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Synergistic Effects of Pre-Cooling and MAP on Postharvest Quality During Storage of 'Blanca de Tudela' Globe Artichokes

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Abstract

The globe artichoke (*Cynara cardunculus* var. *scolymus* L.) is one of the most economically important vegetable crops in Spain. 'Blanca de Tudela' is the most widely grown and consumed cultivar and it is also highly valued on international export markets. Postharvest preservation is crucial for maintaining the quality of this highly perishable product. This study focused on comparing the effectiveness of two different postharvest strategies in preserving the quality of whole artichokes and extending their shelf-life: packaging in modified atmosphere packaging (MAP), and pre-cooling to 4 °C followed by MAP. In addition, one batch of artichokes was stored under refrigeration conditions, i.e., without packaging, at a temperature of 2 °C and a relative humidity of 85%. Parameters such as respiration rate, weight loss, firmness, total phenolic content, chlorophyll levels and visual sensorial quality were analyzed throughout 42 days of refrigerated storage at 2 °C. The results showed that non-packed artichokes exhibited rapid deterioration, with weight loss exceeding 45% and phenolic and chlorophyll content decreasing by over 50% and 78%, respectively, by the end of the storage period. In contrast, MAP drastically reduced quality deterioration, reduced weight loss to 2%, and preserved approximately 60% more phenolic compounds. The combined application of pre-cooling and MAP further enhanced preservation, reducing weight loss by an additional 25% compared to MAP alone and retaining nearly double the chlorophyll content. Thus, this treatment also ensured the highest preservation of phenolic compounds, with final values about 45% higher than MAP alone. Visual sensory assessment confirmed that both MAP and Pre-cooling + MAP maintained acceptable appearance and consumer-relevant quality parameters throughout storage. Overall, the results of this study indicate that MAP, particularly when combined with pre-cooling, effectively maintained the physical, biochemical, and sensory quality of whole 'Blanca de Tudela' artichokes over 42 days under cold storage conditions, demonstrating the potential of this integrated strategy to support postharvest preservation for long-distance export markets.

Keywords: *Cynara scolymus*; modified atmosphere packaging; forced-air; whole artichokes; Pearson's correlation; sensorial analysis; shelf-life

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Academic Editor: Isabel Lara

Received: 5 November 2025
Revised: 23 January 2026
Accepted: 26 January 2026
Published: 27 January 2026

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1. Introduction

The artichoke (*Cynara cardunculus* var. *scolymus* L.) is a perennial plant belonging to the *Asteraceae* family. It is widely cultivated in the Mediterranean region, where the warm

and arid climatic conditions favor its growth [1]. In addition to its historical role in regional diets, the crop has gained significant economic importance as an export commodity. This is due to updated international standards emphasizing quality attributes and postharvest handling requirements [2]. Italy is the main producer, Spain the main exporter and France the largest importer of fresh and canned artichokes [3]. In Spain, artichoke production predominantly relies on 'Blanca de Tudela' cultivar, which is protected under the Geographical Indication "Alcachofa de Tudela" and is considered the reference variety due to its early maturity, premium head quality, and strong market recognition [4–6]. Maintained through clonal propagation, this cultivar also serves as the primary planting material in other Mediterranean production areas. The economic significance and cultural value of this cultivar, combined with its distinctive bioactive composition, highlight the need for optimized postharvest strategies to maintain quality and extend shelf-life.

From a nutritional and functional perspective, artichoke is a valuable source of phenolic compounds, such as chlorogenic acid and cynarin [7]. These compounds are recognized for their antioxidant, anti-inflammatory, antimicrobial, and anticancer properties [8]. However, the stability of these bioactive compounds is influenced by multiple factors, including genotype, farming practices, and postharvest treatments [9]. Despite its nutritional and commercial value, the artichoke is highly perishable due to its high respiration rates, which make it susceptible to dehydration, enzymatic browning, and microbial deterioration [10]. Quality loss during storage manifests as texture degradation, weight loss, a reduction in bioactive compounds content, and color changes. In particular, the conversion of chlorophyll into pheophytin during degradation is a critical factor affecting visual quality, as it results in brownish hues that negatively impact consumer acceptability [11].

In recent years, the growing demand for artichokes in distant markets has made it necessary to develop more efficient preservation strategies to extend their shelf-life. Although various postharvest techniques have been investigated for minimally processed products, such as edible coatings, calcium chloride applications, and ozone treatments [12–14], fewer studies have focused on preserving whole artichokes. In this sense, precooling is a critical process for maintaining the postharvest quality of fresh vegetables. The rapid reduction in temperature after harvest minimizes metabolic activity and slows the degradation of bioactive compounds [15]. This technique is essential for reducing the respiration rate, preventing excessive water loss, and limiting microbial growth [16,17]. Additionally, modified atmosphere packaging (MAP) has proven to be an effective strategy for extending the shelf-life of artichokes. MAP involves altering the gaseous composition surrounding the product by reducing oxygen (O_2) levels and increasing carbon dioxide (CO_2) concentrations, thereby delaying physiological deterioration and preserving firmness and color [18]. However, the effectiveness of MAP depends on various factors, such as the specific atmospheric composition, the permeability of the packaging materials, and the characteristics of the treated product [10,19].

Still, most postharvest studies have focused on the effects of storage temperature and gas composition rather than on integrating temperature management and packaging strategies. Palma et al. [20] evaluated several commercial packaging systems for 'Spinoso Sardo' artichokes stored at 5 °C plus simulated marketing and reported that macro-perforated films that maintained high relative humidity and near-ambient O_2/CO_2 levels effectively preserved visual quality, phenolic content and antioxidant activity. The retention of these phenolic compounds is particularly important for the visual appearance of artichokes since their degradation triggers the browning process. This browning has been shown to be strongly negatively correlated with the overall acceptability of the artichokes, indicating that preserving phenolic content is key to maintaining both aesthetic and consumer-desired quality, as reported by Giménez-Berenguer et al. [21]. In parallel, Capotorto et al. [22,23]

showed that short-term high-CO_2 treatments (up to 24 h) applied prior to cold storage improved the quality of artichoke heads by reducing the respiration rate, limiting physiological disorders, and preserving the volatile profile of artichokes during subsequent storage at low temperatures.

The objective of film packaging is to preserve the quality and freshness of produce by establishing a modified atmosphere inside the package that results from the interaction between film permeability and product respiration, leading to stabilized levels of water vapor, O_2, and CO_2 that avoid the development of physiological disorders [20]. However, the literature reports contrasting outcomes regarding the effectiveness of MAP in artichokes. While several studies describe beneficial effects, such as reduced mass loss, maintenance of firmness, and delayed browning, others report only moderate or negligible advantages, highlighting the variability of responses among studies [18,24,25]. Although storage atmospheres in the range of 1–6% O_2 and 2–7% CO_2 have been proposed as reference optimal conditions for artichokes [22], the physiological response to these atmospheres is strongly cultivar-dependent and influenced by the characteristics of the packaging system used [26,27]. Certain cultivars, such as 'Madrigal', exhibit high sensitivity to CO_2, with concentrations as low as 3% promoting pappus development in the receptacle, while levels exceeding 10% induce browning of internal bracts and blackening of the internal core. Similarly, atmospheres with O_2 concentrations below 2%, may trigger fermentative metabolism and internal blackening [25,28]. Therefore, the effectiveness of MAP in artichokes should be interpreted as dependent on the specific atmosphere passively generated by the interaction between cultivar physiology and packaging properties, rather than on compliance with a single predefined optimal O_2/CO_2 formulation. Consequently, a MAP configuration that is suitable for one cultivar may not be directly transferable to others.

In other horticultural commodities, the combination of rapid precooling and modified or controlled atmospheres has been shown to markedly improve postharvest performance [16]. For instance, in apricot Dorostkar et al. [29] applied an active MAP pretreatment for 6 days using gas mixtures enriched in O_2 and CO_2, followed by storage at 2 °C for 28 days. This protocol reduced weight loss and softening, limited the development of physiological disorders, and almost doubled the commercial shelf-life, while maintaining higher contents of vitamin C, carotenoids and total phenolics that in control fruits. On the other hand, in fresh-cut broccoli, Dai et al. [30] rapidly cooled the product and stored it at 4 °C under MAP with 100% O_2, observing that this combination extended shelf-life by up to 15 days, preserving the green color, firmness and antioxidant compounds, and reducing microbial growth compared to open-air storage. These studies support the hypothesis that temperature management and atmosphere modification may interact synergistically to maintain quality.

However, despite the extensive use of precooling and MAP as individual technologies, information is still scarce regarding their combined effect on whole globe artichokes stored for extended periods under commercial-like cold conditions. To our knowledge, no study has evaluated the effect of combining forced-air precooling with microperforated MAP on 'Blanca de Tudela' artichokes stored at 2 °C for up to 42 days, integrating physiological (respiration and ethylene production), physicochemical (weight loss, firmness, color, phenolic content, antioxidant capacity) and sensory responses. This specific knowledge gap is addressed in the present work, which aims to determine whether combining forced-air precooling with microperforated MAP can effectively delay senescence and preserve the external and internal quality of whole artichokes compared with MAP alone and non-packed controls.

2. Materials and Methods

2.1. Experimental Design

Globe artichokes of the 'Blanca de Tudela' cultivar were grown in a commercial plot located in southern Alicante (Spain), an area characterized by a Mediterranean climate with mild, relatively humid winters and hot, dry summers. Crop management followed standard agronomic practices commonly adopted by growers in southeast Spain. Throughout the growing cycle, conventional fungicide and insecticide treatments were applied as required, and mineral fertilization was supplied via drip irrigation at rates of 250 kg N ha^{-1}, 120 kg P_2O_5 ha^{-1}, and 300 kg K_2O ha^{-1}. No gibberellic acid treatments were applied during the cultivation period. All artichokes were harvested on 6 May 2024 according to commercial standards. For the experiment, only secondary flower heads at an intermediate developmental stage were selected, harvested when heads had reached their typical marketable size and morphology, exhibited a firm texture, and showed tightly closed, compact bracts with no visible signs of opening or senescence. After harvest, the artichokes were transported to the postharvest laboratory of Miguel Hernández University (Orihuela, Spain) in less than half an hour, where the conservation trial was conducted on the same day. Prior to postharvest experiments, secondary heads at an intermediate developmental stage were visually graded to ensure uniformity in size and morphology and the absence of external defects. The harvested artichokes exhibited a mean fresh weight of 131.26 ± 3.22 g. The experiment included three groups of artichokes: (i) packaged in film (MAP), (ii) pre-cooled to 4 °C and then packaged in MAP film (Pre-cooling + MAP), (iii) unpackaged and stored at 2 °C and 85% relative humidity (Non-packed). In the non-packed group, artichokes were placed directly under cold storage into open food-grade boxes without any film packaging. In the MAP treatment, the artichokes were packed in 30 × 27 cm bags made of 35 µm thick, biaxially oriented polypropylene (BOPP) film, with gas permeabilities of 1100 mL O_2 m^{-2} d^{-1} atm^{-1} and 3600 mL CO_2 m^{-2} d^{-1} atm^{-1}. The film featured two lines of micro perforations, enabling a passive modified atmosphere to be established inside the package. The perforations had a diameter of 80 µm and a density of 335 holes m^{-2}. Each bag contained four artichokes, with a total product mass ranging from 512.16 to 537.98 g, yielding a headspace volume of ≈10%. Bags were sealed using a manual heat sealer (Audion Sealmaster Magenta, Audion Packaging Machines, Weesp, The Netherlands) and no gas flushing was applied. Lastly, in the Pre-cooling + MAP treatment, artichokes underwent a pre-cooling process prior to packaging. At harvest, the internal temperature of the artichokes was approximately 18 °C, while the storage chamber was set at 2 °C, resulting in a temperature differential of 16 °C. Based on the 7/8 pre-cooling rule, the target internal temperature after pre-cooling was established at 4 °C [31,32]. Pre-cooling was carried out using a forced-air system. Internal temperature was monitored using four calibrated temperature probes, which were inserted into the central receptacle tissue of four representative artichoke heads. These heads were strategically positioned at different locations within the forced-air system (air inlet, air outlet, and intermediate positions) to account for spatial variability in airflow and cooling efficiency. Temperature data were continuously recorded using data loggers to generate cooling curves and determine the time required to reach the target temperature. Pre-cooling was considered complete when all monitored artichokes reached an internal temperature of 4 °C, indicating uniform cooling across the system. Under these conditions, the target temperature was achieved within 30 min, with minimal variability among monitored heads (±0.5 °C). Immediately after pre-cooling, artichokes were packaged in MAP bags and transferred to cold storage.

For each treatment, three bags of four artichokes each were prepared for each sampling day. All samples were stored at 2 °C and 85% of relative humidity (RH). On each sampling day (14, 28, and 42 days) and for each packaging condition, three bags were

analyzed. Additionally, a single set of 12 artichokes was evaluated on day 0 to determine the initial quality parameters of the freshly harvested artichokes upon arrival from the field. Respiration rate, weight loss, and firmness were analyzed. Furthermore, bract samples from each artichoke were collected and frozen for subsequent analysis of total phenolic and chlorophyll content.

2.2. Dry Matter Determination

A portion of the outer and intermediate bracts from each artichoke head was reserved for dry matter determination and subsequent recalculation of biochemical parameters on a dry weight basis. For each treatment and sampling date, the dry matter content of individual artichoke bracts was determined by oven-drying subsamples at 65 °C (JP Selecta, Barcelona, Spain) until constant weight was reached according to Giménez-Berenguer et al. [33]. Dry weight basis determination was used to express total phenolic content and chlorophyll concentrations, minimizing variability associated with changes in tissue hydration and allowed for a more reliable comparison among treatments and storage times.

2.3. Internal Package Atmosphere (O_2 and CO_2) and Respiration Rate of Artichokes

The gas composition inside the packages was analyzed daily during the first four days of storage (a total of nine bags were evaluated, with duplicate measurements per bag) and subsequently on each sampling day, when three bags per treatment were analyzed in duplicate. For gas sampling, the packaging film was carefully punctured using a hypodermic needle, and a 1 mL gas sample was withdrawn from the internal atmosphere of each bag. During the first four days of storage, when repeated measurements were performed on the same packages, the puncture site was immediately and carefully sealed with silicone after each sampling in order to maintain package integrity and prevent gas leakage, allowing the same bags to be monitored over time. This sealing procedure ensured the preservation of the modified atmosphere conditions until the next sampling point. For the subsequent sampling days, gas samples were extracted immediately prior to opening the packages for the remaining physicochemical and quality analyses, and therefore no resealing was required at these stages. The concentrations of O_2 and CO_2 were quantified using gas chromatography (Shimadzu 14B-GC, Kyoto, Japan) equipped with a thermal conductivity detector (TCD), following the methodology described by Giménez et al. [34]. Duplicate measurements were performed per bag. Results were expressed as the percentage of O_2 and CO_2 inside the packaging and presented as the mean ± standard error (SE) of nine replicate bags for the initial period (days 0–4) and three replicate bags for the subsequent sampling days for each treatment.

The respiration rate was assessed at harvest (D0) and on each sampling day immediately after the packaging has been opened. Three replicates of four artichokes were placed in rigid plastic jars (3.7 L) equipped with an airtight cap with a rubber septum attached, ensuring hermetic sealing. The jars were tightly closed and kept sealed for 60 min at ambient temperature. After this incubation period, a 1 mL gas sample was withdrawn from the internal atmosphere through the septum using a syringe, avoiding any disturbance of the internal atmosphere. The CO_2 concentration was quantified using gas chromatography (Shimadzu 14B-GC, Kyoto, Japan) with a TCD according to the methodology described by Giménez-Berenguer et al. [35]. The respiration rate was expressed as mg CO_2 kg^{-1} h^{-1}. Duplicate measurements were performed per jar, and results were expressed as the mean ± SE of three replicate bags for each treatment.

2.4. Weight Loss

The weight of each artichoke was recorded individually using a Radwag WLC 2/A2 precision balance (Radwag Wagi Elektroniczne, Radom, Poland) which had a readability of

two decimal places. The artichokes were weighed on day 0 and on each subsequent sampling day. Weight loss was expressed as a percentage, and the results were the mean ± SE of 12 artichokes from the three replica bags.

2.5. Firmness Measurement

Firmness was evaluated for each artichoke individually using a TX-XT2i texture analyzer (Stable Micro Systems, Godalming, UK), which was connected to a computer. The diameter of each artichoke was measured, and a compressive force was applied until a 5% deformation was achieved using a steel compression plate [34]. Firmness was always measured at the equatorial section of the artichoke head. Firmness was expressed as the force/deformation ratio (N mm^{-1}) and reported as the mean ± SE of 12 artichokes from the three replica bags.

2.6. Total Phenolic Content Determination

Phenolic compounds were extracted using the method described by Giménez-Berenguer et al. [35], with slight modifications. In brief, 2 g of artichoke bracts were homogenized in 15 mL of 80% methanol containing 2 mM sodium fluoride (NaF) to inhibit polyphenol oxidase activity and prevent phenolic degradation. Homogenization was performed for 1 min using an Ultra-Turrax® TP 18 homogenizer (IKA, Staufen, Germany) at 12,000 rpm. The samples were then centrifuged at 10,000 rpm for 12 min at 4 °C. The supernatant was used to quantify the total phenolic compounds in duplicate using the Folin–Ciocalteu reagent (Sigma-Aldrich, St. Louis, MO, USA). The absorbance was then measured at 760 nm using a UV spectrophotometer (UV1700 Pharmaspec, Shimadzu, Kyoto, Japan).

The results were analyzed in duplicate and are presented as the mean of 12 artichokes ± SE, obtained from three replicate bags and expressed as grams of gallic acid equivalents per kilogram of dry weight (g GAE kg^{-1} DW).

2.7. Total Chlorophyll Content Determination

Chlorophyll extraction and quantification were performed according to the protocol described by Nizar et al. [36], with minor modifications. 2 g sample of artichoke bracts were homogenized in 15 mL of 80% acetone using an Ultra-Turrax homogenizer at 12,000 rpm for 1 min to ensure efficient cell disruption. The homogenized samples were then centrifuged at 10,000 rpm for 12 min at 4 °C to remove solid residues. Chlorophyll a and b were quantified using a spectrophotometer (UV1700 Pharmaspec, Shimadzu, Kyoto, Japan) with absorbance measured at 647 nm and 664 nm, respectively. Total chlorophyll content was calculated as the sum of the concentrations of chlorophyll a and b and expressed as g kg^{-1} DW. The results were presented as the mean ± SE of 12 artichokes from the three replica bags.

2.8. Photographic Documentation of Artichokes During Storage

To document the external appearance of the artichokes throughout the storage period, digital images were taken using a Nikon D3400 camera (Minato, Tokyo, Japan) placed inside a light box with a uniform white background. Illumination was provided by two LED light sources with a color temperature of 5600 K. The camera was set to ISO 100, shutter speed 1/5 s, focal length 35 mm, and aperture f/20. Photographs were taken at harvest (day 0) and after 14, 28 and 42 days of refrigerated storage in order to visually monitor changes in external quality over time and to generate a standardized photographic compendium for subsequent visual assessment.

2.9. Visual Sensory Quality Evolution

Visual sensory analysis was conducted on the basis of the photographic compendium obtained during storage. The assessment was carried out by a trained panel from the Department of Agri-Food Technology of Miguel Hernández University (Orihuela, Alicante, Spain), following the general methodology described by M. Giménez et al. and M. J. Giménez et al. [6,37], adapted to image-based evaluation.

The panel consisted of 12 trained judges (6 males and 6 females) with previous experience in sensory analysis. For each treatment and storage time, the corresponding photographic images were independently evaluated using a structured 0–5 scale, where 5 represented optimal appearance and 0 indicated severe deterioration. The visual attributes related to external quality assessed were color, browning, bract opening, dehydration, freshness and overall acceptability, as defined in Table 1. For each treatment and storage day, twelve artichoke images (with two views per artichoke) were evaluated individually.

Table 1. Description of visual sensory attributes evaluated.

Attribute	Description
Color	Visual appearance of the green surface of the outer bracts. High scores indicate an intense and uniform green color; low scores reflect discoloration.
External browning	Presence and severity of brown or dark spots on the external bracts. High scores correspond to no browning; low scores indicate visible damage or oxidation and greater severity.
Bract Opening	Degree of bract separation of external bracts. Maximum scores indicate fully closed bracts; decreasing values represent progressive opening or spreading.
Dehydration	Visual appearance of surface dryness and tissue shrinkage of the external bracts. High scores indicate turgid, well-hydrated tissues; low scores reflect evident dehydration and loss of turgidity.
Freshness	Overall visual perception of product freshness. High scores correspond to freshly harvested appearance; low scores indicate senescence or severe quality loss.
Overall Acceptability	Global visual assessment of the artichoke considering all evaluated attributes. High scores indicate full commercial acceptability; low scores represent rejection due to poor visual quality.

All evaluations were performed under standardized lighting conditions comparable to those used during photographic acquisition, ensuring consistency and minimizing visual bias. A score equal to or lower than 3 for any of the evaluated attributes was considered the limit of commercial acceptability and was used to define the end of shelf-life for each treatment and storage time. Final values for each attribute, treatment and day of storage were expressed as the mean of all panelists' evaluations ± SE.

2.10. Statistical Analysis

Statistical analyses were performed using SPSS v. 20 for Windows (IBM Corporation, Armonk, NY, USA). Mean comparisons were performed using Duncan's multiple-range test to detect significant differences among treatments and storage days for each parameter. Differences were considered significant at $p \leq 0.05$.

Pearson's correlation analysis was additionally conducted as an exploratory tool to examine relationships among postharvest quality parameters of artichoke samples under different storage conditions (MAP, Pre-cooling + MAP, and Non-packed). These correlations

were interpreted descriptively and not as evidence of causality or as a basis for analytical inference, but rather to support and contextualize the experimental results.

3. Results

3.1. Physicochemical and Functional Parameters of Non-Packed Artichokes During 42 Days of Storage

The physicochemical parameters (respiration rate, weight loss and firmness) and functional parameters (total phenols and total chlorophylls) of the non-packed artichokes were analyzed at harvest (day 0) and during 42 days of storage at 2 °C (Table 2). The respiration rate value at harvest was 255.25 ± 6.86 mg CO_2 kg^{-1} h^{-1}. The respiration rate decreased during the first 14 days of refrigerated storage (85.16 ± 3.43 mg CO_2 kg^{-1} h^{-1}). However, after 28 days of storage, the respiration rate increased to 143.17 ± 7.17 mg CO_2 kg^{-1} h^{-1} reflecting a decline in artichoke quality over storage time.

Table 2. Respiration rate (mg CO_2 kg^{-1} h^{-1}), weight loss (%), firmness (N mm^{-1}), total phenols (g gallic acid equivalents (GAE) kg^{-1} DW) and total chlorophylls (g kg^{-1} DW) of non-packed artichokes at day 0, 14, 28 and 42 days of storage at 2 °C.

Days	Respiration Rate	Weight Loss	Firmness	Total Phenols	Total Chlorophylls
0	255.25 ± 6.86 c	-	10.10 ± 0.34 c	7.03 ± 0.67 b	3.64 ± 0.10 c
14	85.16 ± 3.43 a	17.82 ± 0.78 a	2.21 ± 0.17 b	6.69 ± 0.43 b	2.94 ± 0.24 b
28	143.17 ± 7.17 b	30.06 ± 0.85 b	1.84 ± 0.20 ab	4.16 ± 0.12 a	0.84 ± 0.08 a
42	-	46.94 ± 1.76 c	1.52 ± 0.17 a	3.30 ± 0.25 a	0.80 ± 0.12 a

Data are the mean ± SE. Different letters show significant differences on the evaluated parameters among different days of storage at 2 °C, according to Duncan's multiple range test at $p < 0.05$.

Regarding weight loss, after 14 days of storage, the non-packed artichokes had lost 18% of their weight, showing noticeable signs of dehydration. Although the product may no longer be marketable, it was kept under refrigerated conditions for up to 42 days alongside the treated samples in order to evaluate the evolution of the analyzed quality parameters. The weight loss increased to 46.94 ± 1.76% after 42 days of refrigerated storage.

At harvest time, the firmness value was 10.10 ± 0.34 N mm^{-1}, decreasing to 2.21 ± 0.17 after 14 days and to 1.52 ± 0.17 N mm^{-1} at the end of the experiment (42 days). With respect to total phenols, the results showed values of 7.03 ± 0.67 g GAE kg^{-1} DW at harvest time. Values decreased throughout the storage period, reaching 3.30 ± 0.25 g GAE kg^{-1} DW after 42 days. Finally, total chlorophylls content was 3.64 ± 0.10 g kg^{-1} DW on the day of harvest, showing a reduction from day 14 (3.32 ± 0.28 g kg^{-1} DW) to day 42 (0.80 ± 0.12 g kg^{-1} DW).

3.2. Effect of MAP Strategy and Pre-Cooling on the Physicochemical Parameters and Postharvest Quality of Artichoke

3.2.1. Composition of the Internal Atmosphere Within the Packaging

The oxygen and carbon dioxide concentrations inside the packaging films were assessed on days 2, 3, and 4 and on days 14, 28, and 42 of storage (Figure 1). A sharp decrease in oxygen concentration together with a rapid increase in carbon dioxide levels was observed during the first days of storage in both treatments, reflecting the high respiration rate of the artichokes. Measurements during days 2–4 indicated that the internal atmosphere stabilized early in the storage period, reaching a relatively steady state by day 3, with only gradual changes occurring thereafter.

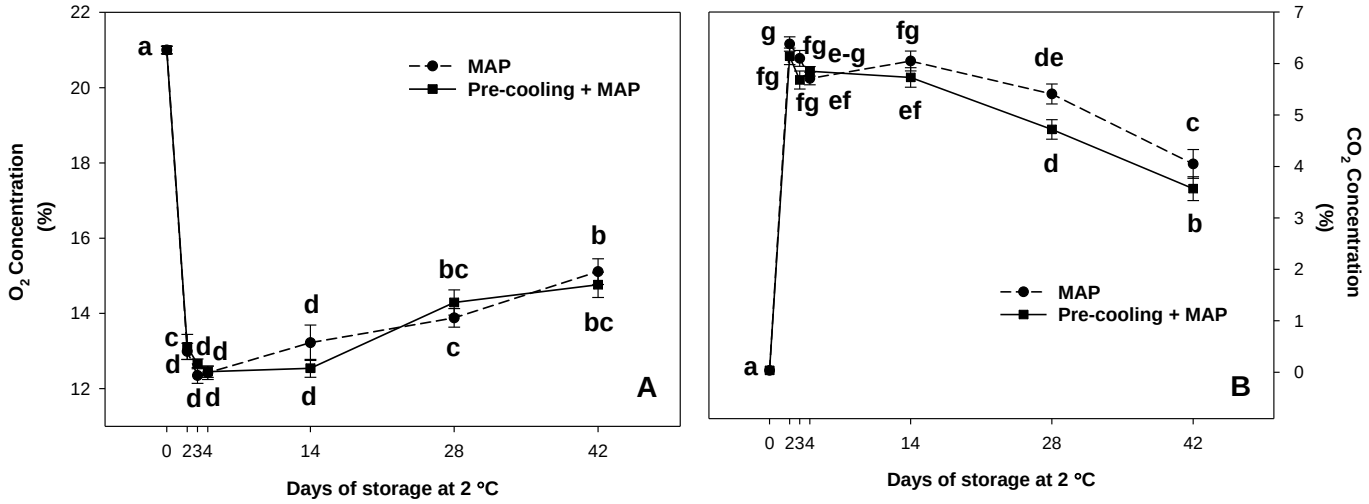


Figure 1. Evolution of the concentration of (**A**) O_2 (%) and (**B**) CO_2 (%) inside the artichokes packaged under MAP and Pre-cooling + MAP conditions at harvest and during 42 days of refrigerated storage at 2 °C. Data are expressed as mean ± SE. Different lowercase letters indicate significant differences among treatments and days of storage at 2 °C, according to Duncan's multiple range test at $p < 0.05$.

Regarding oxygen concentration (Figure 1A), significant ($p < 0.05$) differences were detected throughout storage time. After the initial decrease, oxygen levels showed a gradual increase during refrigerated storage. Differences between MAP and Pre-cooling + MAP treatments were observed at specific sampling times, particularly at intermediate and late storage stages, with slightly higher oxygen concentrations generally recorded in the MAP treatment.

With respect to carbon dioxide concentration (Figure 1B), a rapid accumulation was detected during the first days of storage, followed by a progressive decrease over time. Significant ($p < 0.05$) differences were observed both among storage days and between treatments. From day 14 onwards, the MAP treatment consistently showed higher CO_2 concentrations compared to Pre-cooling + MAP, with these differences becoming more pronounced at days 28 and 42 of storage.

3.2.2. Respiration Rate

The respiration rate of artichokes packaged under MAP and Pre-cooling + MAP conditions was monitored during refrigerated storage (Figure 2). At harvest, artichokes showed a high respiration rate (255.25 ± 6.86 mg CO_2 kg^{-1} h^{-1}); however, a significant ($p < 0.05$) reduction in respiration rate was observed during storage in both treatments, with marked differences among storage times. On day 14, respiration rates significantly decreased compared to harvest, with Pre-cooling + MAP samples showing higher values than MAP. At day 28, a further reduction was detected, particularly in the Pre-cooling + MAP treatment, which exhibited the lowest respiration rate during the entire storage period (134.16 ± 19.29 mg CO_2 kg^{-1} h^{-1}), significantly lower than that observed in MAP samples (182.25 ± 2.64 mg CO_2 kg^{-1} h^{-1}).

By day 42, respiration rates increased again in both treatments, although significant differences between treatments were still detected, with MAP samples showing higher values than Pre-cooling + MAP.

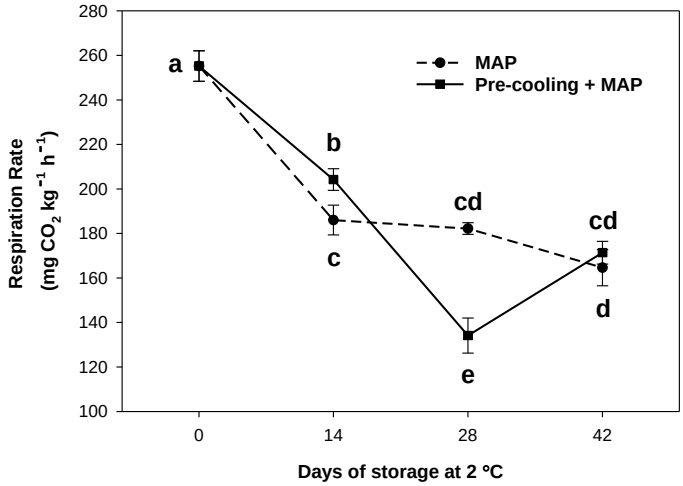


Figure 2. Evolution of the respiration rate (mg CO_2 kg^{-1} h^{-1}) of artichokes packaged under MAP and Pre-cooling + MAP conditions at harvest and during 42 days of refrigerated storage at 2 °C. Data are expressed as mean ± SE. Different letters indicate significant differences among treatments and storage days at 2 °C according to Duncan's multiple range test at $p < 0.05$.

3.2.3. Weight Losses

Weight loss of artichokes packaged under MAP and Pre-cooling + MAP conditions increased progressively during refrigerated storage (Figure 3) and significant ($p < 0.05$) differences were observed among storage times and between treatments.

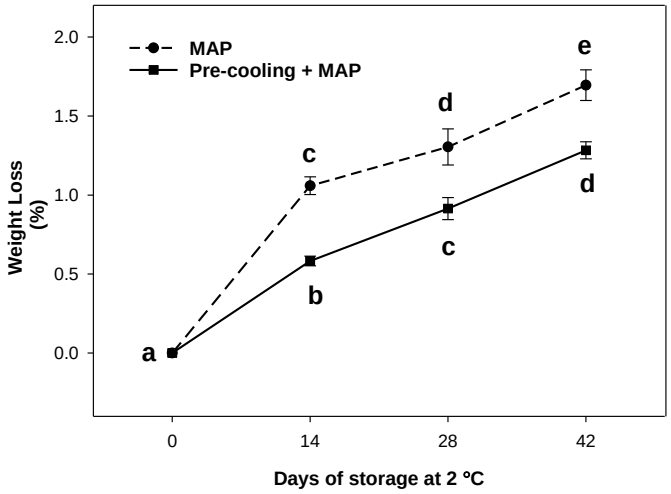


Figure 3. Weight loss (%) of artichokes packed under MAP and Pre-cooling + MAP conditions at harvest and during 42 days of refrigerated storage at 2 °C. Data are expressed as mean ± SE. Different letters indicate significant differences among treatments and days of storage at 2 °C, according to Duncan's multiple range test at $p < 0.05$.

Artichokes packaged under MAP showed a higher weight loss than those subjected to Pre-cooling + MAP at all sampling times. On day 14, MAP samples reached a weight loss of 1.06 ± 0.06%, whereas Pre-cooling + MAP samples showed significantly lower values (0.58 ± 0.03%). This increasing trend continued throughout storage. On day 28, weight loss further increased in both treatments, with MAP samples showing higher values than Pre-cooling + MAP. After 42 days of storage, weight loss remained below 2% in both treatments, reaching 1.70 ± 0.10% in MAP samples and 1.28 ± 0.05% in Pre-cooling + MAP samples, with these differences being statistically significant.

3.2.4. Firmness Evolution During Storage

No significant differences in firmness values were observed between the MAP and Pre-cooling + MAP treatments throughout the storage period (Figure 4). At harvest (day 0), artichokes exhibited an initial firmness of 10.10 ± 0.34 N mm^{-1}. As storage progressed, firmness values remained relatively stable during the first stages of storage, with slight fluctuations observed thereafter.

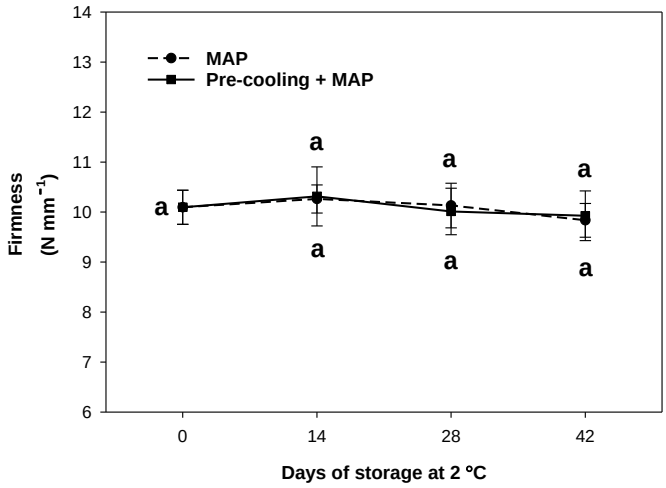


Figure 4. Evolution of firmness (N mm^{-1}) of artichokes packaged under MAP and Pre-cooling + MAP conditions at harvest and during 42 days of refrigerated storage at 2 °C. Data are expressed as mean ± SE. Different letters indicate significant differences among treatments and days of storage at 2 °C, according to Duncan's multiple range test at $p < 0.05$.

In the MAP treatment, firmness values were 10.26 ± 0.28 N mm^{-1}, 10.13 ± 0.45 N mm^{-1}, and 9.83 ± 0.34 N mm^{-1} at 14, 28, and 42 days, respectively. Similarly, the Pre-cooling + MAP treatment showed firmness values of 10.31 ± 0.59 N mm^{-1} at day 14, 10.01 ± 0.47 N mm^{-1} at day 28, and 9.93 ± 0.50 N mm^{-1} at day 42.

Overall, both treatments exhibited comparable trends, with no statistically significant differences between MAP and Pre-cooling + MAP at any sampling time.

3.2.5. Changes in Total Phenolic Content During Storage

The total phenolic content of artichokes at harvest was 7.03 ± 0.67 g GAE kg^{-1} DW (Figure 5). During storage, significant ($p < 0.05$) changes in total phenolic content were observed depending on storage time and treatment. In both MAP and Pre-cooling + MAP treatments, phenolic content increased during the first 14 days of storage, reaching values of 10.08 ± 0.26 and 13.86 ± 0.95 g GAE kg^{-1} DW, respectively. At this sampling time, Pre-cooling + MAP samples showed significantly higher phenolic content than MAP samples.

After day 14, a significant decrease in total phenolic content was recorded in both treatments. On day 28, phenolic levels declined but remained higher in Pre-cooling + MAP samples compared to MAP. By the end of storage (day 42), total phenolic content further decreased in both treatments, reaching values of 5.40 ± 0.48 g GAE kg^{-1} DW in MAP samples and 7.88 ± 0.55 g GAE kg^{-1} DW in Pre-cooling + MAP samples, with statistically significant differences between treatments. Overall, Pre-cooling + MAP samples maintained higher total phenolic content than MAP samples throughout storage, and notably, phenolic levels in Pre-cooling + MAP remained higher than those recorded at harvest at the end of storage, whereas MAP samples showed lower values than at day 0.

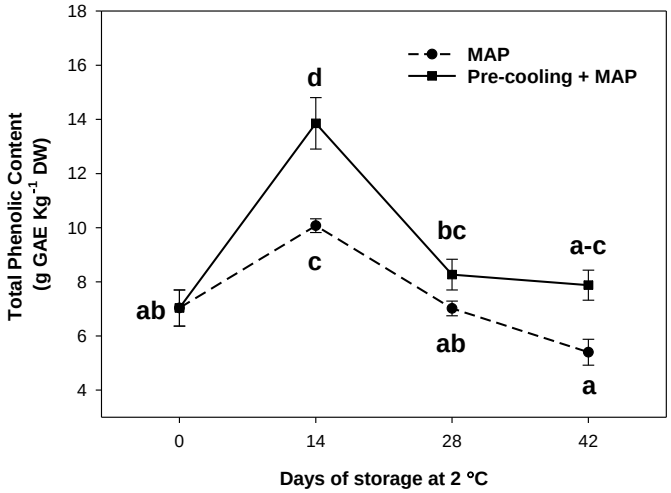


Figure 5. Evolution of total phenolic content (g GAE Kg^{-1} DW) of artichokes packaged under MAP and Pre-cooling + MAP conditions at harvest and during 42 days of refrigerated storage at 2 °C. Data are expressed as mean ± SE. Different letters indicate significant differences among treatments and days of storage at 2 °C, according to Duncan's multiple range test at $p < 0.05$.

3.2.6. Evolution of Chlorophyll Content During Cold Storage

At harvest, the total chlorophyll content in artichokes was 3.64 ± 0.10 g kg^{-1} and during refrigerated storage, this parameter exhibited significant ($p < 0.05$) changes as a function of both storage time and treatment (Figure 6). After 14 days of storage, chlorophyll content remained relatively stable in both treatments, although Pre-cooling + MAP samples showed significantly higher values (3.89 ± 0.10 g kg^{-1} DW) than MAP samples (3.52 ± 0.12 g kg^{-1} DW). After this period, a significant decrease in total chlorophyll content was observed in both treatments. On day 28, chlorophyll levels declined further, with Pre-cooling + MAP samples maintaining significantly higher values than MAP samples. By the end of storage (day 42), a pronounced reduction in total chlorophyll content was recorded in both treatments, reaching values of 1.32 ± 0.26 g kg^{-1} DW in MAP samples and 2.51 ± 0.13 g kg^{-1} DW in Pre-cooling + MAP samples, with statistically significant differences between treatments. Overall, Pre-cooling + MAP samples maintained higher total chlorophyll content than MAP samples throughout storage.

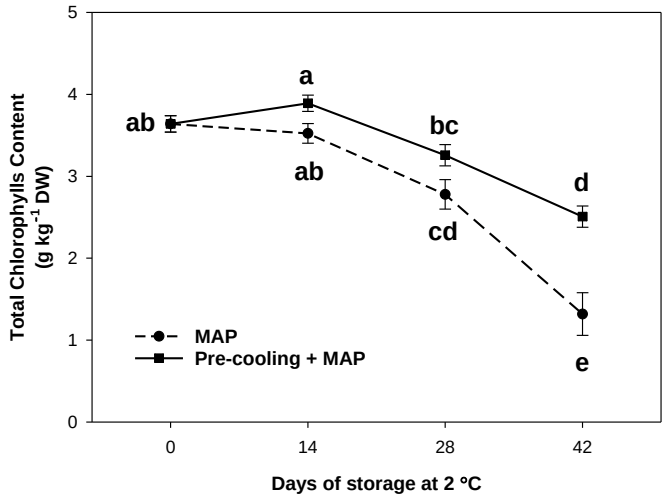


Figure 6. Evolution of total chlorophyll content (g kg^{-1} DW) of artichokes packaged under MAP and Pre-cooling + MAP conditions at harvest and during 42 days of refrigerated storage at 2 °C. Data are expressed as mean ± SE. Different letters indicate significant differences among treatments and days of storage at 2 °C, according to Duncan's multiple range test at $p < 0.05$.

3.3. External Visual and Sensory Quality Evolution

The evolution of the external visual quality of whole 'Blanca de Tudela' artichokes stored at 2 °C under the different postharvest treatments is presented in Figure 7. These radar plots provide an integrated overview of the main visual quality attributes (color, external browning, bract opening, dehydration, freshness and overall acceptability) and clearly illustrate the different rates of quality degradation among treatments during storage.

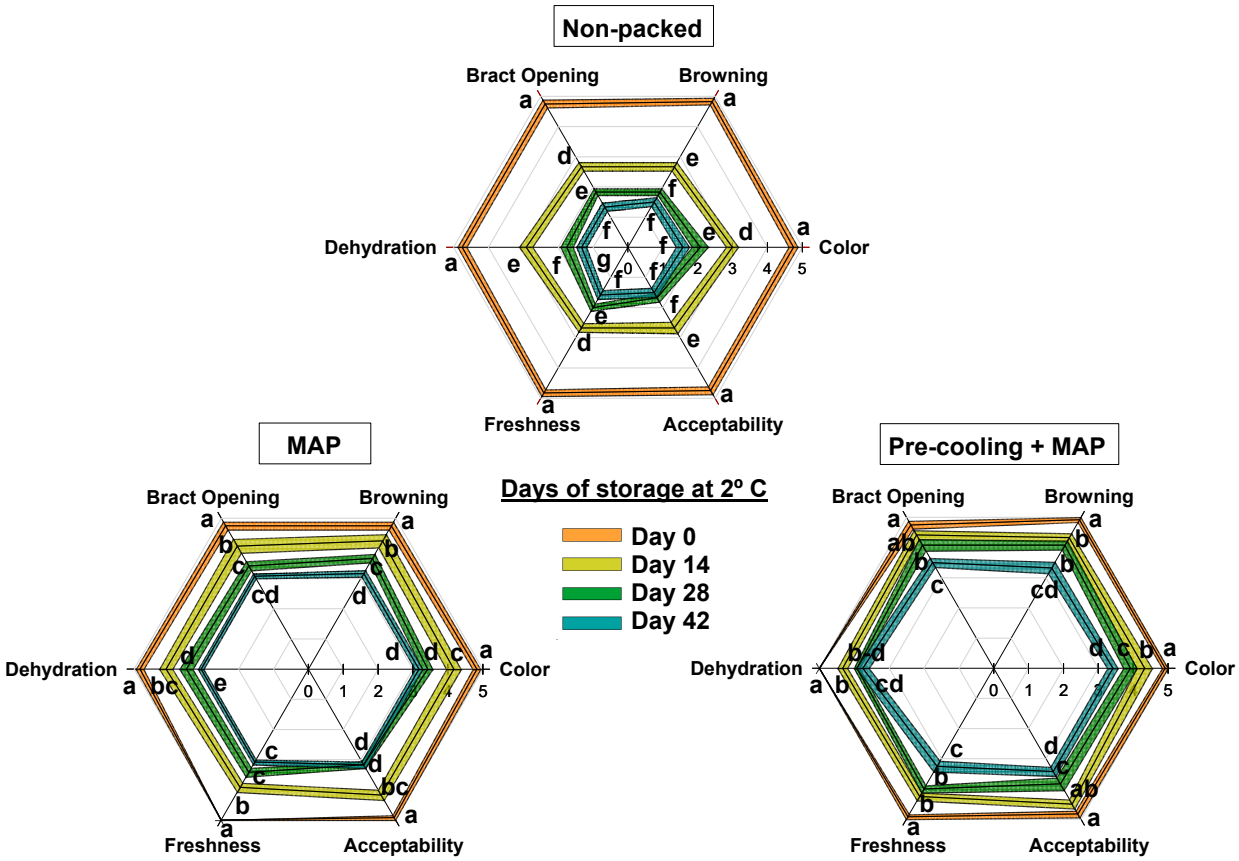


Figure 7. Evolution of the sensorial quality attributes (Color, External Browning, Bract Opening, Dehydration, Freshness and Overall Acceptability) of Non-packed artichokes and artichokes packaged under MAP and Pre-cooling + MAP conditions at harvest and during 42 days of refrigerated storage at 2 °C. Each point represents the mean score (0–5 scale) ± SE for each attribute. Different letters indicate significant differences among treatments and days of storage at 2 °C for each quality attribute, respectively, according to Duncan's multiple range test at $p < 0.05$.

At harvest (day 0), all artichokes exhibited very high sensory scores, ranging from 4.7 to 5.0 for all evaluated attributes, with no relevant differences among treatments. As storage progressed, marked differences became evident. Non-packed artichokes showed a rapid and pronounced decline in all visual attributes, particularly color, freshness and overall acceptability, from day 14 onwards. By day 28, none of the non-packed samples reached a score above 3 for overall acceptability, which in this study was defined as the minimum threshold for general commercial acceptance. This indicates a clear loss of marketability at this stage.

In contrast, artichokes stored under MAP exhibited a significantly slower deterioration. Although moderate reductions in color and freshness were observed from day 28 onwards, MAP samples maintained overall acceptability scores above the acceptability threshold throughout the entire storage period, including at day 42. However, the combined Pre-cooling + MAP treatment showed the best performance, consistently presenting the highest

scores for all visual attributes during storage. Even after 42 days at 2 °C, Pre-cooling + MAP samples maintained overall acceptability values above 3.4, evidencing a strong preservation of external quality.

The photographic documentation shown in Figure 8 corroborates the sensory results obtained from the radar charts. Non-packed artichokes displayed evident visual deterioration from day 14 onwards, characterized by intense browning, dehydration symptoms and loss of bract integrity, which became particularly severe by day 28. Conversely, MAP-treated artichokes retained a visually acceptable appearance for a longer period, while those subjected to Pre-cooling + MAP preserved the best external quality throughout storage, with limited browning, reduced dehydration and structurally intact bracts even at the end of the 42-day storage period.



Figure 8. Evolution of the visual appearance of artichokes subjected to three different treatments: non-packed artichokes, packaged in MAP and Pre-cooling + MAP, during storage at 2 °C.

Overall, both the results consistently demonstrate that the application of MAP, and especially its combination with pre-cooling, was effective in maintaining the external visual quality and commercial acceptability of artichokes during prolonged refrigerated storage, whereas non-packed artichokes rapidly fell below acceptable quality limits.

3.4. Exploratory Correlation Coefficients Analysis Among Postharvest Quality Parameters

The Pearson correlation coefficients (r) among postharvest quality parameters of artichoke samples under different storage strategies (Non-packed, MAP, and Pre-cooling + MAP) are presented in Figure 9. Due to the limited number of sampling points, these correlations should be interpreted as exploratory indicators rather than definitive physiological relationships. Perfect or near-perfect correlations ($r = \pm 1.00$) observed in some cases primarily reflect the small sample size and the sequential nature of the time points and should not be overinterpreted.

Despite this limitation, the correlation patterns provide insight into general trends. Overall, storage duration showed negative relationships with total phenolic content, total chlorophylls, firmness, and respiration rate, which may indicate a general tendency toward a decline in biochemical attributes, pigment levels, and metabolic activity as storage progressed. Conversely, weight loss exhibited a strong positive correlation with storage time

across all treatments, which could suggest its usefulness as a key indicator of progressive deterioration during cold storage.

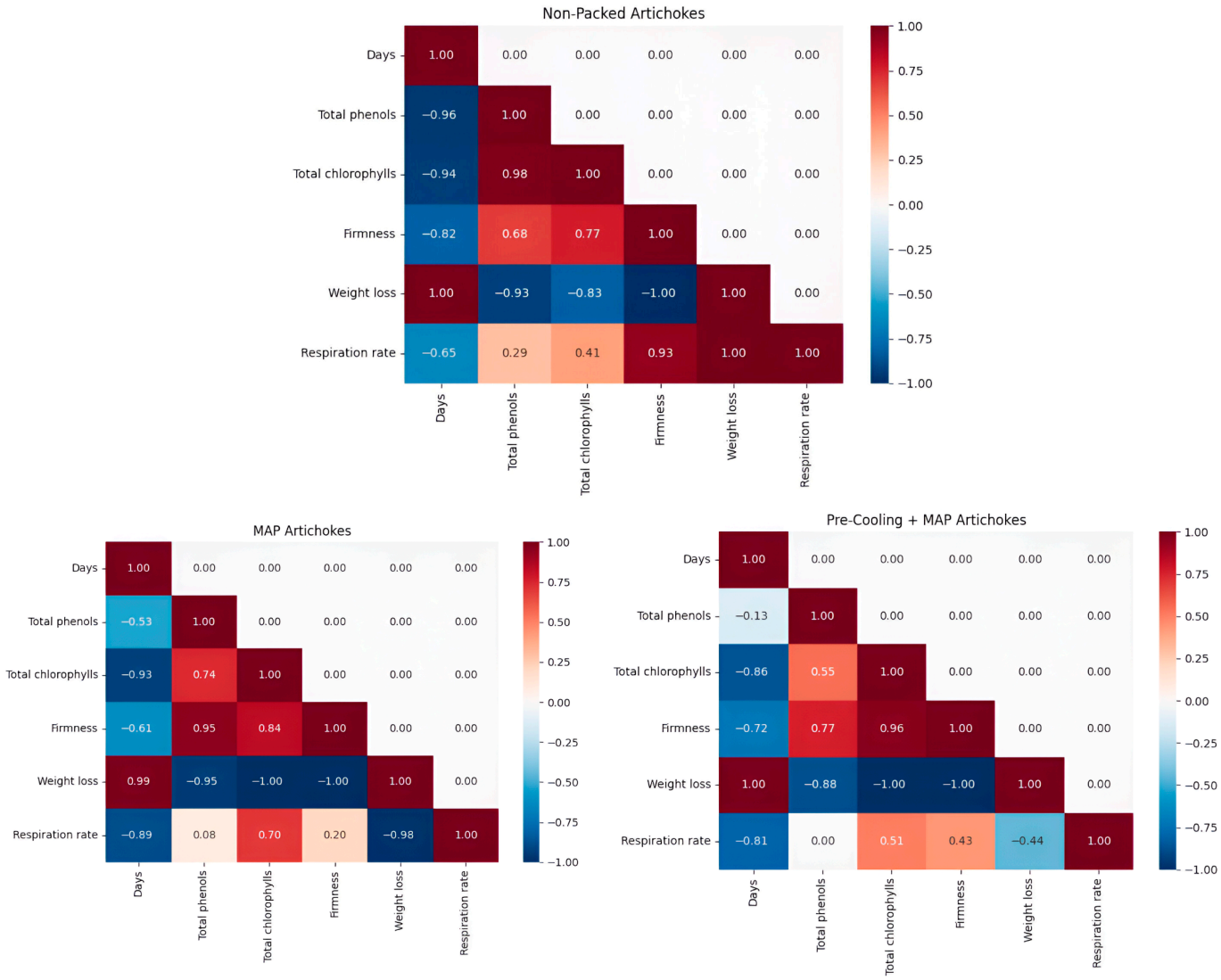


Figure 9. Heatmaps showing exploratory Pearson correlation coefficients among postharvest quality parameters of artichoke samples under three storage conditions: Non-Packed, MAP, and Pre-Cooling + MAP. Variables included are storage duration (Days), total phenolic content, total chlorophyll content, firmness, weight loss, and respiration rate. Color intensity indicates the strength and direction of the correlations (red: positive; blue: negative), and the numerical values in each cell represent the Pearson correlation coefficients (r).

When comparing treatments, differences in the strength of the correlations were observed. In non-packed artichokes, storage time showed negative associations with total phenolic content (r = −0.96), total chlorophylls (r = −0.94), and firmness (r = −0.82), and a strong positive association with weight loss (r = 1.00), consistent with the expected deterioration of quality during cold storage. These associations may suggest that, in the absence of protective packaging, deterioration-related processes progressed more rapidly and were closely interrelated. Respiration rate also showed positive associations with firmness (r = 0.93) and weight loss (r = 1.00), which could indicate that metabolic activity was closely associated with tissue softening and moisture loss, potentially contributing to accelerated senescence. In addition, total phenolic content and chlorophylls were strongly

correlated (r = 0.98), suggesting that their degradation may have occurred concurrently, which could be linked to faster browning and visual deterioration.

Under MAP storage, these relationships were generally weaker, which may reflect the protective role of the modified atmosphere. In this condition, storage time exhibited a moderate negative correlation with phenolic content (r = −0.53) and firmness (r = −0.61). The reduced strength of these associations could suggest that MAP delayed biochemical and structural degradation processes. Respiration rate showed a stronger correlation with storage duration (r = −0.89) than in non-packed artichokes, which may indicate that MAP contributed to a reduction in respiratory activity and a slowdown of biochemical senescence. Firmness and total phenolic content maintained a strong positive correlation (r = 0.95), suggesting that tissue integrity may be associated with the retention of bioactive compounds under MAP conditions, while chlorophyll content and firmness also displayed moderate to strong positive correlations (r = 0.84).

In the Pre-cooling + MAP treatment, overall correlations were weaker, consistent with the protective effect of combining pre-cooling with modified atmosphere. Storage time showed minimal correlation with phenolic content (r = −0.13), whereas respiration rate remained negatively correlated with storage progression (r = −0.81), indicating that the combined treatment effectively limited metabolic activity and preserved overall quality. Within this treatment, moderate positive correlations were observed between respiration rate and chlorophyll content (r = 0.51) and firmness (r = 0.43), while moderate negative correlations were noted with weight loss (r = −0.44). Strong positive associations between chlorophyll content and firmness (r = 0.96), together with perfect negative correlations with weight loss (r = −1.00), may highlight the link between tissue hydration and preservation of visual and structural quality.

All correlations are exploratory and should not be interpreted as causal. Nevertheless, the observed patterns align with expected postharvest behavior, suggesting that MAP and specially Pre-cooling + MAP treatments may contribute to mitigating quality loss by maintaining tissue integrity, slowing water loss, and preserving metabolic balance.

4. Discussion

The postharvest behavior of globe artichoke is governed by the interaction between metabolic activity, water balance, and biochemical stability, all of which may directly determine visual, textural, and nutritional quality. The present study integrates these dynamics using a treatment-oriented approach, highlighting how MAP, and particularly its combination with pre-cooling, could modulate these mechanisms during prolonged cold storage.

The use of polypropylene packaging in MAP and Pre-cooling + MAP treatments may play a decisive role in stabilizing the internal atmosphere and limiting metabolic acceleration. In the present study, early stabilization of gas composition by day 3 (Figure 1) suggests that both packaging strategies could rapidly reach a quasi-equilibrium state, as a result of the interaction between film permeability and product respiration. This dynamic equilibrium, rather than strict compliance with target O_2 and CO_2 concentrations, appears to be critical for mitigating respiratory stress during the initial postharvest phase. Accordingly, the mechanistic interpretation of MAP effectiveness in the present study should be framed in terms of packaging-driven atmospheric regulation tailored to cultivar physiology, instead of assessment with universal optimal storage ranges. This interpretation is consistent with previous reports indicating that polypropylene packaging, due to its lower permeability to O_2 and CO_2 compared with other common materials such as polyvinyl chloride or polyethylene, can effectively maintain a modified internal atmosphere and stabilize internal gas composition [18]. Importantly, the present findings

suggest that the physiological responses observed should be interpreted in relation to the atmosphere dynamically generated by the tested packaging system, rather than by comparison with generalized recommended O_2/CO_2 ranges reported in the literature. This packaging-specific perspective helps reconcile discrepancies among studies and highlights the relevance of film properties and package design in determining MAP effectiveness in specific globe artichokes cultivars.

Artichokes are characterized by inherently high respiration rates, which may strongly limit their postharvest life [38]. In non-packed samples, the observed initial decline followed by a later increase in respiration (Table 2) could reflect progressive tissue dehydration and cellular disruption under uncontrolled atmospheric conditions. This biphasic pattern might indicate an early metabolic slowdown followed by stress-induced respiratory reactivation as senescence progresses [39]. In contrast, both MAP-based treatments appeared to moderate respiratory activity throughout storage, with respiration rates remaining substantially lower and more stable than in non-packed artichokes, with rates ranging from 134 to 182 mg CO_2 kg^{-1} h^{-1} (Figure 2). These values are considerably higher than those reported by Gil-Izquierdo et al. [18], who documented respiration rates of 35–40 mL CO_2 kg^{-1} h^{-1} at 5 °C in 'Blanca de Tudela' artichokes stored in modified atmosphere packaging. The observed differences may be attributed to several factors: in the study by Gil-Izquierdo et al. [18], harvested artichokes were stored at 0 °C until the next day before the experiment, the harvest took place in January, and the average head weight was larger (≈170 g) compared to the present study (≈131 g). In addition, that study did not specify either the flower head order or the developmental stage of the artichokes at harvest, both of which are known to significantly influence respiratory behavior [34]. In the present work, only secondary flower heads harvested at an intermediate developmental stage were used. Previous research by Giménez et al. [34] demonstrated that respiration rate in 'Blanca de Tudela' artichokes varies significantly with flower head order, with secondary heads exhibiting intermediate respiration rates between primary and tertiary heads. Respiration rate is also strongly influenced by harvest timing and environmental conditions, and similar results were reported by Giménez et al. [34] in 'Blanca de Tudela' and Palma et al. [40] in 'Spinoso Sardo', where respiratory activity at harvest was higher in spring than in winter. These factors likely explain the higher respiration rates observed in our May-harvested, smaller secondary heads compared to the January-harvested, larger heads of Gil-Izquierdo et al. [18].

It is hypothesized that this phenomenon is attributable to the metabolically active state of artichokes, as seen with the 'Blanca de Tudela' cultivar, which has previously been identified as having remarkably high respiration levels [10,18]. Recent studies further suggest that respiration in whole artichokes could be strongly influenced by cultivar, storage temperature and atmospheric composition. Capotorto et al. [22] reported considerable variability in respiration among different cultivars and demonstrated that pre-cooling can effectively suppress metabolic activity during the early stages of storage. Similarly, Palma et al. [20] showed that modified atmosphere packaging (MAP) helps to reduce browning and preserving phenolic compounds, which are crucial for both visual and nutritional quality. These findings emphasize the importance of integrating pre-cooling with MAP as a combined postharvest strategy, particularly for intact 'Blanca de Tudela' heads, to optimize shelf-life and maintain product quality under commercial storage conditions. Consistent with this interpretation, Gomaa et al. [41] reported that MAP significantly reduced respiration rates during cold storage of whole artichokes. In the present study, although respiration was reduced under both MAP-based treatments, the combination of pre-cooling and MAP resulted in a more pronounced and sustained decrease during the intermediate storage period compared to MAP alone. This enhanced effect may be likely attributable to

the synergistic action between rapid field heat removal and the establishment of a stabilized modified internal atmosphere. Pareek et al. [39] emphasized that pre-cooling is a fundamental postharvest step which, when integrated with controlled atmosphere technologies, can significantly reduce metabolic activity. Similarly, Saltveit [38] highlighted that lowering storage temperature effectively suppresses respiration and extends shelf-life. The decline in respiration observed after 28 days in the Pre-cooling + MAP treatment indicates the efficacy of this integrated approach in reducing initial tissue temperature, limiting water loss and maintaining metabolic stability throughout storage. The relationship between respiration rate, weight loss and firmness is critical, as elevated metabolic activity accelerates transpiration and the consumption of internal reserves, leading to faster deterioration [39,42]. In this study, exploratory Pearson correlation analysis revealed strong associations between respiration, firmness and weight loss under non-packed conditions. Under MAP and Pre-cooling + MAP, these correlations were weaker, indicating a decoupling of metabolic activity from structural degradation and suggesting improved physiological stability. This observation aligns with previous findings that low respiration rates are associated with prolonged shelf-life, reduced nutrient loss and improved visual and textural quality [43]. Furthermore, Giménez-Berenguer et al. [21,35,44] reported that tertiary artichoke heads, which had lower respiratory rates, were more suitable for prolonged storage [34]. Together, these results underscore the importance of applying integrated storage strategies, such as Pre-cooling + MAP, to effectively modulate respiration and delay senescence in globe artichokes [45].

Dehydration emerged as one of the main drivers of postharvest deterioration and reduced shelf-life in globe artichokes, particularly in non-packed samples, where water loss could rapidly exceed commercially acceptable thresholds. In contrast, both MAP and Pre-cooling + MAP treatments significantly reduced weight loss throughout storage, with the combined strategy consistently showing the lowest values over the 42-day period (Figure 3). In these treatments, weight loss remained below 2%, confirming their superior effectiveness in limiting transpiration and preserving product quality. This protective effect is attributed to the barrier properties of the packaging films, which reduce vapor pressure gradients around the product, together with the moderation of metabolic activity under refrigerated conditions [18,38,46,47]. Similar reductions in weight loss have been reported for minimally processed artichokes stored in low-permeability films [46], as well as for other vegetables subjected to rapid cooling strategies, such as vacuum or container cooling [48]. The superior performance of Pre-cooling + MAP highlights the importance of early field heat removal in preventing accelerated moisture loss during the initial postharvest stages, in agreement with studies showing that delayed pre-cooling significantly increases dehydration and decay in artichokes [49]. Recent research further supports the effectiveness of MAP in reducing water loss and preserving firmness and bioactive compounds in whole artichokes [20,22], while pre-cooling has been shown to minimize initial water loss and metabolic stress, thereby extending shelf-life [50,51]. Despite refrigeration, artichokes may still experience substantial dehydration, with reported weight losses of up to 15% after 14 days [34], whereas storage at lower temperatures markedly limits moisture loss compared to higher temperatures [52]. In the present study, Exploratory Pearson correlation analysis may suggest strong positive associations between storage duration and weight loss across all treatments, confirming dehydration as a primary indicator of quality decline and tissue degradation over time, a process that could be mitigated by appropriate storage strategies [53,54]. Although the observed weight-loss differences are statistically significant, the absolute magnitude (≈0.4–0.5%) is relatively small and, by itself, unlikely to represent a decisive economic advantage within typical export chain tolerances, where natural variability due to handling, storage, and transport is expected. Therefore, this result should be interpreted primarily

as an indicator of improved postharvest performance rather than a standalone economic outcome. Importantly, the relevance of the treatments is reinforced by their combined positive effects on other critical quality parameters, including reduced respiration rate, maintenance of phenolic and chlorophyll content, firmness stability, and visual acceptability during storage. Taken together, these improvements contribute to a more consistent preservation of overall product quality under export-oriented cold storage conditions, while the economic significance of such incremental gains ultimately depends on commercial handling practices and acceptance thresholds defined by exporting companies.

Firmness is closely linked to weight loss and represents a key quality attribute influencing consumer acceptance [40,53]. In this study, firmness was consistently measured at the equatorial section of the artichoke heads using a well-established and sufficiently sensitive method for instrumental texture evaluation validated in previous studies [34,53,55]. Both MAP and Pre-cooling + MAP treatments maintained relatively stable firmness during refrigerated storage, with only a slight decreasing trend observed after day 14 (Figure 4), whereas non-packed artichokes exhibited a rapid and pronounced loss of firmness. The marginally higher firmness values recorded on day 14 compared to harvest could be attributed to inherent biological variability among individual heads, as independent samples were evaluated at each sampling point. No significant differences were detected between MAP and Pre-cooling + MAP, indicating that once dehydration is effectively controlled, the barrier properties of the packaging film alone may be sufficient to preserve tissue turgor throughout storage. Firmness loss in artichokes is primarily associated with dehydration and bract opening, which are natural physiological processes linked to postharvest senescence [56]. This interpretation is supported by Pearson correlation exploratory analysis, which may reveal near-perfect negative correlations between firmness and weight loss across all treatments, which could reflect a direct biophysical mechanism whereby transpiration-driven water loss reduces cellular turgor pressure and leads to tissue collapse and perceived softening [47,53]. In addition, the relationship between firmness and respiration appeared treatment-dependent: under non-packed conditions, firmness was closely associated with both respiration rate and weight loss, whereas these correlations were markedly weaker under MAP and Pre-cooling + MAP, suggesting that controlled atmosphere storage may stabilize metabolic activity relative to structural degradation.

Phenolic compounds play a central role in both the nutritional value and oxidative stability of artichokes due to their bioactive and antioxidant properties [57–60]. In agreement with Gil-Izquierdo et al. [18], phenolic content increased during the early stages of storage under MAP, likely as a stress-induced response involving activation of the phenylpropanoid pathway and accumulation of di-caffeoylquinic acids, which are among the main bioactive compounds in artichokes. However, those authors also reported a subsequent decline during prolonged storage, attributed to compound degradation or metabolic alterations within the tissue [18]. The present study substantially extends these observations by suggesting that the application of pre-cooling prior to MAP could not only enhance the initial accumulation of phenolics but also sustains significantly higher levels throughout extended storage. Notably, even after 42 days, Pre-cooling + MAP samples retained phenolic concentrations above harvest values, whereas MAP-only samples declined below initial levels (Figure 5). This prolonged retention may indicate that pre-cooling improves tissue physiological resilience, possibly by inducing early metabolic adjustments that favor antioxidant synthesis and slow oxidative degradation. Exploratory correlations might further support this interpretation, revealing strong positive associations between phenolic content, firmness, and chlorophyll, highlighting possible protective role of phenolics in maintaining structural integrity and pigment stability during storage [35,53]. In contrast, phenolic content showed negative correlations with weight loss, underscoring the importance of

moisture retention in limiting oxidative degradation [47]. Moreover, in Pre-cooling + MAP samples, correlations between phenolics and respiration appeared negligible, suggesting that pre-cooling may partially decouple phenolic metabolism from respiratory activity and mitigate oxidative losses.

Chlorophyll content is a key determinant of both the visual and nutritional quality of artichokes, influencing consumer perception of freshness and acceptability [12,61–63]. During storage, total chlorophyll exhibited a progressive decline, which was strongly treatment-dependent. Non-packed artichokes experienced rapid pigment loss from day 28 onwards, reaching critically low levels by day 42, which may reflect accelerated senescence driven by dehydration and oxidative breakdown of chlorophyll [5,53,64]. In contrast, MAP and, particularly, Pre-cooling + MAP effectively delayed chlorophyll degradation, maintaining higher pigment levels throughout the storage period (Figure 6). Although a slight decrease was observed during the first two weeks, these treatments may provide substantial protection against pigment loss in the later stages, with Pre-cooling + MAP yielding the highest retention on day 42. The protective effect could be likely related to reduced oxygen availability and lower respiration rates, which may limit reactive oxygen species (ROS) accumulation, a key driver of chlorophyll catabolism during senescence [5,62]. Chlorophyll content also appeared to correlate strongly with firmness and negatively with weight loss, which may emphasize the interdependence between tissue hydration, structural integrity, and visual quality [35,40,47]. Additionally, the influence of respiration on chlorophyll degradation could be modulated by treatment, being more pronounced in non-packed samples and attenuated under MAP or Pre-cooling + MAP, reflecting the stabilization of metabolism under controlled storage conditions.

Visual and image-based sensorial assessments of whole 'Blanca de Tudela' artichokes further suggest the superior performance of Pre-cooling + MAP in preserving postharvest quality (Figures 7 and 8). At harvest, all treatments exhibited similarly high scores (4.7–5.0) for color, freshness, and overall acceptability, but during storage, Pre-cooling + MAP maintained the highest values for all visual attributes, remaining above the commercial acceptability limit ($\geq$3) even after 42 days at 2 °C. MAP-only samples ranked intermediate, while non-packed artichokes declined rapidly, falling below the threshold by day 28. The enhanced sensory performance of Pre-cooling + MAP aligns with previous reports on fresh-cut 'Blanca de Tudela' artichokes, where maintenance of visual quality and overall liking was closely associated with reduced browning and dehydration, and where scores around 3 were considered indicative of practical shelf-life limits [6,21,37]. This advantage may be likely related to more effective control of physiological activity, reduced oxidative degradation of phenolics, lower browning, and better maintenance of external turgidity, as evidenced by higher scores for color, bract opening, and dehydration over time. Image analysis reinforced these observations, showing that MAP-based strategies could effectively mitigate water loss and firmness decline, while non-packed samples exhibited accelerated deterioration due to higher metabolic activity and absence of a protective barrier [18].

Overall, the integration of pre-cooling with MAP appears to be the most effective strategy for delaying senescence and preserving the physicochemical, functional, and sensory quality of whole 'Blanca de Tudela' artichokes. While MAP alone may significantly improve storage performance compared to non-packed samples, the addition of pre-cooling could provide an added advantage by mitigating early metabolic stress and reinforcing long-term quality retention. It is important to note that these conclusions are grounded in the defined sensory acceptability thresholds (score $\geq$ 3) and represent measured quality retention under controlled conditions; true commercial shelf-life would require validation under actual supply-chain scenarios, including transport, retail handling, and buyer-specific criteria.

It should also be acknowledged that the capacity of artichokes to respond to postharvest strategies such as MAP and pre-cooling may be strongly conditioned by preharvest environmental and agronomic factors. Previous research indicates that genotype, climatic conditions, and crop management practices influence key quality determinants at harvest, including macro and micro mineral content, quantitative and qualitative phenolic profile, respiration rate, firmness, and overall physiological status, which in turn affect postharvest performance [33,65–68]. For example, variation in phenolic accumulation and browning susceptibility among different cultivars and flower head orders has been observed, with both genetic background and developmental factors contributing to these differences [21,35,44]. Indeed, in the study of Giménez-Berenguer et al. [21], it was shown that cultivar and flower head order determine suitability for fresh-cut processing, with secondary heads often presenting an intermediate balance between phenolic content and browning risk relative to main or tertiary heads. In the present study, secondary heads were selected because they may offer intermediate suitability for both fresh and fresh-cut markets, reflecting a compromise between nutritional attributes and visual quality. Nonetheless, environmental variables such as soil conditions, irrigation, and light exposure during cultivation may further modulate physiological traits that determine how artichokes respond to storage environments [33,66,69–71]. Therefore, while postharvest handling has a direct impact on quality retention, the preharvest physiological status of the produce may shape the extent and direction of these responses, and should be considered when extrapolating results across growing regions or production systems.

Nevertheless, these findings demonstrate treatment-specific mechanisms and highlight the added value of combining temperature management with atmospheric control for extended cold storage of globe artichokes.

5. Conclusions

In conclusion, the MAP strategy effectively preserved the quality of the artichokes during storage. MAP treatments maintained firmness, and the combined use of Pre-cooling and MAP further improved storage performance by significantly reducing respiration rates and weight loss. Both treatments helped to retain total phenolic and chlorophyll content compared to non-packed artichokes, with Pre-cooling + MAP treatment showing greater effectiveness in preserving these bioactive compounds. These results demonstrate that combining packaging and pre-cooling techniques can enhance the storage ability of artichokes, maintaining both physical and nutritional properties over time.

Furthermore, the application of these strategies not only could support the commercial potential of globe artichokes by potentially prolonging their shelf-life but also might offer economic advantages by reducing postharvest losses and increasing the profitability of this crop, especially in long-distance export markets, as visual sensory analysis confirmed that both MAP and Pre-cooling + MAP treatments maintained acceptable appearance and consumer-relevant quality parameters up to 42 days.

Future research should expand the scope by considering additional pre-cooling methods, diverse packaging types, and varying storage conditions. Extending these studies to other cultivars will further enhance the applicability of postharvest optimization strategies and provide a broader understanding of how to maintain the quality and nutritional value of globe artichokes during storage, including validation under actual supply-chain conditions.

Author Contributions: Conceptualization, P.J.Z., M.J.G. and V.S.-E.; methodology, S.D.-F. and M.J.G.; software, S.D.-F., M.G.-B. and M.J.G.; validation, P.J.Z., M.J.G. and V.S.-E.; formal analysis, S.D.-F. and M.G.-B.; investigation, S.D.-F. and M.J.G.; data curation, P.J.Z. and M.J.G.; writing—original draft preparation, S.D.-F.; writing—review and editing, P.J.Z., M.G.-B., M.J.G. and V.S.-E.; supervision, P.J.Z., M.J.G. and V.S.-E.; visualization, P.J.Z., M.J.G. and V.S.-E., project administration, P.J.Z. and

M.J.G.; funding acquisition, P.J.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

MAP	Modified atmosphere packaging
DW	Dry weight
SE	Standard Error
GAE	Gallic Acid Equivalents

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