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Impact of measures to increase packaging recyclability in stability of plant-based burgers: A comparative study between multilayer and monolayer lidding films

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ABSTRACT

The expanding market of plant-based meat analogues (PBMA) drives innovation toward sustainable packaging systems that ensure both product safety and environmental performance. This study aims at investigating the impact of measures to increase packaging circularity on the shelf life of plant-based burgers under refrigerated, modified atmosphere conditions. Two packaging systems were compared: a conventional polyethylene terephthalate (PET)-based tray with multilayer lidding system (STD) and a tray with a recyclable lidding film consisting of a machine-direction oriented polyethylene (MDO PE) monomaterial (NEW). Physicochemical (moisture, pH, titratable acidity, total volatile basic nitrogen, peroxide value, colour, texture, volatiles, and headspace gas composition), microbiological (total viable count, lactic acid bacteria, yeast and moulds, pathogens, and 16S rRNA sequencing), and sensory parameters were monitored during storage for 23 days at 4 ± 2 °C. Packaging materials were characterised for gas barrier and environmental impact. Results showed a similar performance for microbial growth at the end of shelf life in both packages. The NEW packaging showed to protect slightly less against oxidation and protein degradation. Sensory evaluation revealed more complex odour attributes in STD over time, and a greater tendency towards degradation odours in NEW. However, the environmental impact analysis demonstrated that the NEW system presents a 25% lower impact in global warming potential than the STD. Overall, although there are some differences noted in the burger behaviour when packaged in the NEW packaging compared to the STD, results support that the change into the monolayer lid can be performed, favouring circularity without relevant prejudice of the burger preservation. The findings inform sustainable packaging design for PBMA, highlighting the trade-offs between product stability and environmental performance in monomaterial versus multilayer systems. Results support packaging circularity strategies and European Packaging and Packaging Waste Regulation alignment for plastic packaging.

1. Introduction

The market of plant-based meat analogues (PBMA) is increasing, promoted by the need of protein sources diversification and societal concerns about animal welfare (Boukid, 2021; Ishaq et al., 2022; Lee et al., 2025). Plant-based burgers, typically formulated with pea or soy protein and vegetable fats, are especially popular due to their nutritional profile and broad appeal (Singh et al., 2021). However, few studies have examined how packaging systems affect their shelf life and quality.

As with all perishable foods, maintaining quality and microbiological safety during refrigerated storage is critical. Most PBMA research has focused on formulation and processing to mimic meat texture and

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flavour, while shelf life and microbial safety remain less studied (Abdullah et al., 2024). Spoilage dynamics vary with ingredients, processing, and storage conditions (Barmettler et al., 2025). Due to their high water activity, nutrient-rich composition, and slightly acidic pH, PBMA are susceptible to microbial growth, including both spoilage organisms and pathogens (Kabisch et al., 2023; Liu et al.,2023; Barmettler et al., 2025).

Effective cold-chain management and preservation strategies such as modified atmosphere packaging (MAP) and vacuum packaging are therefore essential. Today, industries are applying MAP to meat products in most cases. Although vacuum-sealed packaging can also be efficient in removing oxygen and slowing down the microbial aerobic growth responsible for food spoilage, vacuum deforms soft components. This deformation makes the product look squashed and less appealing to consumers. Therefore, industry tend to follow the same approach to PBMA although few studies have examined these techniques specifically for plant-based burgers (Fernandes et al., 2023; Abdullah et al., 2024; Neo et al., 2024; Hanus et al., 2025; Miao et al., 2025).

The success of MAP packaging depends heavily on barrier properties and sealing integrity (Abdullah et al., 2024; Siddiqui et al., 2022). Most studies rely on conventional multilayer materials, similar to those used for meat burgers. However, concerns about plastic waste and fossil resource depletion have intensified scrutiny of packaging's environmental impact. The European Packaging and Packaging Waste Regulation (PPWR) and RecyClass Design-for-Recycling Guidelines now promote monomaterial structures compatible with existing recycling streams. Evaluating monolayer systems against conventional multilayers is, therefore, crucial for both product stability (because changing the material structure can affect the barrier of the package) and regulatory compliance. Recyclability varies across common plastics such as polyethylene terephthalate (PET), low-density polyethylene (LDPE), high-density polyethylene (HDPE), and polyethylene (PP), with implications for waste generation, carbon footprint, and circular economy strategies (van den Tempel & Picchioni, 2025). Multilayer plastics provide functional benefits - strong barrier properties, design flexibility, and cost-efficiency - but their recyclability is limited. Combining different polymers complicates mechanical recycling, creating challenges for waste management and sustainability (Anukiruthika et al., 2020). Prioritizing recyclable monomaterials can reduce plastic pollution and improve the environmental profile of PBMA packaging, provided they maintain chemical, microbiological, and sensory integrity comparable to multilayer systems.

Machine-direction oriented polyethylene (MDO PE) has emerged as a promising alternative to PET, offering enhanced recyclability in flexible packaging (Krisnamurti et al., 2024). As a polyethylene-based material, MDO PE can be combined with LDPE to form monomaterial structures compatible with polyethylene (PE) recycling streams. It also provides improved mechanical strength, barrier performance, and processability, while enabling thinner, lighter films compared to non-oriented PE (Christmann et al., 2024). These attributes align with design-for-recycling principles and support more sustainable packaging solutions.

This study addresses that gap by comparing two packaging systems: (i) a standard PET-based tray with a multilayer lidding film (STD) used today by industries, and (ii) a NEW system in which the lidding film was replaced by an MDO PE structure, to improve recyclability. Assessments included chemical, microbiological, and sensory analyses, alongside evaluations of packaging performance (gas barrier properties, recyclability, and global warming potential). The objectives were: (i) to assess the impact of changing the packaging on the shelf life of PBMA, (ii) to determine the gain in terms of packaging circularity as represented by recyclability and reduction of global warming potential. This integrated approach provides insights into sustainable packaging alternatives and their role in maintaining PBMA shelf stability, with broader implications for waste reduction and circular economy strategies.

2. Materials and Methods

2.1. Plant-based burgers characteristics

Plant-based burgers (mass: 223.4 ± 2.4 g) were prepared by Noel Alimentaria SA (Girona, Spain). The burgers were composed of water, sunflower vegetable oil, textured pea protein (15%), pea protein (5%), chicory vegetable fibre, stabilizer (methylcellulose), white alcohol vinegar, pea starch (2%), coconut vegetable fat, flavours, onion, salt, potato extract, garlic, caramelized glucose syrup, iron, vitamin B12, and lactic ferments. According to ingredient label, the plant-based burger used in this study contains 11% of protein, 11% fat of which 3,9% saturates, 11% of carbohydrates of which sugars 1.9%, 1.8% of salt, and the energy 916 kJ (220 kcal) per 100 g of product. The use-by-date was expected to be around 18 days.

Samples were packaged in the standard tray/lid packing system (STD) and in the new system (NEW), at the industrial line in a form-fill-seal machine. In this machine, the tray is thermoformed, filled, flushed with the gas mixture and sealed. The composition of the gas mixture was 15% CO_2 / 85% N_2. The verification of the gas concentration in the finished trays was done in the beginning of the run by sampling 5 trays, and measurements were performed as indicated in Section 2.4.3.

2.2. Experimental design

Burgers were stored at 4 °C (± 2 °C) and sampled (in replicate) for monitoring physicochemical and microbiological characteristics at the following times: 2, 6, 9, 13, 17, 20 and 23 days after packaging. The burgers were analysed in duplicate for moisture, water activity (a_w), pH, titratable acidity (TA), total volatile basic nitrogen (TVB-N), peroxide value (PV), colour, texture, and microbiological parameters. A portion of each burger was frozen at −20 °C for later determination of volatiles by gas chromatography with mass spectrometry detection (GC-MS) and sensory evaluation. The packages were analysed for headspace gas composition.

2.3. Burger quality monitoring

2.3.1. Moisture and Water Activity

For moisture determination, 3 g of sample were mixed with 25 g of sand and dried at 105 ± 2 °C in an oven (Memmert ULE 600) for 2 h and weighted. It was further dried for 1 h periods until a constant weight (difference between two consecutive weights ≤ 0.003 g). The a_w was determined using a water activity meter, at 25 °C ± 2 °C (LAbMaster-aw neo, Novasina AG, Switzerland).

2.3.2. pH and Titratable Acidity

pH was measured in a suspension of 10 g of sample in 100 mL of deionized water at the temperature of 20 ± 2 °C, with gentle magnetic stirring, using a calibrated pH meter (Crison GLP 22 +, Crison, Spain) equipped with a combined pH electrode (Crison 50 14 T, Crison, Spain).

For titratable acidity determination, 10 g of sample was dispersed and diluted with deionized water in a 100 mL volumetric flask and filtered. A 10 mL aliquot of the filtrate was titrated with a 0.01 mol L^{-1} NaOH standard solution using phenolphthalein as the indicator.

2.3.3. Total Volatile Basic Nitrogen

The TVB-N was determined using the Conway microdiffusion method, based on the NP 1848 (IPQ, 1987), using the trichloroacetic acid extract of the sample. After incubation with sodium carbonate, the released bases were absorbed in boric acid and quantified by titration with HCl. Details of the method are presented in Supplementary Information.

2.3.4. Peroxide Value

The PV was determined according to ISO 3960 (ISO, 2017), after fat

extraction at room temperature, by titration of the liberated iodine with standardized sodium thiosulphate solution, using starch as the indicator. Details of the method are presented in Supplementary Information.

2.3.5. Volatile compounds

2.3.5.1. Sample preparation. Samples were thawed at room temperature, and 2.7 g portions were introduced into 20 mL headspace vials in replicate. An internal standard solution (1 μL) was then added prior to SPME analysis. A vial containing only 1 μL of internal standard served as a reference, while an empty sealed vial was analysed as a blank between each sample or standard.

2.3.5.2. Chromatographic analysis. GC–MS analysis (system Bruker® EVOQ 456 TQ GC/MS) was conducted with the mass spectrometer operating in electron impact mode in FULL SCAN mode within the mass range 20–350 (m/z). The sample was extracted using a SPME fibre. Details of the method are presented in Supplementary Information.

The identification of volatile substances was carried out by comparing their retention indices, based on a homologous series of n-alkanes (C8–C24), and respective mass spectra data with those from the NIST Tandem Mass Digital Library (Version 2.3, build May 4, 2017). Semi-quantification of volatiles is performed using an internal standard (1,2-dichlorobenzene, concentration of 25 mg L^{-1}).

2.3.6. Microbiological analyses

Microbiological analyses were performed in two replicates (burgers). Sample suspensions (1:10 wv^{-1}) and appropriate decimal dilutions were prepared in Ringer's solution for enumeration total viable microorganisms (TVC) at 30 °C (ISO, 2013); yeasts and moulds (IPQ, 1987a); lactic acid bacteria (LAB) (ISO, 1998); Enterobacteriaceae (ISO, 2017a); *Escherichia coli* (ISO, 2001); coagulase-positive staphylococci (ISO, 2021); *Pseudomonas* spp. (ISO, 2010), *Bacillus* spp. (heated sample at 80 °C - 10 min; Trypto Casein Soy agar (TSA); 37 °C - 48 h); and for detection of sulphite-reducing *Clostridium* spores (IPQ, 1986).

Detection of *Salmonella* spp. was performed according to ISO 6579-1 (ISO, 2017b). For the detection of *Listeria monocytogenes* and *Listeria* spp., the ALOA® One Day method (AFNOR AES 10/03–09/00) was applied. Detailed descriptions of the microbiological methods are presented in Supplementary Information.

Using the DMFit tool (ComBase, USDA-ARS, USA), the Baranyi and Roberts model (Baranyi & Roberts, 1994) was fitted to the experimental TVC and LAB data. The kinetic parameters, maximum specific growth rates (μmax in log CFU g^{-1} day^{-1}), and lag phase (λ in day) were estimated for TVC and LAB at both packaging systems.

2.3.7. DNA extraction and Illumina partial 16S rRNA amplicon sequencing

Approximately 2 g of defrosted sample were added to 18 mL of sterile peptone water and homogenized for 1 min in stomacher bags with a filter. 2 mL homogenate per sample were collected directly after homogenization and pelleted by centrifugation at 13000 ×g for 5 min. The pellet was frozen at −20℃ until the time of analysis. DNA extraction from pellets was done with the DNeasy PowerLyser PowerSoil kit (Qiagen) following the kit protocol, the pellets were homogenised by tissue homogeniser (Precellys Evolution 24 Tissue homogeniser) for 3 × 40 s at 7400 rpm with 10 s between intervals.

16S rRNA gene PCR (V4 region) and paired end sequencing (2 ×150 bp) using the MiSeq Reagent Kit (v2–300 cycles Micro) on a MiSeq instrument (Illumina) was performed using the protocol presented by Caporaso et al. (2012). The sequences were processed in QIIME2 (qiime2–2023.5) (Bolyen et al., 2019). Briefly, the data processing was: demultiplexed using demux, paired ends were joined using search, quality filtered based on a q-score above 30, denoised using deblur 16S, and taxonomy was achieved using classify-sklearn with the SILVA database (Silva 138 99% OTUs from the 515 F/806 R region) as previously described (Moen et al., 2023). Mitochondrial- and chloroplast sequences were removed by filtration. The genus level taxonomy table was exported to text files and further processed in Excel. Representative sequences of the most dominating sOTUs were subjected sequence similarity searching using the BLAST blastn suite (https://blast.ncbi.nlm.nih.gov/) (accessed 30 June 2025). The standard nucleotide collection database and the highly similar sequences option were used. The sequencing data have been deposited in the National Center for Biotechnology Information (NCBI) archives under BioProject no. PRJNA1355048

2.3.8. Colour and Texture

The surface colour of the meat analogue was measured in the CIE L*a*b* colour space (Konica-Minolta CR−400 spectrophotometer, Osaka, Japan) equipped with a D_{65} illuminant and a 2-degree Standard Observer for colour interpretation. The L* value indicates lightness, a* represents the degree of greenness (negative values) to redness (positive values), and the b* axis indicates the degree of blueness (-) to yellowness (+). The measurements (6) were obtained immediately after opening and removal of the sample from the packaging,

The burger texture was analysed with a texture analyser (TA-XT2 Plus, Stable Micro Systems, Surrey, United Kingdom) equipped with a 5 kg load cell. The force to drive a 6 mm diameter cylindrical probe to penetrate 5 mm into the tissue, at a speed of 5 mm s^{-1} was recorded. Hardness and chewiness were reported.

For both analysed parameters (colour and texture), measurements were performed randomly distributed locations across the burger surface area.

2.3.9. Sensory Evaluation

A generic descriptive sensory analysis (GDA) (Lawless & Heymann, 2010) was performed to evaluate the odour (orthonasal evaluation) profile of meat analogue samples packaged in the STD and NEW systems over storage time. Odour descriptors were selected based on a literature review (Fiorentini et al., 2020; Han et al., 2024). A pre-trial sensory evaluation session conducted by two senior panellists from the UCP sensory evaluation panel, with over fifteen years of experience in sensory descriptive analysis.

GDA evaluation was performed by a trained panel (eight-members) highly experienced and qualified in the sensory descriptive analyses of food products. The panellists were semi-trained specifically for this meat analogue. One pre-trail training session was performed, by providing the panel with product (in triplicate) with 2, 13 and 23 days of storage. These products, with different attribute intensities, were used to calibrate the panelists regarding the evaluation of the different attributes and to train them in the use of the rating scale, promoting the reproducibility of evaluations among panelists. While the use of semi-trained panelists does not support absolute quantification of attribute intensity, it is highly effective for comparative profiling (Simiqueli et al., 2015; Lawless & Heymann, 2010).

The evaluation followed the standard ISO 13299:2016 (General Guidance for establishing a sensory profile by a sensory panel consisting of trained assessors). Samples were thawed 24 h before and prepared for testing 2 h beforehand. Samples were labelled with three-digit codes and presented simultaneously to panellists in random order. The following odour attributes were selected for GDA evaluation: total intensity, sour / fermented, rancid, grilled, smoky, condiment, degradation. Attribute intensity was evaluated using a discrete anchored scale (1 – odour not detected, 9 – strong intensity). All sensory evaluation sessions were conducted in a sensory analysis laboratory equipped with individual booths at 20–22 ºC.

2.4. Packaging Characterisation

2.4.1. Materials structure

Two packaging systems were tested: the standard multi-material

(STD) and the new with a lid monomaterial (NEW), with the following structure:

- STD lid film - PET/Adhesive/PE- Ethylene Vinyl Alcohol (EVOH)-PE with 62 μm of thickness
- NEW lid film - MDO PE 25/LDPE-EVOH-LDPE 35 with 60 μm of thickness
- STD and NEW tray sheet - PE/EVOH/PET with 300 μm of thickness.

Details of the material specifications, as provided by the supplier, are presented in Supplementary Information.

The composition of the material structure and thickness were confirmed, respectively by FTIR - Fourier transform infrared spectroscopy (PerkinElmer Spectrum BX FTIR System spectrophotometer, Massachusetts, USA) and using a micrometer (Adamel Lhomargy M120). The mid-infrared spectra were obtained within the wavenumber interval of 4 000–600 cm^{-1}, with a resolution of 4 cm^{-1} with a deuterated triglycine sulphate (DTGS) detector, in diffuse reflectance mode through a Gladi attenuated total reflectance (ATR) accessory (PIKE Technologies, Wisconsin, USA).

2.4.2. Geometrical features

The trays were formed-filled-sealed in an industrial line. The final dimensions of trays were approximately 20 × 13 × 3.0 (LxWxD). Total empty packaging weights were 10.6 ± 0.3 for STD and 10.4 ± 0.2 for NEW.

The gas to product ratio was determined with the total volume of the empty sealed tray, the volume of the burger (2 in each tray) and assuming the burger density as 1.

2.4.3. Head-space gas composition

The headspace atmosphere composition was analysed for CO_2 and O_2 levels (%) at each sampling time using a headspace gas analyzer (CheckMate 3®, Dansensor, MOCON Europe A/S, Denmark). Gas sampling was performed by inserting a needle through a self-sealing septum in the lid.

2.4.4. Gas transmission rate

The gas transmission rates for the whole system (trays with sealed lid), accounting for changes in thickness due to thermoforming and for transmission though the seal, were measured in 10 trays. OTR (oxygen transmission rate) and CDTR (carbon dioxide transmission rate) of the whole trays (sealed) were calculated from changes in volumetric fractions of the gases inside the packages over time (non-linear regression of the data) applying the Eq. 1 (Larsen & Liland, 2013).

$$\frac{(C_t - C_{air})}{(C_i - C_{air})} = \exp\left(-\frac{TR}{V}t\right) \quad (1)$$

where TR is the gas transmission rate (mL per package per day), V is the volume of the package headspace, t is the time, Cair is the volumetric concentration of gas in the air (0.21 O_2, and 0.03 CO_2), Ct the volumetric concentration of gas in time t, Ci the volumetric concentration of gas in the package at the initial measurement. Trays were filled with the same gas-mixture used to pack the burgers. Empty trays were injected with 40 mL of water to create an atmosphere of about 100% relative humidity and stored in a chamber at 4 °C and 70–80% relative humidity. Every two weeks, two trays were sampled for gas composition, as previously described.

The specifications for gas transmission rate were provided by the supplier with measurements in flat samples and standard conditions of temperature (see Supplementary Information).

2.4.5. Circularity factors

Several factors must be considered when assessing the circularity of packaging (Pauer et al., 2019). The present packaging systems are entirely fossil-based plastics; therefore, considerations regarding bio-based materials, compostability and reusability do not apply. However, recyclability is a key aspect due to the different composition of the lidding materials.

The recyclability of the films was calculated using the RecyClass Packaging Methodology (Plastics Recyclers Europe, 2025). An online questionnaire was completed for both lidding films, following classification into one of the categories.

Additionally, differences in the environmental impact of the packaging production step may be relevant to compare both lidding films because they are obtained using different technologies and with materials originating from different places, therefore impacting the transportation burden. A comparison of the two lidding films regarding the impact on global warming was conducted. The system boundary was defined to focus exclusively on the life cycle of the lidding films, from raw material extraction to end-of-life, following a cradle-to-grave approach and according to ISO 14040 (ISO, 2021a) and ISO 14044 (ISO, 2021b). The functional unit was 1 tonne of multilayer film. The production of the burgers, their refrigerated storage, and the associated energy used during distribution, retail, or consumer storage were excluded from the LCA, as these stages are identical for both packaging systems and do not affect the comparative outcome.

All steps, from the extraction of the raw materials to the disposal of the films, were included and real data from a Vizelpas converter plant (Portugal) were used. This company imports the polyolefin pellets and additive masterbatches for extrusion, as well as PET film, from different places of the world. The company extrudes the MDO PE film and co-extrudes the LDPE/EVOH/LDPE structures. The combination of the co-extruded layer with either MDO PE or PET film is performed by adhesive lamination. The final films are packaged and transported to the burger factory for filling and sealing, following market distribution to the point of sale. After domestic use, the packaging waste is collected and transported to the sorting centre, where various end-of-life methods are applied, either landfilling, incineration or recycling. The end-of-life scenarios from Porto Municipalities Waste Management were considered (Mota et al., 2025). These shares reflect current waste management practices and were applied according to the material composition of each packaging system. The specific rates for recycling, incineration and landfilling are presented in Supplementary Information (Table S1).

The transport processes include the movement of raw materials from various locations to the converter facilities, as well as the materials used in packaging (pallets, stretch film, wrapping paper, tubes for film reels and labels). In addition, the transport of the finished film to the burger producer, to the point of sale and to the end of life are included.

Other packaging materials used in the burger producer were not considered because they are assumed to be the same for each system. The impact of burger production was also excluded because it is the same burger packaged in both tray/lids. Regarding plastics additives, major components, namely the maleic-anhydride-based compatibilizer and the polyurethane lamination adhesive, which together represent approximately 9–11% of the total film mass, were fully included in the model. Due to lack of specific data in the Ecoinvent database, some additives were excluded from modelling. However, these represent only approximately 3% of total film mass for the MDO-PE and PET-based structures. These excluded components consist mainly of minor polymer-compatible masterbatches. Given their low mass fraction and polymeric nature, the excluded additives are not expected to significantly influence the global warming potential relative to the dominant contributions from primary polymer production and end-of-life treatment. These exclusions are acceptable according to the cut-off criteria established by the ISO 14044.

The Ecoinvent 3.10 cut-off database (Wernet et al., 2016) was used to calculate the potential environmental impacts. Market datasets with default allocation (Alloc Def, S) were used for raw materials, energy and transport processes. The SimaPro v9.5.0 (PRé Sustainability, 2024) was used for inventory and impact assessment modelling. The

characterisation factors applied were from the ReCiPe 2016 midpoint v.1.08 method (Huijbregts et al., 2017).

2.5. Statistical Treatment

Two-way ANOVA and Tukey's multiple comparison test (IBM SPSS Version 29.0.2.0 (20), SPSS Inc., USA) were performed to analyse the effect of time and packaging in the quality parameters of the burger. Assumptions regarding normality of residuals and homogeneity of variance were verified and non-parametric tests were used where necessary.

XLSTAT software (Addinsoft SARL, France) was used to carry out the statistical analysis of sensory data. For each attribute significant differences between samples were investigated using Sign test and Wilcoxon signed-rank test. To obtain a consensual product and attributes configuration for the samples and descriptors a Generalized Procrustes Analysis (GPA) was performed. GPA reduces scale effects by detecting and minimizing individual differences and allowing a comparison of the proximity between sensory descriptors and samples (Naes et al., 2018).

The significance of statistical tests was evaluated at $p < 0.05$, unless otherwise stated.

3. Results and Discussion

3.1. Physical-chemical parameters of the burgers

Fig. 1 presents the results for the chemical parameters of the burgers over the storage time for the two packaging systems (STD and NEW). The pH of burgers in both packages remained relatively stable up to day 13, ranging from 5.7 to 5.9. These values are consistent with those reported for plant-based formulations as in the literature, where pH values typically range from 5.3 to 6.5, with a mean of 5.7 (Barmettler et al., 2025). After this time, a sharp decrease in pH was observed with values of ca. 4.8 – 5.1. The pH values recorded for the NEW packaging system were slightly higher ($p < 0.05$) than those for the STD packaging system.

The pH values were consistent with those of total acidity, TA (Table S2). TA remained stable during the first days of storage and increased significantly over time in both packages, particularly after day 9, hinting towards the possibility of progressive microbial activity and accumulation of organic acids (see "Carboxylic acids" in Fig. 2). On day 13, both samples reached a peak acidity (around 2.8 cm^3 NaOH/100 g), without a specific attributable reason. Afterwards, TA seemed to reach a plateau, suggesting that microbial activity stabilized in later stages of storage.

PV and TVB-N increased steadily in burgers packaged in both systems over storage time (Fig. 1). PV values in the NEW packaging system peaked at 5.6 ± 0.1 mEq O_2kg^{-1} on day 13. This peak was not observed in burgers packaged in the STD system, for which PV values were statistically lower ($p < 0.05$) than those observed for the NEW system. These results suggest that burgers in the NEW system are more susceptible to oxidative degradation.

Protein degradation gradually increased in both the STD and NEW packages during the 24 days of refrigerated storage. The TVB-N values increased up to day 13, showing a decreasing pattern after that storage time, for both packages. While both samples showed low initial TVB-N values, as expected for freshly prepared products, the NEW sample exhibited consistently higher values throughout the storage period, peaking in day 13 at 29.5 ± 0.1 mg N/100 g. This also suggests a higher susceptibility to spoilage when the burger is stored in the NEW packaging.

Values of water activity were relatively constant, varying between 0.9 and 1 (Table S2). Overall, low values of water loss were recorded as the moisture content decrease was below 1% for the whole storage period. No statistically significant differences ($p > 0.05$) were found between both packages for these parameters.

3.2. Volatile Organic Compounds (VOCs) Profile

Formulation of meat analogues using plant proteins typically aims to

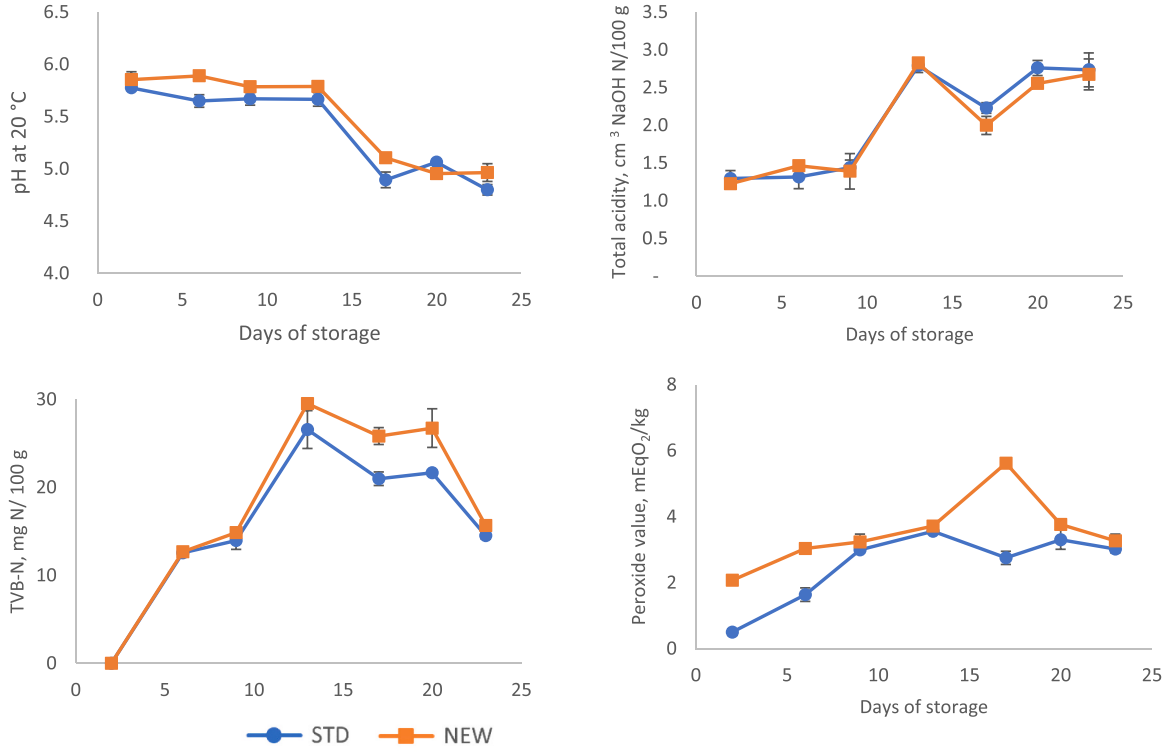


Fig. 1. Chemical analysis (average ± standard error) of plant-based burgers samples stored in different packaging systems (STD and NEW).

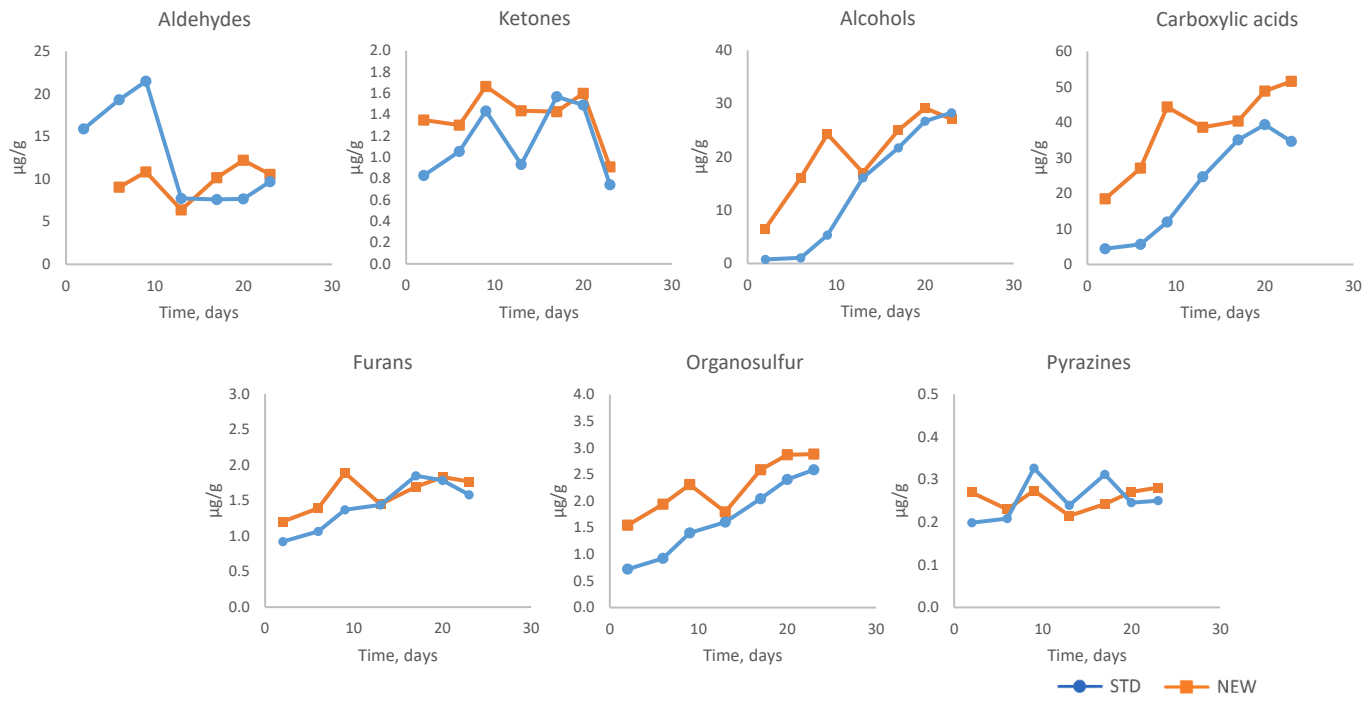


Fig. 2. Total concentration of classes of VOCs along the storage time for both packaging systems.

achieve sensory properties that closely align with those of traditional meat products, ensuring widespread consumer acceptance (Fiorentini et al., 2020). However, a common challenge associated with plant proteins in meat analogues is the generation of volatile compounds resulting from oxidation of unsaturated fatty acids, leading to undesirable odours and flavours. To mitigate this issue, spices, seasonings, and flavour enhancers are often incorporated to mask beany and grassy aromas, which are particularly prevalent in pulses (Fiorentini et al., 2020).

Volatile compounds in the burgers were monitored over the storage period to assess compositional changes and spoilage indicators, with particular emphasis on differences between packaging systems. Results are presented in Fig. 2 and Tables S3 and S4. Concentrations were obtained by semi-quantification and should therefore be interpreted as relative values for comparison between different times and packaging systems, rather than absolute concentrations.

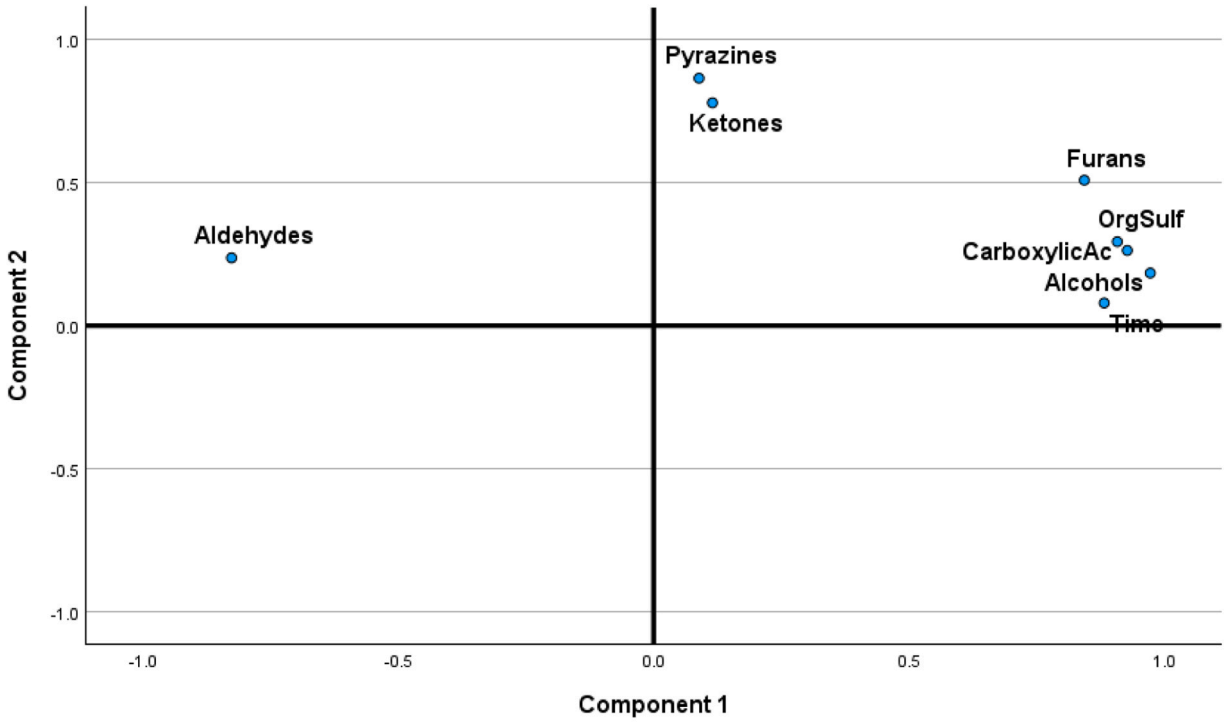
The detected compounds were grouped into major classes: aldehydes, alcohols, ketones, pyrazines, organosulfur compounds, carboxylic acids, monoterpenes, and furans. These volatiles contribute to the sensory properties of plant-based burgers, by shaping aroma and flavour profiles that mimic those of real meat products. Their presence or absence plays a critical role in consumer acceptance.

The aldehydes detected at the highest concentration were hexanal, 2-heptenal and nonanal. These derive from lipid oxidation and are respectively associated with green/grassy oxidised, and fatty/cardboard odours (Wang et al., 2022). The values for the aldehydes tended to be lower in the NEW packaging system at earlier storage times, while similar values were found in both systems at later stages. Ketones, namely 2-heptanone, 2-octanone and 2,5-octadien−2-one, also formed through lipid degradation and fermentation processes, were detected and slightly higher values were found in the NEW packaging compared to the STD.

The compound 2-pentylfuran (containing a furan ring) is typically associated with beany flavours in meat analogues and originates from the oxidation of linoleic acid; it is plant-specific and not found in meat products (Fiorentini et al., 2020). 2-Methyltetrahydrofuran−3-one was also detected. This compound, containing a furan ring bearing a ketone group, has been associated with sweet, bread-like, and buttery flavours (Zhang et al., 2024). Sulphur containing compounds were expected but at low concentrations because pea, the main protein source in the PBMA used in this study, is low in sulphur-containing amino acids like methionine and cysteine. Among these compounds, diallyl disulphide was the most relevant. Pyrazines were detected at low and relative constant concentrations along the time, which is consistent with the fact that the burgers under study were not produced by extrusion. When applied, extrusion process contributes to the formation of pyrazine through Maillard reactions, promoting a roasted, grilled and nutty flavours, typical of meat products (Jiang et al., 2024).

Aldehydes and ketones did not show an increasing trend over time, although an increase could be expected due to oxidation occurring during storage. However, the high variability of the results does not allow a clear trend to be observed, despite the increasing tendencies observed for PV and TVB-N values. In contrast, alcohols (mainly 1-hexanol) and acids (primarily acetic acid), as well as organosulfur (mainly diallyl disulphide) and furan containing compounds, showed concentrations tending to increase with time, after six days following packaging. Generally, burgers packaged in the NEW system consistently presented higher relative concentrations of volatiles than that those packaged in the STD system, except for furans and pyrazines, particularly after day nine. These observations are consistent with the pH and TA results.

To evaluate the contribution of different VOCs to sample discrimination, a principal component analysis (PCA) of VOCs concentrations was conducted. Fig. 3 shows that the first two principal components explain 85% of the variance. PC1, accounting for 65% of the total variance, clusters the chemicals into three main groups from the negative to the positive axis, from aldehydes, followed by pyrazines together with ketones, and the last group joins the organosulfur, furans, carboxylic acids and the alcohols. The distribution along PC1 indicates the relevance of different volatiles along the storage time. PC2 with 20% of variance depends only on pyrazines and ketones (Fig. 3a). Fig. 3b indicates that no relevant differences between the packages are noticed in the volatile fraction. Overall, results from volatiles are also consistent with both the microbiological and the sensory analyses discussed below.



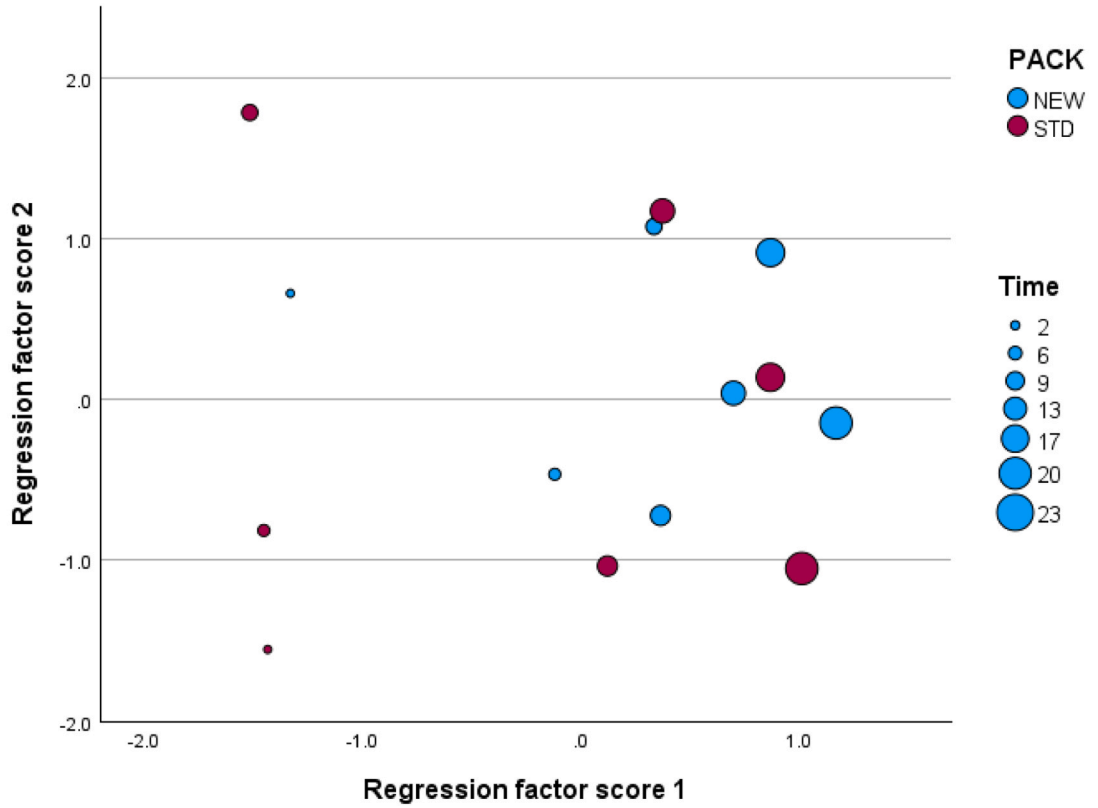


Fig. 3. PCA of VOCs analysis. a: Component plot in rotated space; b: Scatter plot of regression factor 1 score versus regression factor 2 score by packaging and time.

3.3. Microbiological analyses

Results for total viable counts (TVC) and lactic acid bacteria (LAB) are shown in Fig. 4, with average values reported in Table S5. Growth curves were modelled and the fitted curves are presented in Figure S1. The kinetic parameters obtained: maximum growth rates (μmax) and lag times (λ) were determined to facilitate the comparison between the experimental curves. Overall, the model provided acceptable fits for both packaging systems, with slightly better statistical performance for the NEW system.

Two days after production, the TVC of the burgers averaged 3.9 log CFU g^{-1} in the STD packaging system and 4.1 log CFU g^{-1} in the NEW

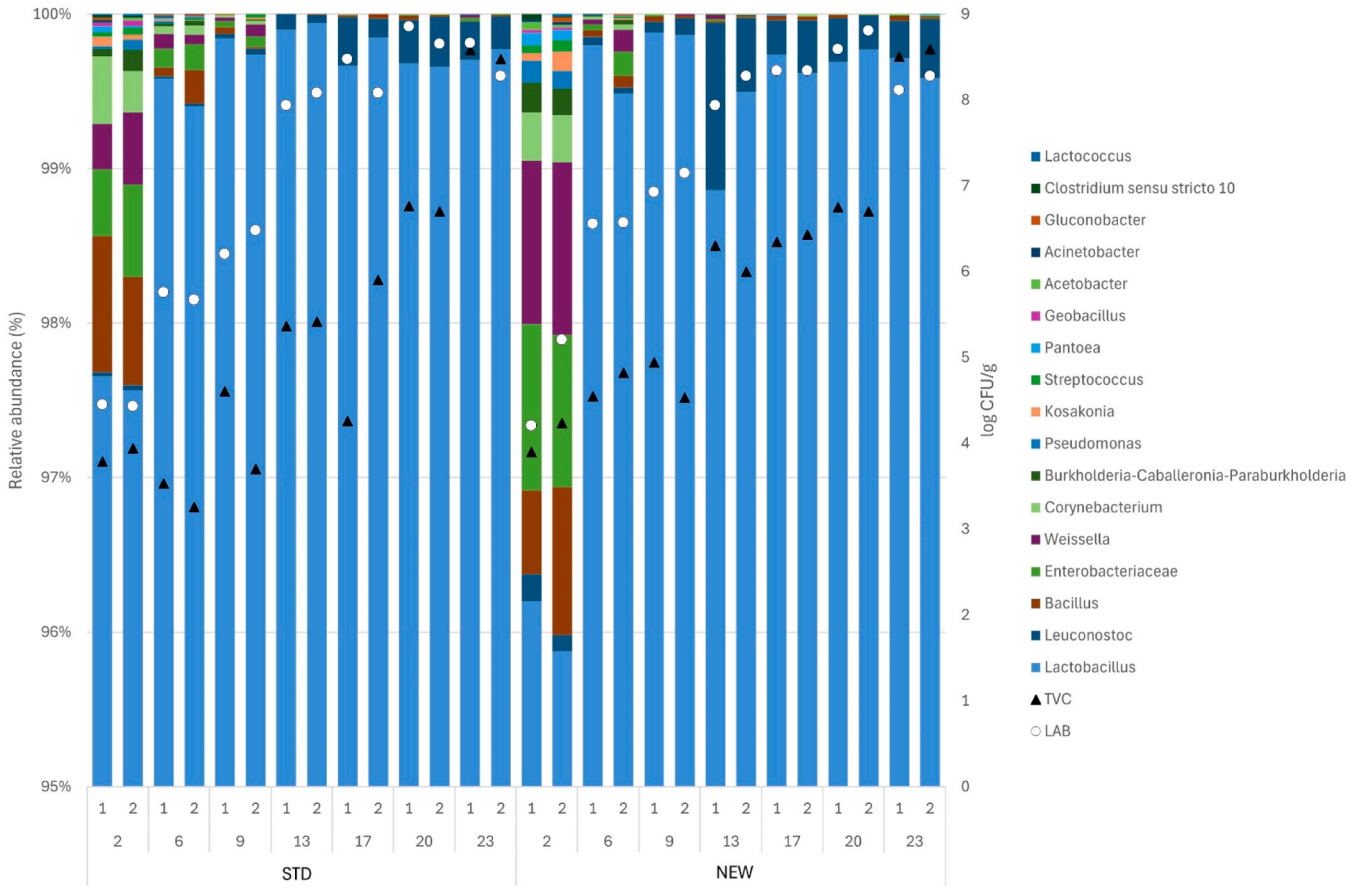


Fig. 4. Bacterial counts (log CFU g^{-1}) represented by filled black triangle (total viable counts) and open circles in white (lactic acid bacteria). Vertical bars represent the microbiota of the plant-based burgers in the STD and NEW packaging systems. The relative abundance of the genera/families present is shown from 95% to 100%. The different colours represent the different genera/families. Values for the two replicates analysed are plotted.

packaging system. TVC increased during storage in both packaging systems, although differences in growth behaviour were observed (Figure S1a). Burgers packaged in the STD system exhibited a longer lag phase (15.7 ± 1.4 days and 5.6 ± 3.0 days for STD and NEW packaging system, respectively), indicating delayed microbial adaptation, whereas the maximum specific growth rate (μmax) was higher in the STD system (0.61 ± 0.15 log CFU g^{-1} day^{-1} for STD and 0.23 ± 0.040 log CFU g^{-1} day^{-1} for NEW packaging system), indicating faster growth once adaptation occurred. By day 23, TVC levels converged, and no differences between packaging systems were observed.

LAB growth was well described by the Baranyi model in both packaging systems (Figure S1b) and showing similar kinetic behaviour. Initial LAB counts (4.4 log CFU g^{-1} and 4.7 log CFU g^{-1}, for the STD and NEW packaging systems) were consistent with the inclusion of a LAB culture in the formulation, and final LAB counts did not show marked differences between systems. LAB may be relevant for PBMA stability (Roch et al., 2024); however, they can also be responsible for undesirable changes (such as acidification, gas formation or ropy slime) even when the product is stored at low temperatures (Iulietto et al., 2015; Barmettler et al., 2025).

The results obtained are aligned with previous studies on plant-based meat analogues. Liu et al. (2023) observed initial low microbial counts, both in soy-based and pea-based formulations, most likely due to the thermal processing of the ingredients, but after 10 days of storage at 4 °C, the TVC and LAB reached levels around 7 log CFU g^{-1}.

Yeast remained relatively stable throughout the study in both packaging systems (Table S5). In the STD packaging, counts ranged from 2.7 log CFU g^{-1} on day 6 to 3.6 log CFU g^{-1} on day 23, whereas in the NEW packaging they varied from 2.8 log CFU g^{-1} on day 2 to 4.0 log CFU g^{-1} on day 23. Mould counts were below the detection limit (<1.0 log CFU g^{-1}) during the entire storage period, and no differences were observed between the two packaging systems.

Only low levels of *Enterobacteriaceae* were detected during the early storage days (up to 1.3 log CFU g^{-1}) under both packaging conditions, and counts dropped below the detection limit (<1.0 log CFU g^{-1}) after day 9. The presence of these bacteria would be indicative of inadequate hygiene practices during production, contamination of raw materials, or possible cross-contamination (Barmettler et al., 2025). Moreover, regardless of the packaging system, counts of coagulase negative staphylococci never exceeded 2.5 log CFU g^{-1} throughout storage and coagulase-positive staphylococci (potentially enterotoxin-producing) were not detected (<1.0 log CFU g^{-1}).

The number of *Bacillus* spp. spores varied over the storage period, showing similar behaviour in both types of packaging. Microbial loads ranged from 2.4 log CFU g^{-1} (day 13) to 3.2 log CFU g^{-1} (day 9) in STD, and from 2.3 log CFU g^{-1} (day 13) to 3.5 log CFU g^{-1} (day 23) in NEW. These results suggest that the product and/or its environmental conditions, particularly storage temperature, were not favourable for spores' germination (Rodrigo et al., 2021). The results for counts of sulphite-reducing *Clostridium* spores and *Pseudomonas* spp. remained below the detection limit (<1.0 CFU g^{-1}), for both packaging systems. Overall, these results reflect good hygiene practices and good sample handling conditions.

Potential pathogenic microorganisms were analysed only at the beginning of storage. *Escherichia coli* (<1.0 log CFU g^{-1}), *Salmonella* spp. and *Listeria* spp. (including *L monocytogenes*) were not detected in 25 g, indicating a safe product. Although these pathogens are typically associated with meat products, their occurrence in plant-based alternatives

cannot be excluded. Contamination may originate from raw materials or result from cross-contamination during processing, as many facilities produce both meat and plant-based products. Indeed, the presence of pathogenic microorganisms in plant-based foods available on the market has been reported, and several studies have shown that, when present, these pathogens can grow under favourable conditions (Barmettler et al., 2025; Dušková et al., 2024; Lomas et al., 2024; Liu et al., 2023). Although plant-based burgers are intended to be cooked before consumption, undercooking by consumers is relatively common - possibly even more frequent for plant-based products, as consumers may perceive them as safer than their meat-based counterparts (U.S. Department of Agriculture, 2022).

The results for the microbiota analyses are shown in Fig. 4. The microbiota was completely dominated by the genus *Lactobacillus* with a relative abundance above 95% in all samples, regardless of the packaging system. Among the LAB, *Latilactobacillus sakei* has been reported to grow in meat at low temperatures, compete with other species and survive through storage (Rocchetti et al., 2021). From the microbiological results, obtained through culture-dependent methods, and the fact that the plant-based burgers contained LAB culture in the formulation, this dominance was expected. The most abundant OTU (sub--operational taxonomic unit) representing the genus *Lactobacillus,* showed sequence similarity to *Latilactobacillus sakei* and *Latilactobacillus curvatus* (BLASTnt database), both species commonly used in food cultures (Zhao et al., 2024). It is, however, important to note that the sequencing technique used in this study lacks the phylogenetic resolution to precisely discriminate between *Lactobacillus* species. At the beginning of storage (day 2), other bacterial genera/families present were also detected, including *Bacillus*, *Enterobacteriaceae*, *Weissella* and *Corynebacterium*, although these accounted for less than 5% of the total relative abundance. These genera/families were outcompeted by *Lactobacillus* during storage, as supported by the culture-based microbiological counts. After 13 and 17 days of storage in the STD and NEW packaging systems, respectively, *Lactococcus* was also detected but only at a low relative abundance (around 1% or less). Overall, the two packaging systems resulted in very similar microbiota during storage, although there were some differences in the culture-dependent analysis for TVC.

3.4. Colour and Texture

One of the challenges of meat analogues is to mimic the appearance, and particularly colour and texture, of raw and cooked animal-based meat (Sakai et al., 2022). Colour is a primary factor often associated with wholesomeness and determining purchase intention for meat products (Dhanapal & Erkinbaev, 2024). The change in the inherent colour of uncooked meat products is mainly due to shifting from oxymyoglobin to metmyoglobin resulting in a browner colour, usually not appreciated by consumers. Uncooked meat analogues typically have a natural yellow or beige colour. Therefore, colorants, such as beet juice extract and soy leghemoglobin, a heme-containing protein found in the root nodules of some leguminous plants, are commercially used to impart the distinct meat colour (Vallikkadan et al., 2023) and early browning may occur in retail packaging conditions of storage (Sakai et. al., 2022). The patty formulation with several ingredients, with different physicochemical properties, combined with specific plant proteins with dissimilar hydration and solubility properties, makes colour dependent on complex interactions and possible variations during storage (De Marchi et al., 2021).

The results for burger colour over time are presented in Figure S2. The L* values show a slight trend to increase with storage time for samples stored in both packages. Overall, the values ranged between 53.5 and 55.5, suggesting minimal differences in lightness with no statistical differences between samples ($p > 0.05$). Values were aligned with what is reported in the literature (Dhanapal & Erkinbaev, 2024). The parameter a* did not show a remarkable change along the time for both packages. Values of b* increased steadily for both packages, indicating a progressive increase in yellowness, also perceived visually. However, results do not reveal a consistent trend of differences between the values of burgers packaged in the two systems. Overall, both packaged burgers exhibited similar lightness and chromatic behaviour under the measured conditions, with ΔE* values consistently around 42–44 across time points.

The results for texture are presented in Figure S3. Values are consistent with those reported in the literature for burgers of same type and before cooking (Hanus et al., 2025). No significant differences ($p > 0.05$) were found for burgers packaged in the STD and NEW systems over the different sampling days due to the high degree of variability in texture values.

3.5. Sensory Evaluation

Consumer acceptance of PBMA is highest when products closely replicate the sensory attributes of meat, such as flavour and texture, particularly among consumers who still continue to include animal products in their diets (Appiani et al., 2023; Giezenaar et al., 2024). Flavour challenges involve a lack of savoury notes, the presence of beany, grassy, or earthy undertones, and occasional undesirable aftertastes (Appiani et al., 2023).

Univariate statistical analysis revealed no significant differences across all samples and evaluated attributes (Sign test and Wilcoxon signed-rank test, $p > 0.05$). To further explore the data, a multivariate Generalized Procrustes Analysis (GPA) statistical analysis was applied to reduce assessor bias and obtain a consensus map of the results. Fig. 5 depicts the GPA map obtained. The two main factors (F1 and F2) explained 62.5% of the variance. The representation of samples and descriptors indicates somewhat different sensory profiles for burgers packaged in the NEW and STD systems, with differences observed over the storage period. Samples packaged in the STD system appeared to exhibit a more complex odour, subtle differences, with higher intensities of grilled, condiment and smoky flavours, compared to those in the NEW system. In contrast, plant base burgers in the NEW packaging showed smaller changes in their sensory profile over shelf life, as indicated by a shorter trajectory along the F1 axis. A trend towards higher overall and sour/fermented intensity of odour at the end of storage time is apparent for STD, while the burger in the NEW package displayed a tendency toward degradation-related odours at later storage stages. It is recognised that the use of a semi-trained panel introduces higher variability, but results indicate that the approach followed enabled the identification of sensory trends and the discrimination between PBMA in different packages, which aligns with the primary objectives of this study.

3.6. Packaging Characteristics

3.6.1. Materials structure

The FTIR analysis confirmed the structure of packaging materials. The identification of the different layers and respective thicknesses were used for the environmental analysis in the Section 3.7.

3.6.2. Gas barrier

The OTR for the standard and new packages was respectively, 0.21 ± 0.01 cm^3 day^{-1} per package and 0.24 ± 0.01 cm^3 day^{-1}. The CDTR was respectively 1.56 ± 0.08 cm^3 day^{-1} and 1.82 ± 0.10 cm^3 day^{-1}. The standard error corresponds to ca 5% of the estimated value.

The OTR value was compared with the specification provided by the suppliers, applying the packaging geometrical factors (tray and lid surface area). The specifications were provided in normalised units, obtained in measurements in flat samples and standard conditions of temperature (23 ºC and 50% relative humidity). The OTR of tray sheet was ≤ 1.5 cm^3 m^{-2} d^{-1} bar^{-1} and the surface area of the tray was determined as 0.0345 m^2. The OTR values of the lidding materials were 1.99 cm^3 m^{-2} day^{-1} bar for the STD material and 1-2 cm^3 m^{-2} day^{-1}

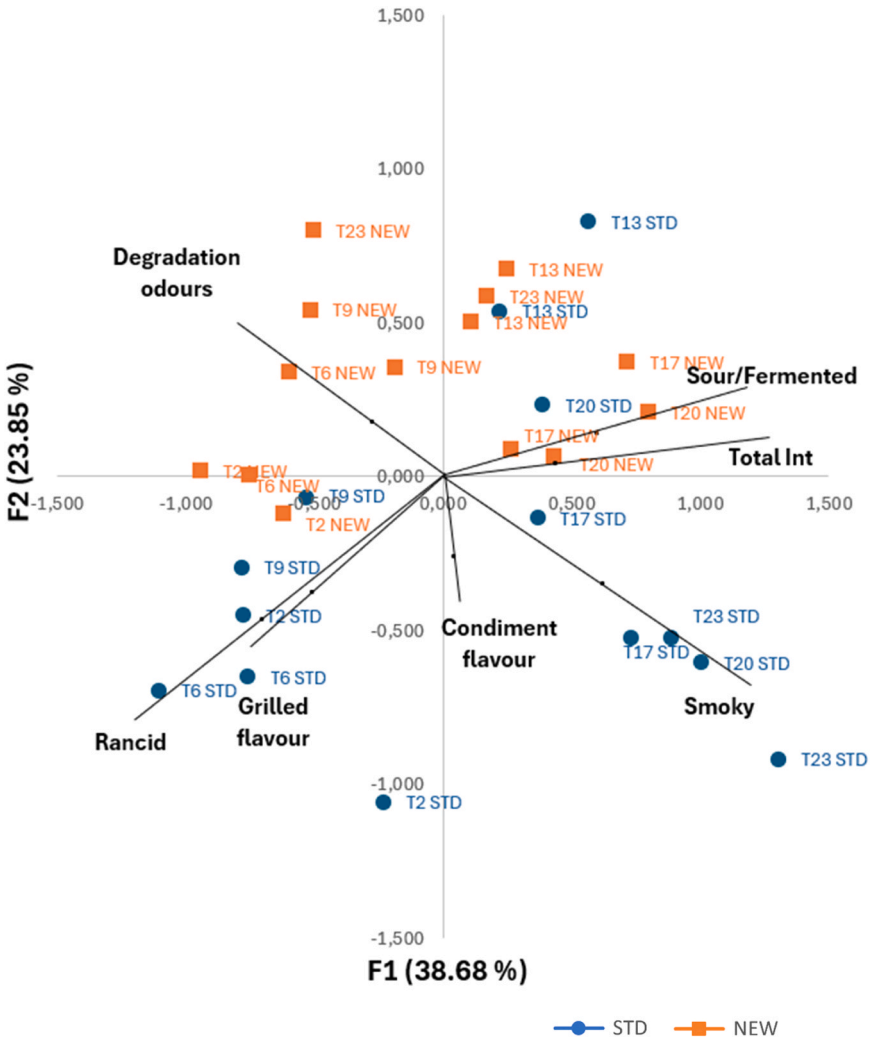


Fig. 5. GDA biplot of the sensory evaluation.

bar^{-1} for the NEW one, with a measured surface of 0.0238 m^2. When converting the specified values of the tray and of the lid with the respective surface area and with the average observed difference in oxygen partial pressure, the OTR of the system is estimated as ca. 0.02 cm^3 day^{-1}, that is 10 times less than the value actually measured.

The experimental values account for the gas transfer through the tray and the lid materials, as well as through the seal. It is recognized that the gas transmission rate of multilayer materials may change after thermoforming, due to the impact of this process on material thickness in walls, corners, and the bottom, as well as on crystallinity in the constituent layers, resulting in increased gas permeability (Buntinx et al., 2014). Furthermore, the sealing area also accounts for additional gas transfer (Reinas et al., 2016). Consequently, the declared barrier properties in material specifications, typically obtained with flat film and under normalised conditions of temperature and relative humidity, are poor predictors of in-package performance. Therefore, it is key for industry to determine barrier properties under experimental conditions representative of the storage conditions.

3.6.3. Gas/Product Ratio and Gas Composition

The average headspace volume per burger mass was calculated assuming that the volume of the burgers was constant as it is a moulded product. The average value was 1.48 ± 0.01 cm^3 g^{-1}. As expected, the range was narrow with values from 1.46 to 1.50, indicating a homogenous mass of product per package as could be anticipated for moulded paste products, such as the patty burger.

Regarding the package headspace gas composition, the initial values could not be measured because the packages were filled and sealed in the producer and then transported to the laboratory. Therefore, as for the other properties, the laboratory measurements were initiated at day 2 after packing, at the arrival. Overall, results showed differences in O_2 and CO_2 concentrations along the storage time, for the two packages (Fig. 6).

The concentrations of gases in the headspace are a result of two main mechanisms – the permeation through the package and the interaction with the product and its microbiota. The initial O_2 level is low (below 2%) and the levels decreased over time, as expected, in both the STD and NEW packages, and after day 17 no oxygen was measured. This is consistent with higher OTR determined for the NEW system. Carbon dioxide shows a trend to increase up to day 17 in both packages. After this time, the values level-off at ca. 23%. The CO_2 concentration in the NEW package is slightly higher than that of the STD, which is consistent with the higher microbiological activity as discussed in Section 3.3. and shown in Figure S1. After day 17 the differences in CO_2 concentration between packages are not statistically significant ($p > 0.05$).

3.7. Circularity factors of the lidding films

3.7.1. Recyclability

The top film STD, the laminated structure containing PET, had a mass distribution of the different layers calculated as approximately 21% PET, 74% PE, and 5% EVOH. The total mass per tray was 1.60 g.

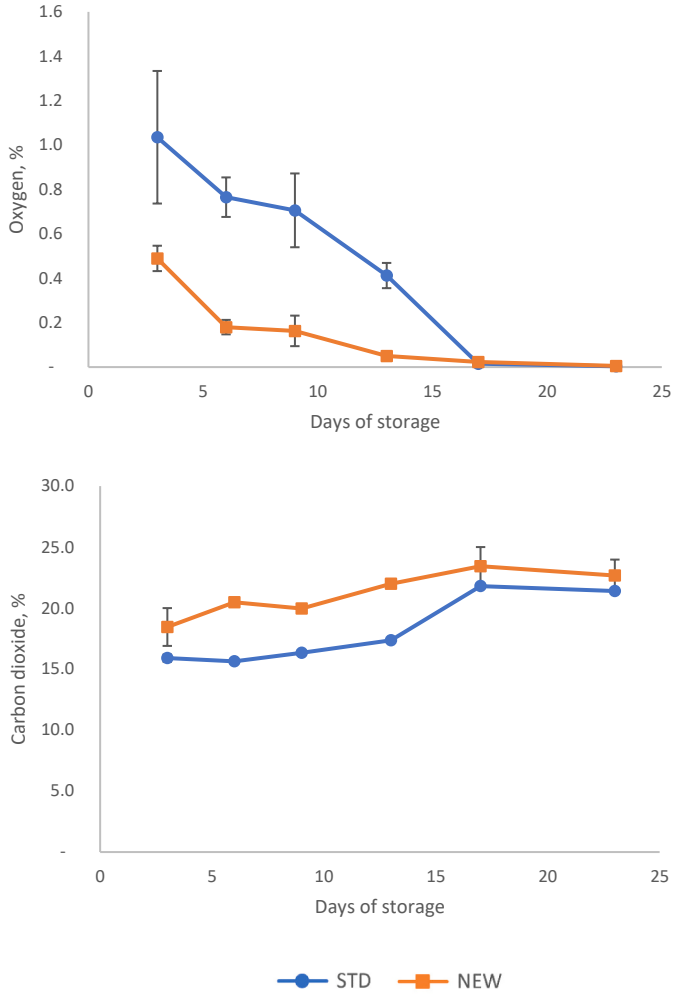


Fig. 6. Gas composition in headspace (average ± standard error) of the meat analogues stored in different packaging systems (STD and NEW).

The film NEW where the PET layer was replaced by a MDO PE layer had a mass distribution of approximately 42% MDO PE, 54% LDPE and 4% EVOH and a total weight of 1.41 g.

The recyclability assessment considered the compatibility of the film structures with the PE and PET recycling streams, the potential impact of barrier layer (EVOH) and the presence of adhesive. The NEW film aligns with the requirements for the PE recycling stream owing to its high PE content and barrier layer proportion below the 5% threshold permitted by RecyClass. This film was attributed a recyclability class A, with a recyclable plastic content of 96.2%. This high score reflects the predominance of the polyethylene component.

The PET-based film was also evaluated for compatibility with the PET recycling stream. According to RecyClass specifications, multilayer PET structures incorporating significant fractions of PE, barrier polymers such as EVOH and adhesives are classified as incompatible with PET recycling. These components hinder the production of high-quality recycled PET (rPET) by introducing contaminants that cannot be effectively removed during the mechanical recycling. In contrast, the STD film was classified as non-recyclable (0% recyclability) in both PE and PET streams. Despite containing 74% PE by mass, the presence of PET layers, EVOH, and adhesives within the structure introduces incompatibilities that hinder separation and contaminate the recovered streams.

It is important to emphasise that this assessment represents the theoretical recyclability potential based on material composition, while the effective recyclability depends on the availability and implementation of dedicated recycling streams within each country. The evolving European regulatory landscape, notably the PPWR, and the validation of new recycling processes by the European Food Safety Authority (EFSA) are expected to accelerate the development of advanced recycling technologies for complex packaging structures. These findings underscore the critical importance of material design, regulatory alignment, and technological innovation in achieving effective and scalable recycling solutions.

3.7.2. *Impact on global warming*

To facilitate the comparison between the two materials of the trays' lids, the various inputs and outputs were grouped into 11 classes, representing the main function in the material structure and according to the nature of the input or output:

- Polyethylene granules for the LDPE EVOH LDPE structure (support of barrier layer and sealing)
- Polyethylene granules for the MDO PE structure (external layer)
- PET film (external layer)
- EVOH granule present in both structures (barrier layer)
- Adhesives and additives present in both film structures (layers bonding)
- Conditioning materials (reels tubes, labels, wrapping paperboard, pallets and stretch film)
- Electricity for the processes
- Transport of the different materials, substances and products to the converter, then to the burger producer, following to the point of sale and to EoL
- Plastics and paper landfilling
- Plastics and paper incineration
- Pallets for incineration

The inventory data and transport profile are presented in Supplementary Information (Table S6 and S7). Fig. 7 represents the impact on global warming (kg CO_2 eq.).

The results show relevant differences between the two material structures, both in terms of the materials employed and the associated processes. Conditioning materials had similar impacts for both structures, as expected, with relatively low values (<100 kg CO_2 eq.). Electricity consumption contributed slightly more to the MDO PE structure (≈200 kg CO_2 eq.), whereas the PET structure exhibited a lower impact, approximately 31% less. This difference may be partially explained by the electricity mix used, since the Portuguese mix was applied for MDO PE, while the PET film was assessed using the country-of-origin mix. Transportation represented a major contributor to the total impact of both lidding materials, with the PET-based structure showing a considerably higher value (≈1 200 kg CO_2 eq.) due to transport from India, compared to ≈ 835 kg CO_2 eq. for the MDO PE structure.

Regarding the EVOH grain, the impact values are low and close between the structures, at less than 105 kg CO_2 eq, although a slightly higher value for the PET-based film. In the case of PE granules for the coextruded structure, the impact values are around 1 000 kg CO_2 eq. The value is higher for the PET structure (around 1 100 kg CO_2 eq.) while the impact value for the MDO PE is ca 855 kg CO_2 eq. This difference is attributed to the thickness of the coextruded layer in the PET structure, which is slightly higher than that in the MDO PE structure, in order to maintain equivalent overall lid thickness for machinability purposes. The impact values for adhesives and the additives were similar for both structures, at approximately 300 kg CO_2 eq.

The highlight is the category of plastics incineration, where the PET structure has an extremely high value of over 2 200 kg CO_2 eq., while the structure with MDO PE has a much lower contribution (1 400 kg CO_2 eq.) because this material is considered to be 35% recycled according to the observed rates for monomaterials in the region (Mota et al., 2025). This factor becomes decisive in the overall comparison between the two structures. The categories of plastics landfilling, and pallets incineration

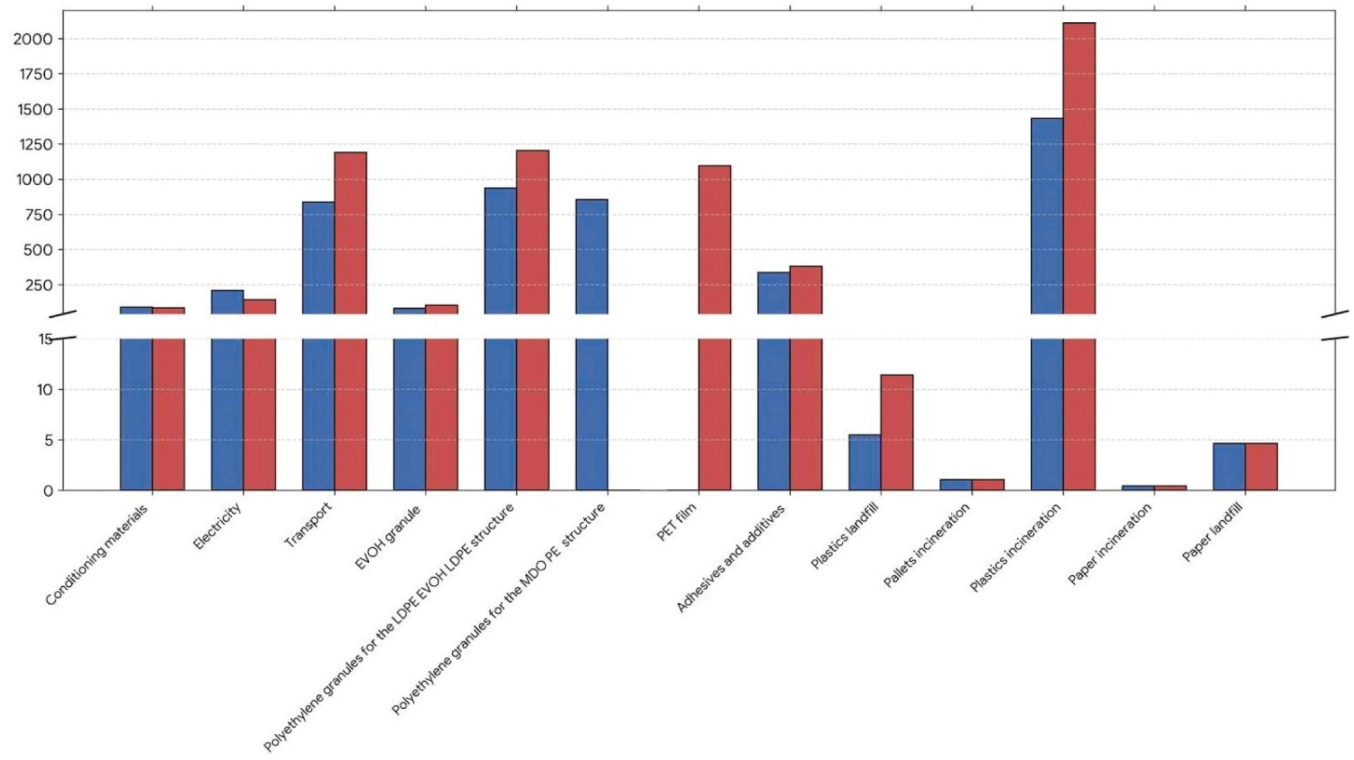


Fig. 7. Global warming impact of different inputs for each packaging (Blue: MDO PE - NEW; Red: PET - STD).

have negligible impacts on both solutions, under the present assumptions.

Thus, it can be concluded that the MDO PE film structure has an overall more favourable environmental performance in the global warming category, totalling 4 800 kg CO_2 eq. per tonne of film, profiting from the absence of PET in its composition and the consequent significant reduction in impacts associated with the EoL, while the total impact value for the PET structure was 6 400 kg CO_2 eq. per tonne of film. The MDO PE structure is therefore the most sustainable option from the point of view of global warming potential, under the specific conditions of use.

4. Conclusions

The objective of this work was to evaluate the impact of replacing the conventional PET-based lidding film with an MDO-PE-based structure in plant-based burgers, focusing on shelf life and stability, while enhancing recyclability and reducing the environmental footprint of the packaging system. While monomaterial packaging systems offer clear advantages in terms of recyclability and reduced environmental impact, the effect of these systems on the quality of PBMA during extended storage is not well known. The data generated are valuable for guiding food manufacturers in the selection of packaging systems. The results obtained in this study contribute to aligning both environmental objectives and PBMA shelf life expectations in packaging decisions.

Results show a delay in the microbial growth at earlier storage times for the burger in the multilayer packaging (STD), but levels converged towards the end of shelf life. Furthermore, monolayer packaging did not affect microbiota. Peroxide values and TVB-N indicated a slightly higher susceptibility to degradation in the monolayer (NEW) packaging. So, multilayer packaging protected better the product as perceived by degradation odours. However, the VOCs did not show significant differences in the PCA. Overall, although there are some differences noted in the burger behaviour when packaged in the NEW packaging compared to the STD, results support that the change into the monolayer lid can be performed, favouring circularity without relevant prejudice of the burger preservation. Despite a higher relative susceptibility to chemical and microbial changes, the NEW system remains a promising alternative for plant-based meat analogues. The equivalent barrier properties, despite the different composition of the lidding material, contributes to similar behaviour of the product during storage. The NEW package presents potential advantages in terms of recyclability and reduced global warming potential in 25%, thereby supporting strategies for circularity and resource efficiency, consistent with RecyClass and PPWR priorities for monomaterial PE recycling streams. The contribution of long-distance transport of raw materials to the global warming potential particularly of the PET based lidding film should also be highlighted. Regional sourcing of raw materials could substantially improve the environmental performance. In addition to enhanced recyclability, shorter supply chains for packaging solutions are key to increasing the robustness of circular packaging systems.

This study was conducted with a single formulation and product type (plant-based burgers), which may limit the generalization of the results to other PBMA. Storage conditions were restricted to a constant temperature of 4 °C; other conditions, such as abuse temperatures, were not considered.

Another limitation of this study is that for assessing the environmental impact, only the global warming potential was considered. The inclusion of other indicators is necessary for an overall evaluation. Furthermore, the recyclability of each packaging structure studied was defined based on the potential for being recycled according to the criteria of Recyclass and applying current recycling rates for monomaterials. It would be valuable to use real, specific recycling rates data for these materials. However, it is well known that obtaining such data is difficult in, particularly in the case of the NEW material which has only recently become available on the market and therefore, there is not yet robust data collected.

By linking shelf life performance with packaging recyclability and climate change impact assessments, this work contributes to advancing strategies for waste reduction and sustainable packaging solutions.

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CRediT authorship contribution statement

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fpsl.2026.101782.

Data availability

Data will be made available on request.

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