5.4^{b}	1.0
Brightness	4.6^{a}	3.8^{b}	3.8^{b}	3.9^{b}	0.8
Odour					
Intensity	5.8	5.6	5.2	5.1	0.5
Flavour					
Intensity	5.8	5.4	5.7	5.3	0.8
Sourness	2.3	2.7	2.8	2.6	1.2
Texture (tactile)					
Hardness	4.0^{c}	5.0^{a}	5.8^{a}	5.4^{ab}	1.1
Waxy	1.5^{b}	3.4^{ab}	3.3^{a}	3.8^{a}	1.5
Texture (mouth)					
Hardness	3.3^{c}	4.1^{bc}	5.1^{a}	4.7^{ab}	1.0
Elasticity	2.5^{c}	2.9^{bc}	3.6^{ab}	3.7^{a}	1.4
Crumbliness	6.1^{a}	5.1^{b}	4.9^{b}	5.0^{b}	1.0
Gumminess	2.1^{b}	2.9^{a}	3.2^{a}	3.1^{a}	1.2

C: Collagen; A: Alginate; EA: E 475 alginate; PA: pea protein alginate; RMSE: root mean square error; n=6. Different letters within a row indicate significant differences between batches ($p < 0.05$).

Table 5. Sensory analysis of mould-fermented (MF) fuet.

Descriptors	**C**	**A**	**EA**	**PA**	**RMSE**
Appearance					
Colour intensity	5.2^{ab}	4.8^{b}	5.0^{ab}	5.3^{a}	0.9
Brightness	3.7	3.5	3.7	4.0	0.7
Odour					
Intensity	6.0	5.9	5.7	5.9	0.9
Mould	1.3^{b}	2.2^{a}	2.2^{a}	2.2^{a}	0.9
Ripened	3.8^{b}	4.5^{a}	4.3^{ab}	4.2^{ab}	0.8
Flavour					
Intensity	6.0	5.5	5.6	5.7	0.8
Sourness	3.3^{a}	3.4^{a}	3.1^{ab}	2.7^{b}	1.0
Ripened	3.1^{b}	3.7^{a}	3.8^{a}	4.2^{a}	0.9
Texture (tactile)					
Hardness	4.7^{b}	5.7^{a}	5.8^{a}	6.2^{a}	1.0
Waxy	2.3^{b}	4.3^{a}	4.0^{a}	4.3^{a}	1.7
Texture (mouth)					
Hardness	4.1^{b}	4.3^{ab}	4.7^{a}	4.8^{a}	0.7
Elasticity	2.6	2.6	2.5	2.8	0.8
Crumbliness	6.0^{a}	5.7^{ab}	5.5^{b}	5.2^{b}	0.8
Gumminess	2.2	1.8	2.1	2.0	0.6

C: Collagen; A: Alginate; EA: E 475 alginate; PA: pea protein alginate; RMSE: root mean square error; n=6. Different letters within a row indicate significant differences between batches ($p < 0.05$).

Conflicts of Interest Statement

The authors Begonya Marcos, Pere Gou, Jacint Arnau, Mª Dolors Guàrdia and Josep Comaposada certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

Author Statement

Begonya Marcos, Pere Gou, Jacint Arnau, Mª Dolors Guàrdia and Josep Comaposada conceived and planned the experiments. Josep Comaposada lead the project and carried out the experiments with Begonya Marcos. Mª Dolors Guàrdia planned and carried out the sensory analysis. Pere Gou and Jacint Arnau helped supervise the project. Pere Gou performed the statistical analysis and together with Jacint Arnau contributed to the interpretation of the results. Begonya Marcos took the lead in writing the manuscript. All authors provided critical feedback and helped shape the research, analysis and manuscript