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A novel combined high-pressure CO_2 technology preserves quality and enhances health-promoting properties of fresh-cut organic cantaloupe melon

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ABSTRACT

The impact of an innovative preservation technology, combining high-pressure processing with CO_2 modified atmosphere packaging (HPMAPCO_2), on the quality, bioactive profile, and nutritional bioaccessibility of fresh-cut organic cantaloupe melon during 21 days of refrigerated storage is shown. Compared to conventional air packaging (MAPair) and modified atmosphere alone (MAPCO_2), the treatment demonstrated a superior capacity to preserve the raw material's freshness and physicochemical stability (ΔE values ~47% lower in HPMAPCO_2 sample after 21 days). Although high pressure initially induced minor changes in color and Brix due to tissue structural modifications, it effectively limited enzymatic browning by significantly reducing polyphenol oxidase (PPO) activity (~23% PPO activity reduction due to the HPMAPCO_2 treatment). Nutritional analyses revealed that it better preserved antioxidant capacity (ORAC values ~28% and ~10% higher in HPMAPCO_2 sample respect to MAPair and MAPCO_2, respectively, after 21 days) and key bioactive compounds, including β-carotene (~40% higher in HPMAPCO_2 sample after 21 days). Notably, the treatment enhanced the bioaccessibility of polyphenols (~13% higher in HPMAPCO_2 sample after 21 days) and DPPH antioxidants (~29% higher in HPMAPCO_2 sample after 21 days) during simulated gastrointestinal digestion, likely due to the pressure-induced disruption of cell walls and chromoplast membranes. Furthermore, it proved most effective in maintaining soluble sugar levels (sucrose, glucose, and fructose) and preserving essential minerals (K, Ca, P, Na, Mg). Sensory evaluation confirmed that this synergistic approach maintains superior aroma, texture, and overall acceptability, positioning as a promising technology for extending the shelf-life and enhancing the health-promoting properties of ready-to-eat fruit products.

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1. Introduction

Melons (*Cucumis melo* L.) are among the most widely produced fruits globally, and according to the Observatory of Economic Complexity (OEC), their global trade growth was estimated at an annual rate of 1.91% over the past five years (OEC, 2025). Due to the fruit's relevant sensory properties and its high nutritional and antioxidant characteristics, consumers have demonstrated increasing interest towards melons, worldwide promoting its demand and indirectly pushing its availability on the market (Pulela et al., 2022). Since melons are consumed fresh, they constitute a valuable source of polyphenols, carotenoids, vitamins, micro and macro elements that can produce beneficial dietary effects for consumers.

In addition, consumers are increasingly targeted on introducing organic fruit and vegetable products into their diet, as they recognize positive direct effects of the organic management on human health (Jiang et al., 2024). It must also be taken into consideration that consumers eating behaviors are changing as there's an increasing interest towards ready-to eat fruit and veggie products which guarantee significant savings in peeling and slicing times allowing fresh fruit to be consumed directly after purchasing (Baselice et al., 2017). Indeed, for more than a decade, several research have been focused on the application of different technologies for the improvement of ready-to-eat melon processing as damages provoked by fresh-cut processing fasten its quality degradation and produce safety risks (Jideani et al., 2017). Moreover, different metabolic changes during postharvest storage accelerate metabolic rates, affecting microbial safety and the overall quality of fresh-cut products (More et al., 2020).

The application of edible coatings has been extensively studied as a valid tool for extending the shelf-life of fresh-cut melons during cold-storage. For example, Mannozzi et al. (2021) performed a study on the effects on the microstructural and nutritional properties of fresh-cut melon after the application, by spraying and dipping, of enriched edible coatings, finding that the dipping application method best maintained the rheological and nutritional quality of the product. More recently, an innovative layer-by-layer edible coating, based on sodium alginate, cedar mucilage, and calcium chloride, was successfully proposed to preserve physicochemical and qualitative traits of fresh-cut melon (Cice et al., 2024) while *lactobacillus* strains were proposed as probiotics to be incorporated into xanthan-based edible coatings to improve the safety of fresh-cut melons (Chikhala et al., 2024). Moreover, in order to support the adoption of organic agricultural practices for their beneficial effects on human health, different fertilizers were used to grow melon fruits prior to the application of edible coatings, showing high potential of these treatments to improve the phenolic content and retain it throughout the cold storage, respectively (Islek, 2025). As a non-thermal technology, atmospheric cold plasma was recently proposed to extend the shelf-life of fresh-cut melon for its ability to inactivate pathogenic microorganisms, demonstrating that a dielectric barrier discharge generated gas plasma can extend the shelf-life by 4 days at 10 °C with minor changes in quality parameters (Figueroa-Pinochet et al., 2022). Even if these techniques can help reduce food waste and improve processing sustainability, further efforts are still needed to optimize formulations and operational parameters to expand their application at an industrial and commercial level.

The use of modified atmosphere packaging (MAP) was previously proposed to control quality decay in fresh-cut honeydew melon, showing that MAP with high O_2 and CO_2 (50% O_2 + 50% CO_2) inhibited the microbial spoilage in melon cubes better than regular air (Zhang et al., 2013). More recently, Shinde et al. (2024) reported the best performance for MA passive micro-perforated packages, but limiting factors such as associated hypoxic fermentation processes with ethyl acetate accumulation were recorded.

Besides this, considering the beforementioned increasing interest of consumers towards organic fruit, the specific challenges of the post-harvest handling of organic melon must be taken into account. Indeed, one of the main positive features of organically grown fruit correlated to the preservation and promotion of human health is that the use of synthetic pesticides is not allowed, both at field and post-harvest level. This may be the cause of higher storage losses due to an increased microbiological risk linked to the presence of pathogenic or alterative microflora in the fruit that are intended to be minimally processed and further cold-stored. As a matter of the fact, when the production of fresh-cut organic products is envisioned, it is strictly recommended to apply good organic husbandry techniques (Yao et al., 2026) and post-harvest handling practices (Brandao et al., 2026). However, the careful application of good practices may not be sufficient to avoid further losses during the storage.

Based on what has been reported so far, there's an urgent need to optimize and validate new technological approaches in the processing of ready-to-eat organic melon in order to improve freshness, quality, and safety while preserving its high nutritional and antioxidant value. Other attempts to control microbial spoilage and enzymatic decay of fresh-cut products were suitably performed by the use of a non-thermal technology such as high-pressure carbon dioxide (HPCD), reporting promising results for the extension of the shelf-life of fresh-cut carrots (Spilimbergo et al., 2013), fresh-cut lettuce (Ma et al., 2022), and fresh-cut Chinese water chestnut (Kong et al., 2021). Anyway, post-process contamination risks associated with the packaging and sealing phases of the processed samples have so far avoided the factual industrial application of HPCD to solid foods.

An innovative, industry-oriented, combined technological approach has been recently set up and validated for the stabilization of pre-packed food products through the joint application of high-pressure and modified atmosphere packaging, HPMAPCO_2. The novel process exploits the inactivation mechanisms of dense-phase CO_2: CO_2 penetrates biological tissues, acidifies the intracellular environment, and interferes with essential metabolic functions, including membrane transport and enzymatic activity (Garcia-Gonzalez et al., 2009). Even if dense-phase CO_2 effectiveness has been extensively studied, the HPMAPCO_2 process allows to use its power directly on pre-packed products, eliminating the risks associated with post-process. After being patented (Spilimbergo et al., 2017), the HPMAPCO_2 process has been recently tested and validated for its efficacy in enhancing microbial safety on a synthetic matrix (Zulli et al., 2024) and on fruit and veggie solid matrices such as carrots (Barberi et al., 2021) and potatoes (Zulli et al., 2023). Very recently, the HPMAPCO_2 process has been applied to organic fresh-cut butternut squash with positive results showing that the process can effectively achieve both microbial and enzymatic stabilization, extending the refrigerated shelf-life, while maintaining the physicochemical, nutritional, nutraceutical, antioxidant, and sensory quality of the fresh product (Zulli et al., 2025).

Based on the above, we hypothesized that HPMAPCO_2 would outperform conventional air packaging (MAPair) and CO_2-modified atmosphere alone (MAPCO_2) in preserving physicochemical stability, nutritional quality, bioactive compound bioaccessibility, and sensory attributes of fresh-cut organic cantaloupe melon throughout refrigerated storage. Thus, in the present research the HPMAPCO_2 process was tested as a potential technological approach to be validated on fresh-cut cantaloupe melons, with the final aim of proposing an industry-oriented process able to preserve the high nutritional, nutraceutical and antioxidant value of this product while assuring an effective improvement of its refrigerated shelf-life. The overall physicochemical and sensory quality, antioxidant capacity, and enzyme activity, together with the sugars, carotenoids, vitamin C, phenolics, micro- and macro-elements contents were determined in HPMAPCO_2 treated samples and compared, as a control, with the same products packed in air or in CO_2 during a 21-days refrigerated storage period.

2. Materials and methods

2.1. Sample preparation and refrigerated storage

"Organic farm Milana Giovanni" company (Ispica, Italy) provided organic cantaloupe melons for the trials. Melons were peeled and cut under a laminar flow hood, taking care to maintain sterility during the processing into cubes (1.5 cm side length; 4 g approximate weight). Melon cubes were then packaged in a regular air or 100% CO_2 (carbon dioxide 4.0, purity >99.8%, Nippon Gases Italia, Milano, Italy) atmosphere using a 100%-recyclable multi-material (coextruded PE/EVOH/PE, Niederwieser, Modena, Italy) high barrier film. The gas to sample ratio was fixed by inserting around 32 g (8 cubes) in a 100 mL package. Samples packaged in a regular air were indicated as MAPair while those packaged in a 100% CO_2 atmosphere were indicated as $MAPCO_2$. Part of the $MAPCO_2$ samples were treated with the patented method (see §2.2) and subsequently indicated as $HPMAPCO_2$. All the samples were further stored at 4 °C for 21 days. Samples were prepared, packaged and treated to ensure a number of at least three biological replicates for each treatment and each time point of the refrigerated storage.

2.2. High-pressure treatment ($HPMAPCO_2$)

$HPMAPCO_2$ treatment was carried out with a water-driven high-pressure equipment as described in our previous studies (Zulli et al., 2023, 2024) consisting of a stainless-steel vessel (high-pressure chamber) with a volume of 4 dm^3, a storage tank with an immersion thermostat (M900-TI, MPM Instruments, Italy), and an air-driven hydraulic pump (G35LVE, Maximator, Italy). The system's maximum operating temperature and pressure are set at 50 °C and 20 MPa, respectively.

Preliminarily to each trial, the high-pressure chamber and the water included within the storage tank were preheated to the desired temperature. Once the pre-packaged products were placed inside the chamber, the chamber was filled with the pre-packaged melon samples and pressurized until reaching the desired pressure. At the operative temperature and pressure conditions, the CO_2 atmosphere inside the packages reached a dense state, exerting its antimicrobial activity. Continuous monitoring of temperature and pressure was maintained throughout the treatment to ensure constant operating conditions. Once each trial was concluded, after the depressurization of the chamber, the products were pulled out and stored at 4 °C prior to further analysis.

Building on findings from previous research (Zulli et al., 2024, 2025), the treatments were conducted at 40 °C and 6.0 MPa. The temperature of 40 °C was chosen as it is above the critical temperature of CO_2 (31.1 °C), ensuring its dense state, while remaining sufficiently low to minimize thermal stress on the heat-sensitive melon tissue. The pressure of 6.0 MPa was selected as a compromise between maximizing CO_2 density and antimicrobial efficacy, while limiting mechanical damage to the delicate cell structure of melon, which has higher water content and softer texture compared to previously tested matrices such as carrots and potatoes. The processing time was fixed at 60 min, a duration deemed necessary to counteract the intrinsically high pH of the cantaloupe melon matrix (pH ~6.0–6.5), which represents a challenging condition for CO_2-based inactivation. Indeed, the antimicrobial efficacy of dense-phase CO_2 is known to decrease at higher pH values, as the acidification mechanism of CO_2 is partially buffered by the food matrix (Spilimbergo et al., 2013; Zambon et al., 2022). A longer exposure time was therefore necessary to ensure sufficient CO_2 penetration and inactivation efficacy, compensating for the reduced driving force of acidification at near-neutral pH. Three independent processing trials were conducted.

2.3. Determination of physicochemical attributes

Physicochemical parameters, including color, pH, and °Brix, were measured for all samples throughout the storage period. Melon cubes were crushed in a blender (BRAUN, Germany) for 5 min and transferred to 3-mL glass cuvettes (1-cm optical path). The sample color parameters (lightness L*, redness a*, and yellowness b*) were then measured by using a Color Quest XE colorimeter (HunterLab, USA). The total color difference between two samples (ΔE) was calculated according to Equation (1):

$$\Delta E = \sqrt{\left(L_1^* - L_2^*\right)^2 + \left(a_1^* - a_2^*\right)^2 + \left(b_1^* - b_2^*\right)^2}. \quad (1)$$

where L*, a* and b* represent lightness, redness, and yellowness, respectively, while 2 and 1 represent the fresh sample and the analyzed ones, respectively.

The °Brix degrees of the solution obtained by squeezing the ground samples were measured using a refractometer (HHTEC, Germany). pH values were determined for ground sample solutions mixed with distilled water (1:1, w/v) and measured using a digital pH meter (pH 1100 L, VWR, USA).

2.4. Determination of polyphenol oxidase (PPO) and peroxidase (POD) enzymatic activities

The spectrophotometric assay described by Szczepańska et al. (Szczepańska et al., 2022) was used to determine the PPO and POD activities, with some modifications. Four grams of polyvinylpolypyrrolidone (PVP), 0.1 mL of Triton X-100, 58 g of sodium chloride, and 100 mL, pH = 6.5 of sodium phosphate buffer were mixed to obtain the extraction solution. Grated samples (5 g) were homogenized with 10 mL of the extraction solution at 16,000 rpm for 3 min and then centrifuged at 11,000 rpm and 4 °C for 30 min. 0.1 mL of the collected supernatants was added to 3 mL of 0.07 M catechol solution (pH = 6.5) and left to react for 10 min at room temperature. The PPO content was measured at 420 nm using a UV–Visible spectrophotometer (Model 6705, Jenway, UK). 0.05 mL of supernatant was mixed with 0.05 mL of 1% p-phenylenediamine, 0.05 mL of 1.5% hydrogen peroxide, and 3 mL of 0.05 M phosphate buffer (pH 6.5), and the mixture was incubated at room temperature for 10 min. The absorbance was recorded at 485 nm. Enzymatic activity was expressed as enzyme units per mg (U/mg).

2.5. Determination of antioxidant activity

The extraction of the bioactive compounds in melon samples was carried out through homogenization and ultrasound (Chen et al., 2024a). Briefly, grated melon samples (5 g) were added to a 50 mL centrifuge tube containing 10 mL of a 80% methanol solution and homogenized in a 4 °C water bath at 16,000 rpm for 10 min. Then, the mixture was ultrasonicated at 45 kHz, 200 W, and 25 °C for 20 min, followed by centrifugation at 11,000 rpm and 4 °C for 5 min. After filtration through a 0.25 μm polytetrafluorethylene membrane the supernatants were used for further analysis.

ABTS·+ and DPPH· radical scavenging activities were measured at 734 nm and 517 nm, respectively, according to a previously described methodology (Chen et al., 2024b),and the results were expressed as μmol/L Trolox equivalents (TE) per 100 g of sample.

The salicylic acid method (Zhu et al., 2022) was used to determine hydroxyl radical (·OH) scavenging. One mL of 9 mM salicylic acid solution (dissolved in 70% ethanol) was mixed with 200 μL of supernatant. Subsequently, 1 mL of a 9 mM H_2O_2 solution was added to the mixture, which was then incubated at 37 °C for 30 min. The absorbance was measured at $\lambda = 510$ nm.

A previously proposed methodology (Chun et al., 2003) was used to determine superoxide ($O2\cdot^-$) scavenging activity. 2 mL of a 0.45 mM NADH, 0.15 mM NBT, and 28 mM PBS (1:1:4 v/v/v ratio) reaction solution was mixed with 0.25 mL of supernatant. Then, 0.25 mL of 0.12 mM PMSc, were added to start the reaction and left in incubation for 5 min. The absorbance was measured at $\lambda = 560$ nm.

Nitric oxide (NO) scavenging was assayed according to the methodology of Sueishi et al. (Sueishi et al., 2011). A mixture containing 250 μL of supernatant, 500 μL of 10 mM SN, and 250 μL of PBS (pH 7.4) was incubated at 37 °C for 2.5 h. Subsequently, 1 mL of Griess Reagent was added to the mixture, which was incubated for 30 min before absorbance was measured at 546 nm.

For oxygen radical absorbance capacity (ORAC) and Folin-Ciocalteu reagent (FCR) assays, 5 g of melon samples were extracted by mixing with 50 mL of an 80% ethanol solution containing 1% citric acid in flasks fitted with caps, left in stirring at 120 rpm for 24 h at 25 °C. After filtration of the hydroalcoholic extract, the residual melon was mixed again with another 50 mL aliquot of the same solvent under the same conditions. Finally, the combined extracts were subjected to vacuum distillation using a rotary evaporator. The resulting concentrated extracts were used for further determinations. Briefly, the ORAC assay was carried out with some adaptations from Cao et al. (Cao et al., 1993) and Ou et al. (Ou et al., 2001). Measurements were performed using a Wallac 1420 Victor III 96-well plate reader (EG & Wallac, Turku, Finland) equipped with fluorescence filters (excitation 485 nm, emission 535 nm). Fluorescein (116 nM) was employed as the target molecule for free radical attack from AAPH (153 mM), which served as the peroxyl radical generator. Trolox (1 μM) and 75 mM phosphate buffer (pH 7.0) were used as the control standard and the blank, respectively. The reaction conditions were 37 °C and pH 7.0. Melon extracts were appropriately diluted with phosphate buffer (1:25–100, v/v) prior to analysis, and results were reported as μmol TE per g of sample (FW). The FCR colorimetric method (Singleton et al., 1999), typically used to determine total phenols, was performed to assess antioxidant activity. 1 mL of appropriately diluted sample extracts were mixed with 5 mL of FCR (previously diluted with water 1:10 v/v) and 4 mL of a 7.5% sodium carbonate solution. The mixture was stirred and left to react for 2 h at room temperature in the dark. The absorbance of the resulting blue solution was measured at $\lambda = 765$ nm, and the results were expressed as mg of gallic acid equivalents per 100 g of sample (FW).

2.6. HPLC characterization of phenolic compounds

The concentrated melon extracts used for the HPLC characterization of phenolic compounds were the same obtained for the ORAC and FCR assays (see §2.5). The phenolic compounds profile was determined by high-pressure liquid chromatography using a Waters Alliance 2695 HPLC (Waters Corporation, Milford, MA) equipped with a Waters 996 photodiode array detector and Empower software. The separation was achieved on a Luna (Phenomenex, Torrance, CA, USA) C18 analytical column (250 mm × 4.6 mm, 5 μm). The binary solvent delivery system was designed as follows: mobile phase A: water/formic acid (99.8:0.2, v/v); mobile phase B: acetonitrile/water/formic acid (50:49.8:0.2, v/v/v). The gradient profile was as follows: 10–35% B (0–30 min), 35–40% B (30–35 min), 40–55% B (35–40 min), 55–75% B (40–50 min), 75–95% B (50–55 min), 95–100% B (55–57 min), 100–10% B (57–60 min). Flow rate was set at 1 mL/min, and all analyses were performed with the column temperature maintained at 35 ∘C, and the injection volume of each sample was 20 μL. The data were analyzed at 320 nm and 280 nm. All analyses were repeated three times. Quantification of the phenolic compounds was performed using external standard calibration curves and expressed as mg per 100 g (FW) of sample.

2.7. HPLC characterization of carotenoids

The determination of carotenoids was carried out with some adaptations from a previously described method (Pulela et al., 2022). 15 mL of a hexane/methanol/acetone (2:1:1, v/v/v) solution was used to extract carotenoids from melon samples (5 g), which were then incubated at room temperature for 30 min under mild shaking. After centrifugation (5 min at 9000 rpm at 5 °C), the supernatant was collected, and this step was repeated twice more. All collected organic portions were evaporated by vacuum distillation using a rotary evaporator at a temperature below 30 °C. The dried extracts were further dissolved in 4 mL of acetonitrile and filtered (nylon, 0.22 μm) before HPLC analysis. Chromatographic analyses were carried out with a Waters Alliance liquid chromatography system equipped with a quaternary pump, a photodiode array detector, an autosampler, and Empower Manager. Carotenoids were identified by comparing the retention times, UV-vis absorption spectra, and chromatography with authentic standards at $\lambda = 450$ nm. Results were expressed as mg of compounds per kg (FW) of sample.

2.8. HPLC characterization of ascorbic acid

50 mL of a 3% metaphosphoric acid solution was used to extract ascorbic acid from melon samples (5 g). Samples were left to react for 4 h at 25 °C g while stirring at 120 rpm. After the extraction, the supernatants were directly filtered (0.45-μm PTFE membrane filter) and injected into the HPLC (20 μL). The chromatographic system was a Waters Alliance 2695 HPLC (Waters Corporation, Milford, MA) equipped with a Waters 996 photodiode array detector and Empower software. Flow rate was set at 1 mL/min, and the mobile phase was a 0.02 M H_3PO_4 solution. The detector was set at $\lambda = 260$ nm, and the results were expressed as mg of ascorbic acid per kg (FW) of sample.

2.9. Micro- and macro-nutrient contents

Inductively Coupled Plasma Spectrometry (ICP-OES Optima 2000DV, PerkinElmer, Italy) was used to determine micro- and macro-elements levels in melon samples. Briefly, 5 g of melon samples were subjected to dry digestion in a muffle furnace (550 °C for 24 h). Samples were then dissolved in a solution containing 4 mL of distilled water and 0.5 mL of concentrated nitric acid. The resulting solution was stirred and transferred into flasks and made up to 50 mL with distilled water prior to measurements, and the results were expressed as mg per 100 g of sample (FW).

2.10. Bioaccessibility study

The INFOGEST method, as described by Brodkorb et al. (Brodkorb et al., 2019) was used for the in-vitro determination of bioaccessibility on freeze dried melon samples. Before digestion and after digestion steps, total phenolic compounds, DPPH antioxidant activity, and total carotenoids contents were determined. As previously described by Borges et al. (Borges et al., 2019), accessible fraction was separated by centrifuging (10,000 rpm, 30 min, 4 °C) the residual fraction of the intestinal phase. The bioaccessibility ratio was reported as the % of the class of components in the accessible fraction with respect to the amount previously recorded before digestion (Reboredo-Rodríguez et al., 2021).

Total phenolic compounds, expressed as mg GAE/100 g DW, were determined using the FCR according to Thaipong et al. (2006). The DPPH method, as developed by Brand-Williams et al. (Brand-Williams et al., 1995), was used to determine the antioxidant activity, expressed as mg TE/100 g DW. Total carotenoids, expressed as mg/100 g DW, were determined according to Yilmaz (Yılmaz, 2010).

2.11. HPLC characterization of sugars

The sugar contents were evaluated for all sample groups throughout the whole storage, except for MAPair, which was spoiled after day 9. They were measured according to the approach of Marszalek et al. (Marszałek et al., 2019) with some modifications. Specifically, 5 g of grated melon was added to a 50 mL centrifuge tube containing 10 mL of ultrapure water. The mixture was homogenized in a 4 °C water bath at 16,000 rpm for 10 min, followed by ultrasonication at 45 kHz, 200 W, and 25 °C for 5 min. Subsequently, the mixture was centrifuged at 11, 000 rpm and 4 °C for 5 min. The supernatant was analyzed using an

HPLC system (Waters 2996, USA). The supernatant was eluted with 0.1 mM calcium disodium EDTA using a Sugar-Pak I and Guard-Pak column at 90 °C and 0.5 mL/min, and detected by a refractive index detector. Results were expressed as g of sugar per L of supernatant.

2.12. Sensory analysis

Quantitative descriptive analysis (Gaowa et al., 2023; Guan et al., 2024; Saha et al., 2023) was used to assess the sensory attributes of melon samples. Four criteria were included in the evaluation form: color, appearance, smell, and texture. The evaluation criterion was based on comparing the samples to a reference material consisting of fresh melon cubes of identical dimensions. For each attribute, the score was set on a scale from 0 to 10, where 0 indicated no intensity, and 10 indicated high intensity. The evaluation was performed in an equipped sensory analysis laboratory that complied with all the requirements imposed by ISO 8589:2010/A1:2014. 16 trained judges, qualified for expert assessment in accordance with ISO 8586:2023, performed the sensory evaluation in independent triplicates. Samples were prepared in equal quantities and at a consistent temperature and placed on a plate covered with a lid before the sensory evaluation. To minimize potential bias, all samples were assigned random code and presented to the panellists in a randomized order. The taste criterion was not considered for safety reasons concerning the expert panel, as microbiological analysis of the samples was not included in the scope of the study at this stage.

2.13. Statistical analysis

All measures were performed in triplicate, and the results were expressed as mean values ± standard deviation. The software GraphPad Prism version 10.2.3. was used to perform a two-way ANOVA test followed by Šídák's multiple comparison test for the separation of mean values.

3. Results

3.1. Physicochemical attributes

Modified atmosphere conditions and high-pressure processes can significantly influence the physicochemical properties of food products during storage, which are critical indicators of product quality and consumer acceptance. Fig. 1 illustrates the evolution of pH, total color difference (ΔE), and °Brix degrees in fresh-cut melon samples for each of the three theses.

The pH values of fresh-cut melon samples remained relatively stable during the 21-day refrigerated storage period for all the three analyzed treatments, with values ranging between 5.9 and 6.5. However, CO_2 packaging caused a slight decrease in pH, particularly in $HPMAPCO_2$ samples. This difference was consistent throughout the storage period, although it was not statistically significant at certain time points.

Color changes were assessed by calculating the total color difference (ΔE) between the samples at different storage times and the fresh sample (day 0). $HPMAPCO_2$-treated samples exhibited minimal color changes, with ΔE reaching a maximum of 2.32 by day 21. Conversely, non-treated samples (MAPair and $MAPCO_2$) showed greater color differences throughout storage, with ΔE values exceeding 4 by the end of the shelf life. No significant differences were observed between MAPair and $MAPCO_2$ samples. Since color is a key parameter for consumer acceptance, a sensory analysis was conducted to further investigate consumer perceptions of the differences observed among the three conditions (see §3.8).

The °Brix degrees of fresh-cut melon samples are shown in Fig. 1C. High-pressure treatment initially caused a slight reduction in °Brix values. Following this reduction, °Brix values across all samples remained relatively stable over the 21-day refrigerated storage period, with minor fluctuations. No clear trend was observed among the three sample types. While °Brix is commonly used to estimate dissolved sugars and total solids, further analysis of individual sugars (glucose, fructose, and sucrose) was performed to gain deeper insights into their behavior in untreated and treated melon samples (see §3.7).

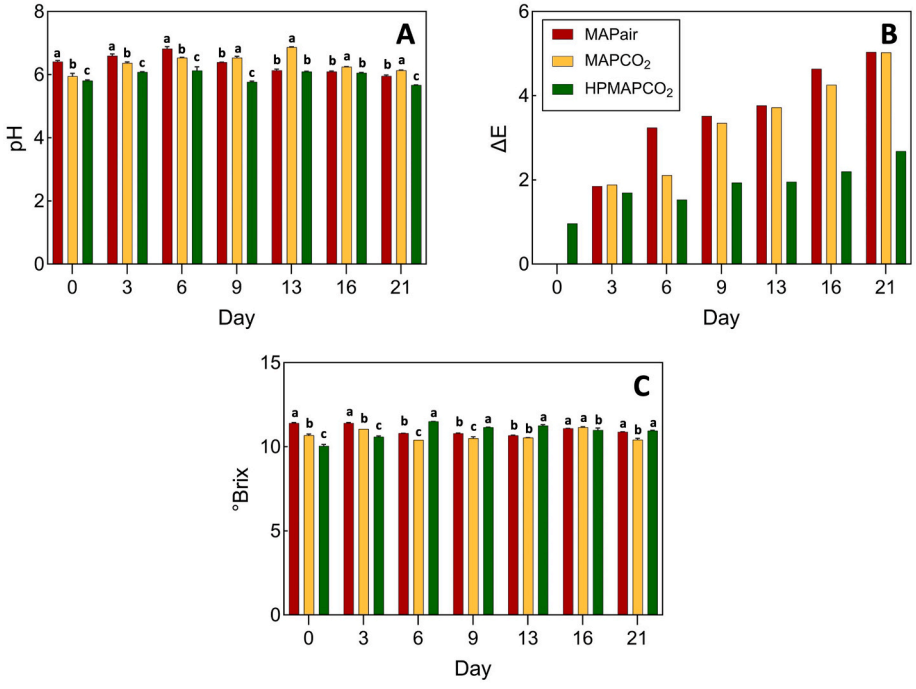

Fig. 1. pH (A), total color difference (B), and °Brix (C) during 21 days of refrigerated storage for fresh-cut melon samples MAPair (red), $MAPCO_2$ (yellow) and $HPMAPCO_2$ (green). Different letters indicate statistically different values (α = 0.05) at the same time point.

3.2. Determination of polyphenol oxidase (PPO) and peroxidase (POD) enzymatic activities

Fig. 2 illustrates the changes in the PPO and POD activities in melon samples during the 21-day refrigerated storage period. At day 0, the effect of the treatment on enzymatic activity can be observed. In particular, PPO activity was lower in the treated products ($HPMAPCO_2$) while POD activity was higher in the same product compared to the untreated ones (MAPair and $MAPCO_2$).

From day 0 to day 21, PPO activity decreased across all treatments, with MAPair showing the most pronounced decline, reaching the lowest activity value by day 21. $MAPCO_2$ samples followed a similar trend to MAPair until day 13, after which the decline became less pronounced. In contrast, $HPMAPCO_2$ melon samples maintained a relatively constant value of PPO activity. Although initially lower than the controls until day 13, $HPMAPCO_2$ samples exhibited higher activity compared to MAPair and $MAPCO_2$ later in the storage period.

Similarly, trends in POD activity differed significantly across the three treatments. In MAPair and $MAPCO_2$ samples, POD activity sharply increased from day 0 to day 3. After a brief stable period, activity began to decline rapidly after day 9, with MAPair samples exhibiting a more pronounced decrease than $MAPCO_2$. $HPMAPCO_2$ samples, which started with slightly higher POD activity at day 0, showed a modest increase through day 6. From day 6 onward, POD activity remained stable until the end of the storage period. Consequently, POD activity in $HPMAPCO_2$ samples was lower than in the other treatments from day 3 to day 9 but became significantly higher thereafter, highlighting the superior stability of POD activity under $HPMAPCO_2$ treatment.

3.3. Determination of antioxidant activity

The results of the radical scavenging activities assays (ABTS, DPPH, OH, O_2^-, and NO) are displayed in Fig. 3. The ABTS radical scavenging activity for all treatments was similar, with MAPair samples slightly lower from day 0 to day 6. All treatments showed a slight increase in radical scavenging activity, particularly $HPMAPCO_2$, which reached its peak earlier and maintained it longer. After day 6, MAPair showed the most significant drop in activity, ending at the lowest value. The $HPMAPCO_2$ treatment showed the highest stability throughout the entire period, whereas $MAPCO_2$ lay between MAPair and $HPMAPCO_2$. $HPMAPCO_2$ exhibited significantly higher ABTS scavenging activity than MAPair, suggesting better preservation of antioxidant properties. About DPPH radical scavenging activity, all treatments showed a decrease until day 9, with MAPair showing the most pronounced decline. $MAPCO_2$ and $HPMAPCO_2$ treatments maintained similar levels until day 9. The $HPMAPCO_2$ treatment showed a significant increase in DPPH radical scavenging activity, peaking around day 16, indicating a robust response. $MAPCO_2$ also showed some recovery, but MAPair continued to increase at a slower rate. By day 21, $HPMAPCO_2$ maintained significantly higher activity levels compared to MAPair and $MAPCO_2$, indicating enhanced antioxidant retention. The $HPMAPCO_2$ treatment showed a consistent and significant increase in OH radical scavenging activity compared to other treatments from day 0 to day 6. MAPair and $MAPCO_2$ also showed an increase, but not to the same extent. $HPMAPCO_2$ maintained higher OH radical scavenging activity throughout the 21 days, whereas MAPair showed a significant decline starting at day 6. $MAPCO_2$ showed intermediate values, but activity declined slowly. The $HPMAPCO_2$ treatment showed superior antioxidant retention by day 21, highlighting its efficacy in maintaining OH radical scavenging activity compared to the other treatments. All treatments showed a decline in O_2^- radical scavenging activity throughout the storage period. $HPMAPCO_2$ retained the highest activity among the treatments, indicating better antioxidant preservation. The difference between $MAPCO_2$ and MAPair became more pronounced over time, with MAPair having the lowest activity by day 21. The statistical analysis showed significant differences between the treatments, with $HPMAPCO_2$ showing a greater O_2^- radical scavenging activity. The $HPMAPCO_2$ treatment consistently increased NO radical scavenging activity, peaking at day 9. $MAPCO_2$ also increased, but MAPair remained significantly lower. All treatments exhibited a decrease in NO radical scavenging activity after day 9, but $HPMAPCO_2$ still maintained the highest levels by day 21. MAPair had the lowest values, indicating a greater loss of antioxidant properties. $HPMAPCO_2$ retained NO scavenging activity more effectively than MAPair and $MAPCO_2$, with significant differences becoming evident by day 21.

The antioxidant activity of fresh-cut melon samples of the three theses was also determined by ORAC and FCR assays (Fig. 4). ORAC units, expressed in μmol TE/g FW, showed significant differences among the three samples during refrigerated storage. In particular, $MAPCO_2$ and $HPMAPCO_2$ samples showed higher values, and the $HPMAPCO_2$ value at the end of the shelf life was statistically equal to the one at day 0, while the MAPair one was much lower. The results of the FCR assay showed that immediately after the $HPMAPCO_2$ process, the total polyphenols content increased. After 6 days, the $HPMAPCO_2$ samples showed a decreasing trend, whereas the other two treatments showed increased values.

3.4. HPLC characterization of phenolic compounds, carotenoids, and ascorbic acid

Individual phenolics were determined by HPLC, and the results showed that the main compounds detected were vanillic acid, caffeic acid, coumaric acid, ferulic acid, and benzoic acid, the last being the most present. The quantitative results are reported in Table 1. Immediately after the process, the phenolic content increased as a result of the $HPMAPCO_2$ process for all the individual compounds, with benzoic acid switching from 23.32 ± 1.54 mg/100 g FW in the fresh sample to 35.50 ± 2.75 mg/100 g FW in the $HPMAPCO_2$ sample. As refrigerated storage progressed, starting from day 6, a slight decline was observed, benzoic acid reaching 26.03 ± 2.09 mg/100 g FW at the end of the storage, a value which still results higher respect to the former content in the fresh sample. The same trend in $HPMAPCO_2$ samples was also observed for vanillic, caffeic, coumaric, and ferulic acids, with higher contents at day 0 immediately after the $HPMAPCO_2$ process, followed by slight declines

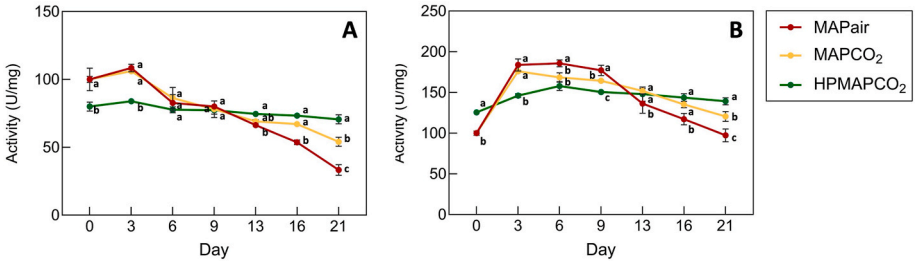

Fig. 2. Changes in enzyme activity of MAPair (red), $MAPCO_2$ (yellow) and $HPMAPCO_2$ (green) samples during 21 days of refrigerated storage. A) PPO activity; B) POD activity. Different letters indicate statistically different values (α = 0.05) at the same time point.

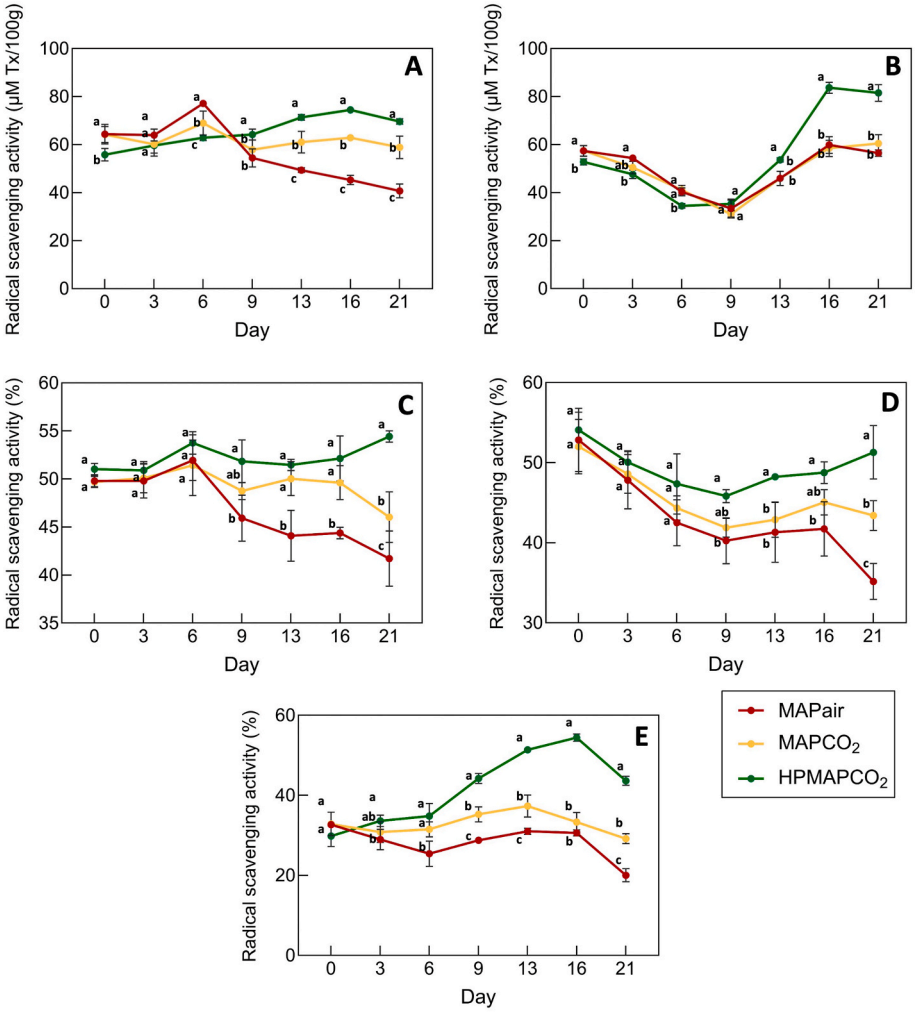

Fig. 3. Antioxidant activity during 21 days of refrigerated storage for fresh-cut melon samples MAPair (red), $MAPCO_2$ (yellow) and $HPMAPCO_2$ (green). A) ABTS radical scavenging activity; B) DPPH radical scavenging activity; C) OH radical scavenging activity; D) O_2^- radical scavenging activity; E) NO radical scavenging activity. Different letters indicate statistically different values ($\alpha = 0.05$) at the same time point.

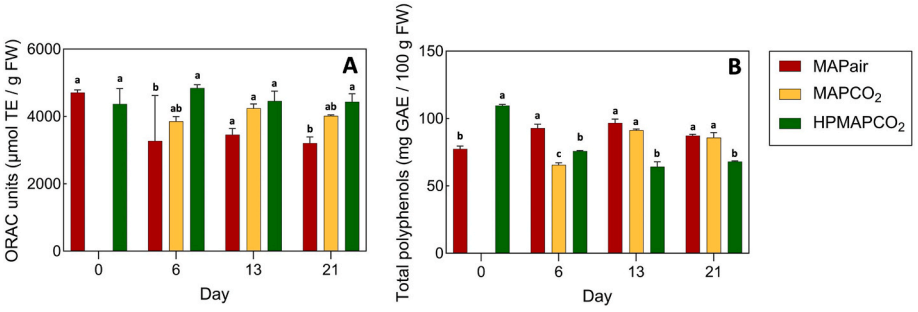

Fig. 4. ORAC units (A) and total polyphenols (B) during 21 days of refrigerated storage for fresh-cut melon samples MAPair (red), $MAPCO_2$ (yellow) and $HPMAPCO_2$ (green). Different letters indicate statistically different values ($\alpha = 0.05$) at the same time point.

during further refrigerated storage, with final contents comparable to those of the fresh fruit at the end of the storage. MAPair and $MAPCO_2$ theses showed a similar trend, recording lower levels of all the phenolic compounds at the end of the refrigerated storage, if compared to $HPMAPCO_2$ samples, except for coumaric acid.

Regarding the carotenoids, the HPLC analysis showed that the main component is β-carotene. Total carotenoids and β-carotene are shown in Fig. 5A and B, respectively. At time 0, immediately after the $HPMAPCO_2$ process, total carotenoids and β-carotene levels were preserved or enhanced, as in the case of β-carotene, which increased from 2.22 ± 0.08 mg/100 g FW to 2.52 ± 0.13 mg/100 g FW. During the shelf life, the total carotenoid and β-carotene contents decreased for all treatments, starting from 6 days of refrigerated storage. From day 13 until the end of the refrigerated storage, the total carotenoids and β-carotene contents remained significantly higher in the $HPMAPCO_2$ treatment with respect to the other two treatments. At the end of the refrigerated storage (day 21), the total carotenoids and β-carotene levels were equal to 3.52 ± 0.33 mg BCE/100 g FW and 2.18 ± 0.14 mg/100 g FW,

Table 1
Individual polyphenol content in the three compared treatments (MAPair, MAPCO2, and HPMAPCO$_2$) during the refrigerated storage of fresh-cut melon. Results are expressed in mg per 100 g FW. Different letters indicate statistically different values (α = 0.05) at the same time point. Cells sharing the same letter are not significantly different.

Storage time (days)	Sample	Vanillic acid	Caffeic acid	Coumaric acid	Ferulic acid	Benzoic acid
0	Fresh	6.11 ± 0.13^{b}	1.77 ± 0.10^{b}	2.68 ± 0.07^{a}	2.62 ± 0.05^{b}	23.32 ± 1.54^{b}
	HPMAPCO$_2$	7.33 ± 0.21^{a}	1.92 ± 0.03^{a}	2.73 ± 0.09^{a}	3.42 ± 0.16^{a}	35.50 ± 2.75^{a}
6	MAPair	6.12 ± 0.03^{b}	1.61 ± 0.08^{b}	2.37 ± 0.20^{b}	3.14 ± 0.01^{a}	27.45 ± 1.30^{a}
	MAPCO$_2$	6.03 ± 0.05^{c}	1.67 ± 0.02^{b}	2.33 ± 0.06^{b}	3.51 ± 0.36^{a}	26.51 ± 0.13^{a}
	HPMAPCO$_2$	6.40 ± 0.02^{a}	1.88 ± 0.05^{a}	2.74 ± 0.09^{a}	3.06 ± 0.09^{a}	24.78 ± 0.96^{a}
13	MAPair	5.74 ± 0.07^{b}	1.54 ± 0.08^{b}	2.26 ± 0.13	2.89 ± 0.07^{b}	24.89 ± 1.32^{a}
	MAPCO$_2$	6.20 ± 0.12^{a}	1.56 ± 0.02^{b}	2.14 ± 0.05	3.12 ± 0.05^{a}	25.95 ± 0.64^{a}
	HPMAPCO$_2$	6.43 ± 0.11^{a}	1.74 ± 0.02^{a}	2.17 ± 0.09	2.78 ± 0.17^{b}	23.91 ± 1.94^{a}
21	MAPair	5.68 ± 0.10^{b}	1.53 ± 0.01^{b}	2.73 ± 0.11^{a}	2.44 ± 0.13^{b}	25.26 ± 0.59^{a}
	MAPCO$_2$	5.62 ± 0.21^{b}	1.49 ± 0.02^{b}	2.72 ± 0.15^{a}	2.56 ± 0.08^{ab}	25.35 ± 0.77^{a}
	HPMAPCO$_2$	6.43 ± 0.04^{a}	1.79 ± 0.04^{a}	2.36 ± 0.08^{b}	2.67 ± 0.04^{a}	26.03 ± 2.09^{a}

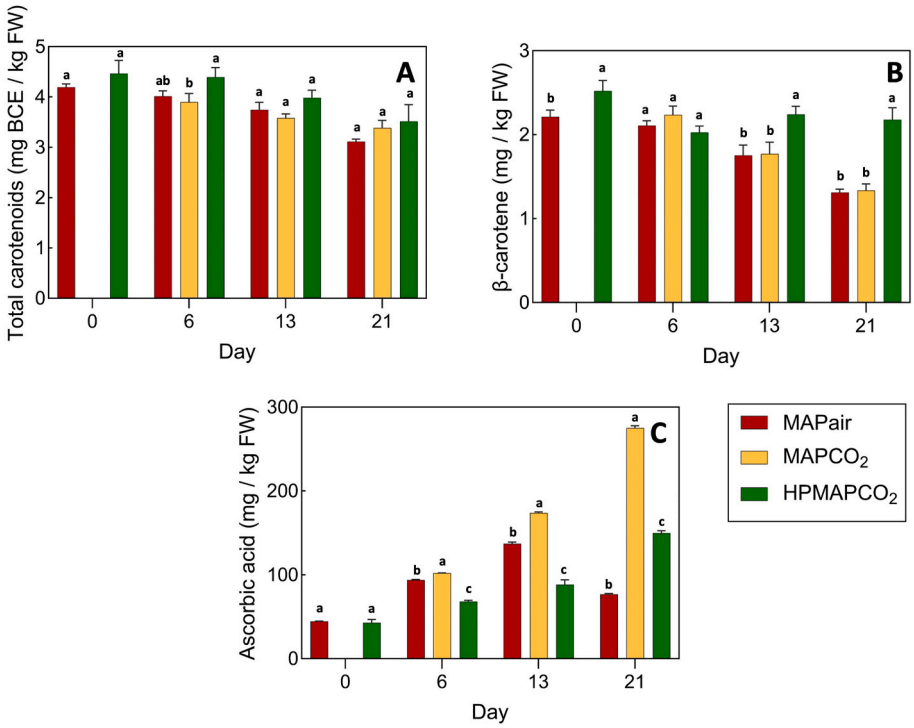

Fig. 5. Carotenoids and ascorbic acid during 21 days of refrigerated storage for fresh-cut melon samples MAPair (red), MAPCO$_2$ (yellow) and HPMAPCO$_2$ (green). A) Total carotenoids (β-carotene equivalents); B) β-carotene; C) Ascorbic acid. Different letters indicate statistically different values (α = 0.05) at the same time point.

respectively.

Ascorbic acid had a concentration of 44.66 ± 0.23 mg/kg FW at day 0; from day 6 onward, it began to increase, more intensively in the CO_2-packaged treatments, with MAP-CO_2 samples showing higher levels of this compound throughout refrigerated storage (Fig. 5C).

3.5. Micro- and macro-nutrient contents

The results of the determination of the micro- and macro-nutrient levels in the three compared treatments (MAPair, MAPCO$_2$, and HPMAPCO$_2$) showed that K, Ca, P, Na, and Mg resulted the most represented minerals (Table S1). At day 0, K and P contents in HPMAPCO$_2$ samples showed significantly increased levels with respect to the fresh sample, this behavior being no longer confirmed from day 6 onward. Indeed, starting from day 6, the mineral contents remained almost constant throughout the refrigerated storage. Only minor decrements were recorded, putatively linked to the washout of salts dissolved in the water released by the melon cubes inside the packages. However, at the end of the refrigerated storage, most of the micro- and macro-nutrient levels were preserved for all three treatments.

3.6. Bioaccessibility study

Bioaccessibility studies were conducted during the storage of the three theses (MAPair, MAPCO$_2$, and HPMAPCO$_2$) by determining total polyphenols, DPPH antioxidant activity, and total carotenoids in the freeze-dried samples and their stomach phase, intestine phase, and bioaccessible fractions. The results are shown in Table S2 of the Supplementary materials, while the bioaccessibility ratio during storage is shown in Fig. 6.

It is possible to observe how the bioaccessible ratio of treated samples is similar or higher than that of the unprocessed samples (MAPair, day 0). This can be noted during the storage period for polyphenols, DPPH antioxidant activity, and total carotenoids while MAPair and MAPCO$_2$ had similar bioaccessibility ratios, the value for treated samples was usually higher for DPPH antioxidant activity and total

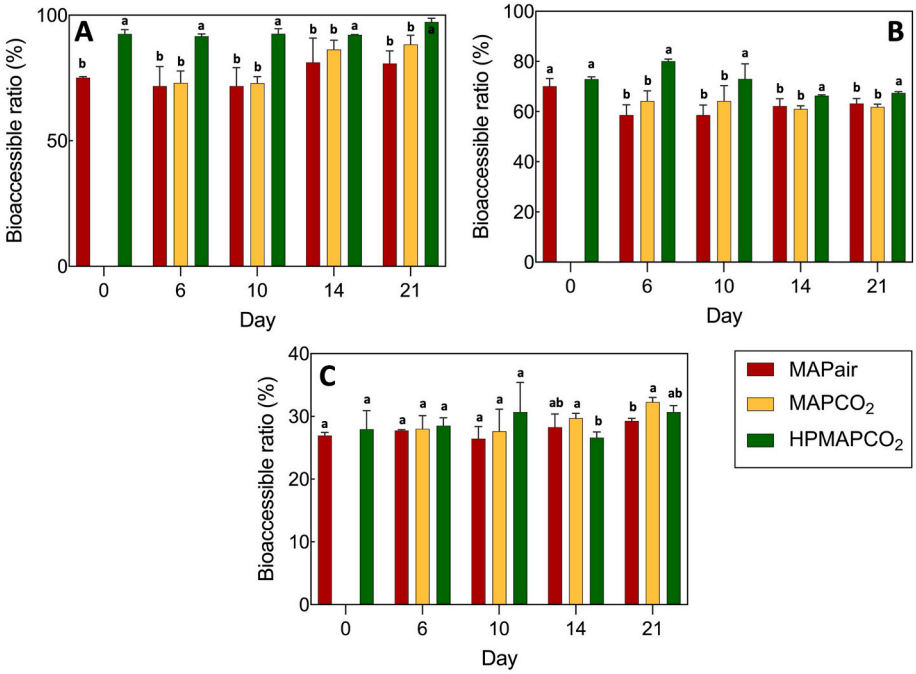

Fig. 6. Bioaccessibility ratio (%) of total polyphenols (A), DPPH antioxidant activity (B), and total carotenoids (C) during 21 days of refrigerated storage for fresh-cut melon freeze-dried samples MAPair (red), $MAPCO_2$ (yellow) and $HPMAPCO_2$ (green). Different letters indicate statistically different values ($\alpha = 0.05$) at the same time point.

polyphenols from day 6 onward.

3.7. HPLC characterization of sugars

Glucose levels increased for all treatments from day 3 to day 9, with $HPMAPCO_2$ showing the highest increase, peaking around day 9 (Fig. 7). MAPair and $MAPCO_2$ treatments also showed a similar trend, but MAPair remained consistently lower. After day 9, glucose levels decreased for all treatments. The decline was most rapid in MAPair, resulting in the lowest glucose concentration by day 21. $HPMAPCO_2$ maintained higher glucose levels throughout the storage period than the other treatments, indicating its effectiveness in preserving glucose levels. $HPMAPCO_2$ consistently had significantly higher glucose concentrations at several time points compared to MAPair and $MAPCO_2$, whereas the MAPair treatment generally resulted in the lowest glucose levels. Fructose concentrations increased for all treatments until day 9, similarly to glucose. $HPMAPCO_2$ again showed the highest peak, while MAPair and $MAPCO_2$ reached a lower plateau. From day 9 onward, fructose levels decreased, with MAPair showing the deepest decline. $HPMAPCO_2$ maintained relatively higher fructose concentrations

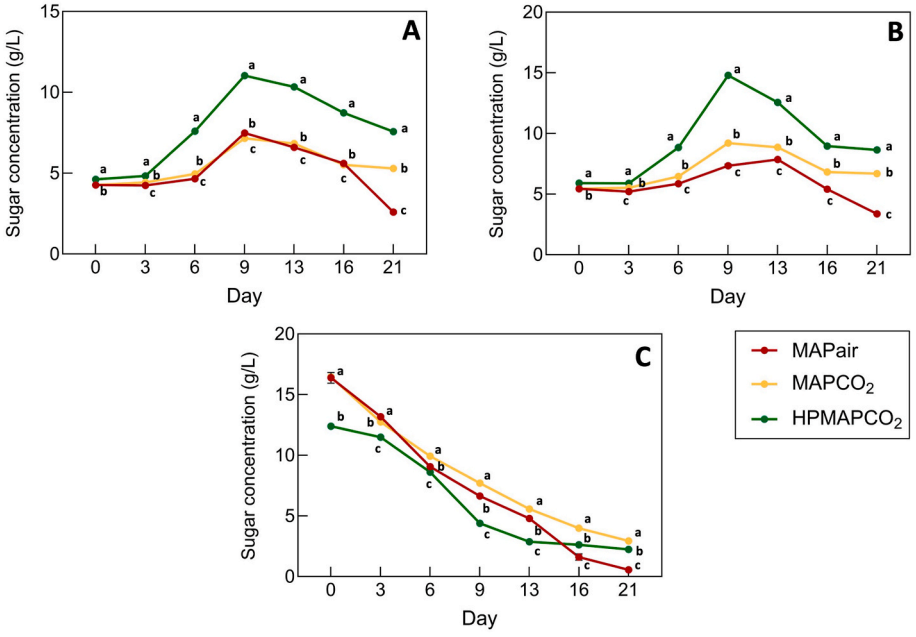

Fig. 7. Sugar contents during 21 days of refrigerated storage for fresh-cut melon samples MAPair (red), $MAPCO_2$ (yellow) and $HPMAPCO_2$ (green). A) Glucose; B) Fructose; C) Sucrose. Different letters indicate statistically different values ($\alpha = 0.05$) at the same time point.

throughout the storage period. $MAPCO_2$ showed intermediate results between $HPMAPCO_2$ and MAPair. Sucrose concentrations were initially high across all treatments and declined throughout the storage period. MAPair showed the most rapid decrease in sucrose content, beginning on day 3 and continuing through day 21. $HPMAPCO_2$ had a slower rate of decline, maintaining higher sucrose levels over time compared to MAPair and $MAPCO_2$. By day 21, MAPair showed the lowest sucrose concentration, while $HPMAPCO_2$ retained higher levels, suggesting better sugar retention under this treatment.

3.8. Sensory analysis

The $HPMAPCO_2$ treatment showed a significant decrease in color score compared to fresh samples, suggesting a minor change from the beginning (Table 2). MAPair and $MAPCO_2$ treatments maintained the highest color scores (10.00 on Day 3 and 9.25 on Day 6), indicating better color preservation during early storage. $HPMAPCO_2$ had consistently lower scores throughout, which might be due to initial high-pressure treatment effects on pigment stability. There was a gradual decline in color across all treatments, but $HPMAPCO_2$ had lower scores than MAPair and $MAPCO_2$. By day 21, $HPMAPCO_2$ still had slightly higher scores (6.88) than the other treatments, indicating less color degradation in the later stages. Fresh samples scored 10.00, while $HPMAPCO_2$ decreased to 7.40, likely due to the pressure treatment affecting visual quality. $HPMAPCO_2$ was consistently lower but remained stable from day 3 to day 6. By day 21, $HPMAPCO_2$ scores dropped to 5.50, whereas MAPair and $MAPCO_2$ were also lower, indicating a gradual decrease in visual appeal over time. However, $HPMAPCO_2$ seemed to be comparable at maintaining appearance at later stages.

$HPMAPCO_2$ had the highest smell score (9.80), indicating an improvement, possibly due to the introduction of CO_2. MAPair and $MAPCO_2$ showed decreases, especially MAPair on day 6 with a score of 8.50. $HPMAPCO_2$ maintained high scores during early storage (8.75 at day 6). All treatments saw a decline, with MAPair dropping the most significantly by day 21 (4.75). $HPMAPCO_2$ retained a higher score (6.38) than the other treatments, suggesting it better preserved the smell attribute. All treatments scored a perfect 10 for texture, indicating optimal firmness at the start. $HPMAPCO_2$ showed a decline in texture from day 6 (8.00) to day 9 (8.00). MAPair and $MAPCO_2$ showed similar scores, indicating better preservation of firmness in the early stages. By day 21, $HPMAPCO_2$ still had a higher texture score (6.13) compared to MAPair and $MAPCO_2$, indicating less texture loss during storage.

4. Discussion

The study outlines the effects of a novel high-pressure process combined with CO_2 modified atmosphere packaging on the physico-chemical, nutritional, antioxidant and sensory properties, of fresh-cut organic cantaloupe melon during 21 days of storage. Besides, the bio-accessibility of bioactive compounds is displayed. A significant impact of the applied preservation technique on the preservation of the raw material's freshness during storage was demonstrated. The innovative $HPMAPCO_2$ technology has previously been described by our research team for squash (Zulli et al., 2025), where similarly promising results were obtained regarding its beneficial effect on preserving the quality and freshness of ready-to-eat products.

Based on the results of this study, the combination of high pressure and a CO_2-enriched modified atmosphere resulted in the smallest color changes compared to fresh samples, along with a slight decrease in pH and a reduced °Brix value, immediately after treatment. The use of $MAPCO_2$ also effectively limited color degradation during the early stages of storage, highlighting the importance of oxygen-limiting strategies in preserving visual quality. However, after subsequent days, the color change reached levels similar to those observed in samples packaged in air. In accordance with this evidence, it has been previously demonstrated that fresh-cut 'Cantaloupe' melon packaged under CO_2 modified atmosphere underwent color deterioration similarly to non-modified atmosphere conditions due to the development of a greater percentage of translucency (Oms-Oliu et al., 2007). Our results indicated that synergistic approaches beyond atmosphere modification alone are necessary to further prolong the product's shelf life. The relatively stable pH observed during storage may be explained by the fact that high-pressure processing generally induces only minor changes in the acidity of fruit matrices. Slight pH decreases may result from the dissolution of CO_2 and the formation of carbonic acid (Zambon et al., 2022). Modified atmosphere packaging with elevated CO_2 and reduced O_2 levels has been shown to reduce metabolic activity and limit browning development in melon during refrigerated storage (Park et al., 2020). The reduced °Brix value observed immediately after $HPMAPCO_2$

Table 2
Sensory attributes of fresh-cut melon of the treatments (MAPair, $MAPCO_2$, and $HPMAPCO_2$) during the refrigerated storage of fresh-cut melon. Different letters indicate statistically different values ($\alpha = 0.05$) for the same parameter at the same time point.

Storage time (days)	Sample	Color	Appearance	Smell	Texture
0	Fresh	10.00 ± 0.00^{a}	10.00 ± 0.00^{a}	9.40 ± 0.55^{a}	10.00 ± 0.00^{a}
	$HPMAPCO_2$	7.80 ± 0.45^{b}	7.40 ± 0.55^{b}	9.80 ± 0.45^{a}	10.00 ± 0.00^{a}
3	MAPair	10.00 ± 0.00^{a}	9.80 ± 0.45^{a}	9.40 ± 0.55^{a}	10.00 ± 0.00^{a}
	$MAPCO_2$	9.00 ± 0.00^{b}	9.80 ± 0.45^{a}	9.40 ± 0.89^{a}	10.00 ± 0.00^{a}
	$HPMAPCO_2$	7.40 ± 0.55^{c}	7.80 ± 0.45^{b}	9.20 ± 0.45^{a}	10.00 ± 0.00^{a}
6	MAPair	9.25 ± 0.50^{a}	9.75 ± 0.50^{a}	8.50 ± 0.58^{a}	9.00 ± 0.00^{a}
	$MAPCO_2$	9.25 ± 0.50^{a}	9.00 ± 0.00^{a}	8.50 ± 0.58^{a}	9.00 ± 0.00^{a}
	$HPMAPCO_2$	8.00 ± 0.00^{b}	7.75 ± 0.50^{b}	8.75 ± 0.50^{a}	8.50 ± 0.58^{a}
9	MAPair	8.67 ± 0.52^{a}	8.17 ± 0.98^{a}	7.33 ± 1.03^{a}	8.33 ± 0.52^{a}
	$MAPCO_2$	9.00 ± 0.00^{a}	8.83 ± 0.41^{a}	8.33 ± 0.52^{a}	8.67 ± 0.52^{a}
	$HPMAPCO_2$	8.00 ± 0.63^{b}	7.33 ± 1.21^{b}	7.83 ± 1.17^{a}	8.00 ± 0.89^{a}
13	MAPair	7.83 ± 0.41^{a}	7.33 ± 0.52^{a}	6.00 ± 0.63^{b}	7.33 ± 0.52^{a}
	$MAPCO_2$	8.33 ± 0.52^{a}	7.83 ± 0.41^{a}	7.50 ± 0.55^{a}	7.33 ± 0.52^{a}
	$HPMAPCO_2$	7.53 ± 0.52^{a}	6.83 ± 0.98^{a}	7.50 ± 1.22^{a}	7.33 ± 0.52^{a}
16	MAPair	7.33 ± 0.52^{a}	7.00 ± 0.63^{a}	5.00 ± 0.00^{b}	6.00 ± 0.00^{b}
	$MAPCO_2$	7.33 ± 0.52^{a}	7.67 ± 0.52^{a}	6.67 ± 0.52^{a}	6.83 ± 0.41^{a}
	$HPMAPCO_2$	7.30 ± 0.55^{a}	6.33 ± 0.52^{a}	7.33 ± 0.52^{a}	7.33 ± 0.52^{a}
21	MAPair	5.75 ± 0.46^{a}	6.38 ± 0.52^{a}	4.75 ± 0.46^{b}	5.13 ± 0.35^{b}
	$MAPCO_2$	5.88 ± 0.64^{a}	6.00 ± 0.53^{a}	4.00 ± 0.00^{b}	5.63 ± 0.52^{ab}
	$HPMAPCO_2$	6.88 ± 0.83^{a}	5.50 ± 0.76^{a}	6.38 ± 0.52^{a}	6.13 ± 0.64^{a}

treatment may be associated with structural changes in fruit tissues induced by hydrostatic pressure. High-pressure processing can cause deformation or disruption of cell membranes, leading to increased membrane permeability, loss of turgor, and leakage of intracellular fluids from plant tissues (Heaney & Padilla-Zakour, 2025). Similar physicochemical trends, including °Brix, have been evaluated in cantaloupe melon puree subjected to high-pressure processing (Mukhopadhyay et al., 2017).

The application of the innovative HPMAPCO$_2$ technology resulted in a reduction in PPO but not in POD activity compared to MAPCO$_2$ and MAPair samples. Both enzymes showed greater stability during storage in pressure-treated samples. After 21 days of storage, the lowest enzymatic activity was recorded in MAPair samples, followed by MAPCO$_2$ and then HPMAPCO$_2$ samples. High pressure treatment can significantly influence enzymatic activity through pressure-induced modifications of protein structure. Disruption of non-covalent interactions, such as hydrogen bonds, electrostatic forces, and hydrophobic interactions, can lead to conformational changes and partial or complete enzyme denaturation, resulting in reduced catalytic activity (Barba et al., 2012; Heaney & Padilla-Zakour, 2025). However, the pressure sensitivity is enzyme specific. PPO, which plays a key role in enzymatic browning reactions in fruits, is generally more susceptible to pressure-induced inactivation than POD. POD is considered a relatively pressure-resistant enzyme due to its more compact tertiary structure and the presence of stabilizing prosthetic groups, which may explain the limited reduction in its activity observed in the present study (Roobab et al., 2022; Terefe et al., 2014). Pressure treatment can increase cell membrane permeability and disrupt cellular compartmentalization, promoting the release of enzymes and substrates from intracellular structures such as vacuoles and plastids. As a result, temporary increases or fluctuations in enzymatic activity may occur immediately after processing due to enhanced enzyme–substrate interactions (Heaney & Padilla-Zakour, 2025). Furthermore, the effect of HHP on enzymatic stability during storage is influenced by processing parameters, including pressure level, holding time, and temperature, as well as by the physicochemical properties of the food matrix, such as pH, water activity, and the presence of natural inhibitors or cofactors (Barba et al., 2012). In fruit tissues with relatively high pH values, such as melon, enzymatic browning reactions may remain active even after pressure treatment, particularly when enzymes with higher pressure resistance, such as POD, are present. The combination of high pressure with modified atmosphere conditions may further affect enzymatic activity. Elevated CO_2 levels in modified atmosphere packaging can limit oxidative enzymatic reactions and slow down metabolic processes in fresh-cut fruits. In addition, dissolved CO_2 may lead to slight acidification of the tissue environment, which can influence enzyme stability and reaction kinetics (Lei et al., 2022). Consequently, the combined application of HP and CO_2-enriched atmospheres may exert a synergistic effect on enzymatic inactivation and quality preservation.

ORAC units are widely recognized as an indicator of the antioxidant capacity of a food commodity and, based on its simple annotation in units, give a numerical indication of the antioxidant potential of the related food. The results of our study highlighted that organic cantaloupe melons are a rich source of antioxidants with values, whatever the treatment, always exceeding at least 3000 ORAC units during refrigerated storage. Higher values of MAPCO$_2$ and HPMAPCO$_2$ were recorded for organic cantaloupe melon samples compared with MAPair samples throughout refrigerated storage, indicating that the CO_2 atmosphere preserved the antioxidant capacity of the samples. This kind of preservation was more evident in HPMAPCO$_2$ samples, where the combined effects of the CO_2 atmosphere and high-pressure produced the better preservation of the ORAC units, until the end of the storage. Our results are in accordance with previous studies reporting the maintenance of high antioxidant activity values in both MAP-treated fruits, such as peach (Dong et al., 2022), and HPMAPCO$_2$-treated vegetables, such as fresh-cut squashes (Zulli et al., 2025).

The FCR assay, being an electron-transfer based assay, showed the contribution of all the sample compounds that exert their antioxidant activity through an electron transfer mechanism. The results showed a significant increase in total polyphenols in HPMAPCO$_2$ samples at time 0, after the high-pressure process, with a further decreasing trend from day 6 onward. On the contrary, total polyphenols began to slightly increase in MAPCO$_2$ and MAPair samples from day 6 until the end of the refrigerated storage. This behavior is consistent with the results of the PPO activity, which later in the storage period showed that HPMAPCO$_2$ samples exhibited higher activity compared to MAPair and MAPCO$_2$. Even if the HPMAPCO$_2$ process induced an increase in total polyphenols, putatively linked to the action of the high pressures combined with the CO_2 modified atmosphere, these levels were not maintained and preserved until the end of the refrigerated storage, probably because the HPMAPCO$_2$ process contemporarily maintained a residual PPO activity, as our results showed. On the other hand, the late rise of total polyphenol levels in MAPair and MAPCO$_2$ samples might be attributable to prolonged refrigerated storage, which elicited the release of more metabolites from the degrading cells, thereby increasing extraction efficiency (Amaro et al., 2018). Moreover, this late rise might be attributable to wounding damage that lately in the storage stimulated secondary metabolites biosynthesis, as previously suggested by Brecht (1995). Indeed, the differential behavior of HPMAPCO$_2$ samples respect to both MAPair and MAPCO$_2$ samples may be due to the residual PPO activity which was significantly higher in HPMAPCO$_2$ samples with respect to the other two theses from day 9 onward. When it comes to individual phenolic compounds, qualitatively and quantitatively characterized by HPLC, HPMAPCO$_2$ samples showed an increase at time 0 again, while whatever the treatments, all the individual compounds showed a subsequent decline after day 6. This behavior may be presumably linked to polymerization reactions that might have occurred between phenolic acids and free sugars or other organic acids naturally present in the melon tissue during the refrigerated storage, as an accumulation of phenolics is induced in cells as a response to further refrigerated storage stresses (Pei et al., 2016).

The HPMAPCO$_2$ treatment also induced an increase in total carotenoids and β-carotene but, starting from 6 days of refrigerated storage, decreasing values were recorded across all treatments, with HPMAPCO$_2$ samples retaining the higher levels of these compounds. It may be hypothesized that the fall in in β-carotene after day 6 may be presumably ascribed to wounding damage which exposed β-carotene to lipoxygenase action, as previously demonstrated (Britton & Khachik, 2009). Our results demonstrated that the high-pressure action was able to preserve β-carotene levels while CO_2 atmosphere modification alone did not produce statistically significant differences. Indeed, MAPCO$_2$ and MAPair samples behaved similarly. According to our results, similar gradual decreases in both air- and MAP-treated shredded orange and purple carrots during a 14-days refrigerated storage were previously found (Alasalvar et al., 2005).

The ascorbic acid levels determined by HPLC showed an increasing trend, whatever the treatment, which may be putatively due to the water loss inside the package that occurred during the refrigerated storage, which indirectly produced a concentration of the ascorbic acid. Also, the increased softening of the melon tissue could have induced a higher extraction efficiency of this compound, as previously observed (Amaro et al., 2018).

Micro- and macro-nutrients determination highlighted that fresh-cut melon is a valuable source of K, Ca, P, Na, and Mg which were the most represented minerals. The HPMAPCO$_2$ treatment seemed to induce an enhancement in K and P levels at time 0, putatively due to the release of intracellular ions (such as K^+ and P) through HPCD damaged cell membranes (Hong & Pyun, 2001). Anyway, from day 6, whatever the treatments, the minerals levels remained mostly preserved or in some cases only slightly decreased, probably due to the water loss and washout inside the packages. These results evidenced how the application of the proposed HPCD technological approach was not detrimental

to the preservation of the mineral content of the raw melon.

Shortly after processing, HP-treated samples exhibited higher polyphenol and total carotenoid bioaccessibility as well as antioxidant activity (DPPH) after digestion, compared to MAPair samples. Moreover, $HPMAPCO_2$ samples maintained superior polyphenol bioaccessibility and antioxidant activity during storage, while carotenoid bioaccessibility remained largely stable across all treatments. These results highlight the potential of $HPMAPCO_2$ to enhance the health-promoting properties of organic fresh-cut melon by improving the gastrointestinal availability of antioxidants. Similar effects have been reported in previous studies on high-pressure processing of fruit and vegetable matrices, where pressure treatment increased the release and bioaccessibility of phenolic compounds and carotenoids during simulated gastrointestinal digestion (Cilla et al., 2018; Trych et al., 2020; Wang et al., 2025). Improved bioaccessibility observed in $HPMAPCO_2$ samples may be associated with the disruption of parenchymal cell structure, characterized by thin primary cell walls and highwater content. The mechanical disintegration of cell walls and membranes may facilitate the release of vacuole-localized phenolic compounds and improve their diffusion during gastrointestinal digestion. (Gómez-Maqueo et al., 2020). Moreover, high pressure may promote the breakdown of chromoplast membranes and associated lipid–protein complexes, thereby facilitating carotenoid transfer into mixed micelles during intestinal digestion (Lara-Abia et al., 2021). Conformational changes in melon proteins caused by pressure may reduce protein–polyphenol binding interactions, increasing the soluble fraction of phenolic compounds available for absorption (Heaney & Padilla-Zakour, 2025). The enhanced bioaccessibility of polyphenols and carotenoids in $HPMAPCO_2$ samples may also be related to the partial inhibition of PPO, demonstrated in this study, which limits the degradation of phenolic substrates, while pressure-induced disruption of plant tissue structures facilitates the release of intracellular antioxidants and improves their incorporation into the bioaccessible fraction during digestion (Alongi et al., 2025; Lou et al., 2022). The increased bioaccessibility of polyphenols may also be associated with the formation of their metabolites during digestion, which can exhibit strong antioxidant activity, such as phenolic acids formed by the breakdown and biotransformation of native polyphenols in the gastrointestinal tract (Matías et al., 2025; Trych et al., 2022).

The initial sucrose content was comparable across all theses and decreased throughout the 21-days storage period, regardless of the treatment applied. In contrast, glucose and fructose levels increased between days 3 and 9 of storage, followed by a subsequent decline in all experimental theses. $HPMAPCO_2$ samples showed the highest concentrations of glucose and fructose, which remained constant throughout the storage. This may be associated with intensified metabolic activity and oxidative processes under aerobic conditions, leading to greater sugar utilization (Wu et al., 2020). By day 21, MAPair samples exhibited the lowest sucrose content, whereas $HPMAPCO_2$ samples retained higher sucrose levels, suggesting more effective sugar preservation as a result of $HPMAPCO_2$ process. Reduced oxygen availability in MAP packaging is known to slow down respiration rates and carbohydrate metabolism in fresh-cut fruits, thereby limiting sucrose degradation and maintaining sugar levels during storage (Park et al., 2020). High-pressure treatment may enhance the stability of soluble sugars in plant tissues during storage by disrupting cellular structures and modulating enzymatic activity, as previously reported for bioactive compounds and their bioaccessibility (Cheng et al., 2026). Overall, $HPMAPCO_2$ process proved to be the most effective method for maintaining elevated glucose and fructose concentrations during storage.

The obtained results highlight that $HPMAPCO_2$ treatment was the most effective for preserving the sensory quality of fresh-cut melon during refrigerated storage. Although it initially affected color, due to pressure-driven tissue and pigment changes, it ultimately maintained superior aroma and texture compared to $MAPCO_2$ and MAPair. This was supported by longer perceived freshness and better overall acceptability. $MAPCO_2$ provided moderate preservation, while MAPair was the least effective, with significant declines in color, aroma, and texture by the end of the storage. The benefits of high pressure processing for the sensory quality of fresh-cut products have been reported in previous studies (Zambon et al., 2022). High-pressure processing is known to minimize thermal degradation of aroma compounds and maintain the natural flavor profile of fruit products by inactivating spoilage microorganisms and slowing enzymatic reactions responsible for quality deterioration. Enhanced sensory outcomes, including higher flavor scores and improved retention of key aroma esters in pressurized melon juice, indicate that pressure-based technologies can effectively preserve desirable sensory attributes (Pei et al., 2023). Furthermore, Shinde et al. (Shinde et al., 2024) reported that both active and passive modified atmosphere packaging effectively preserved the visual quality, aroma, and overall acceptability of fresh-cut melons during refrigerated storage, compared with air packaging. Reduced oxygen availability and increased CO_2 concentrations in MAP systems are known to slow respiration rates and delay senescence in fresh-cut fruit tissues, thereby improving sensory stability during storage (Ghidelli & Pérez-Gago, 2018; Zambon et al., 2022). Based on these results, the combination of pressure processing with CO_2-enriched modified atmosphere may provide synergistic effects by limiting oxidative reactions, maintaining volatile compounds, and preserving structural integrity of melon tissues. All these evidences resulted in protecting sensory quality during storage.

From a commercial perspective, the $HPMAPCO_2$ technology presents both opportunities and challenges for large-scale implementation. The equipment required represents a high capital investment compared to standard MAP lines. However, the technology is inherently batch-scalable, and high-pressure processing units with capacities suitable for industrial production are already commercially available and used in the food industry (e.g., for HPP of juices and ready-to-eat products). The process operates at moderate temperature (40 °C), eliminating the need for costly heating or cooling infrastructure beyond standard refrigeration. Furthermore, the use of 100% recyclable high-barrier packaging, as employed in this study, aligns with current sustainability requirements. Integration into existing fresh-cut processing lines would require a dedicated pressurization unit downstream of the cutting and packaging operations, without major modifications to upstream processes. Overall, these characteristics position $HPMAPCO_2$ as a technically feasible and potentially cost-competitive alternative for premium organic fresh-cut products, where added nutritional value and extended shelf-life can justify a high initial capital investment. However, a thorough techno-economic analysis would be needed to quantify the actual cost of the process at industrial scale.

5. Conclusions

This study demonstrates that the $HPMAPCO_2$ technology represents a valid approach for preserving organic fresh-cut cantaloupe melon, overcoming the limitations of traditional air packaging and standard modified atmospheres. The synergistic effect of high pressure and a CO_2-enriched atmosphere effectively extends the product's shelf-life up to 21 days, maintaining high sensory standards, particularly aroma and texture, while slowing down degradation. From a nutritional perspective, the treatment not only preserves bioactive compounds and minerals but also significantly enhances their bioaccessibility. By facilitating the release of antioxidants during digestion, it adds functional value to the product that exceeds that of the untreated fresh-cut fruit. Despite these promising results, further research is essential to move toward industrial implementation: (i) process optimization, namely refining process parameters to minimize initial structural stress on fruit tissues; (ii) food safety validation, by intense microbiological studies to rigorously evaluate the safety of these minimally processed products; (iii) techno-economic and environmental sustainability assessment, through dedicated Life Cycle Costing (LCC) and Life Cycle Assessment (LCA) studies, to rigorously quantify the economic viability and environmental burden of the process prior to its industrial implementation.

Ethical permission and panelist consent

The sensory research addressed in this work complied with relevant laws and institutional guidelines and was approved by the ethics committee of the Wroclaw University of Environmental and Life Sciences (Doc#: N0N00000.0020.1.6.4.2024). Human participants were required to sign a consent form that declared "I agree to participate in this sensory evaluation" before undertaking the sensory evaluation.

CRediT authorship contribution statement

Riccardo Zulli: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Zhe Chen:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Fabio Santi:** Methodology, Investigation. **Urszula Trych:** Writing – review & editing, Investigation, Formal analysis. **Justyna Szczepańska-Stolarczyk:** Writing – review & editing, Investigation, Formal analysis. **Magdalena Cywińska-Antonik:** Writing – review & editing, Investigation, Formal analysis. **Pietro Andrigo:** Investigation, Formal analysis. **Maria Allegra:** Investigation, Formal analysis. **Claudio Saitta:** Resources, Methodology, Formal analysis. **Martina Papa:** Resources, Methodology, Formal analysis. **Nicolina Timpanaro:** Resources, Methodology, Formal analysis. **Yasin Ozdemir:** Resources, Methodology, Investigation, Funding acquisition. **Seda Kayahan:** Investigation, Formal analysis. **Hasret Altunkanat:** Investigation, Formal analysis. **Aysun Ozturk:** Investigation, Formal analysis. **Alessandro Zambon:** Writing – review & editing, Validation, Formal analysis. **Simona Fabroni:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Krystian Marszalek:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Sara Spilimbergo:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization.

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The graphical abstract was made by FigureLabs V2.2.

Declaration of competing interest

Sara Spilimbergo reports that financial support was provided by the Italian Ministry of Agriculture, Food Sovereignty, and Forests. Krystian Marszalek reports that financial support was provided by the National Center for Research and Development. Simona Fabroni reports that financial support was provided by the Italian Ministry of Agriculture, Food Sovereignty, and Forests and the Italian Ministry of University and Research. Yasin Ozdemir reports that financial support was provided by the General Directorate of Agricultural Research and Policies of the Ministry of Agriculture and Forestry of the Republic of Türkiye. Sara Spilimbergo reports administrative support was provided by H2020 ERA-NETs SUSFOOD2 and CORE Organic Cofunds. Sara Spilimbergo reports financial support was provided by Italian Ministry of Enterprises and Made in Italy. Fabio Santi reports financial support was provided by Italian Ministry of University and Research under the PNRR, Mission 4. Sara Spilimbergo has patent #IT10201700009804 issued to University of Padova. Alessandro Zambon has patent #IT10201700009804 issued to University of Padova. The other 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. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fbio.2026.109356.

Data availability

Data will be made available on request.

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