



Impact of packaging on physiological properties, chemical composition, and bioactive compounds in organic and conventional artichokes during cold storage and in simulated market condition

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ABSTRACT

'Spinoso sardo' is a specialty vegetable with a unique taste and rich in nutraceutical compounds, particularly suitable for early season production, with a short shelf-life even when marketed in modified atmosphere packaging. A survey at local retailers revealed that the short shelf-life is in part due to poor handling procedures, and packaging solutions not based on a rationale design of the packaging which frequently lead to restricted gas exchange and asphyxiating condition. A preliminary study showed that a package made with a macroperforated film able to maintain a high level of humidity without significantly altering the gas composition tested on 'Spinoso sardo' artichokes grown under conventional (CONV) or organic (ORG) protocols, effectively prolonged the shelf-life and the chemical properties of samples of both growing systems for at least 10 d at 5 °C plus 3 d of simulated marketing conditions at 18 °C. Molds developed after 15 d, but no physiological disorder occurred. At harvest ORG artichokes showed levels of phenols and antioxidant activity slightly but significantly higher than CONV samples, but the rate of physio-chemical changes over storage did not differ between the two growing systems.

1. Introduction

Artichoke cultivation is primarily concentrated in the Mediterranean basin, as well as parts of North Africa, North America, and South America. According to the FAO, Europe produces most of the world's nearly 1.5 million tons of artichokes, followed by Africa and South America. The primary European producers are Italy, Spain, and France. Italy is also the largest worldwide artichokes' producer, accounting for over 20 % of the global yield, followed by Egypt, Spain, and Peru (Food and Agricultural Organization, 2021). In Italy, artichoke production amounts to approximately 380,000 tons, with the majority being grown in the regions of Apulia (35 %), Sicily (32 %), and Sardinia (21 %) (ISTAT 2022). The most cultivated variety of artichoke in Sardinia is 'Spinoso sardo', which benefits from 'Protected Designation of Origin' (PDO) regulations under the name 'Spinoso di Sardegna'. This recognition is attributed to its distinctive properties, high levels of nutraceutical substances, and organoleptic qualities, which are primarily or

exclusively associated with the specific geographical environment in which it is cultivated (Spanu et al., 2018).

In Sardinia, artichoke is mainly cultivated as an annual crop using a technique that involves the summer implantation of dormant offshoots subjected to a forcing technique that allows for an early harvesting time from October–November to the end of April (Pisanu et al., 2009, Ledda et al., 2013; Deligios et al., 2019).

During the harvesting season, the artichoke plant continuously produces heads, which are harvested when they reach a weight of around 150 g. The artichokes harvested between October and December, which are produced from the central part of the plant, are classified as first cut or primary artichokes. This is followed by the second cut, which takes place between January and March, and then the third cut, harvested from March to April. The nutritional, nutraceutical, and organoleptic qualities of artichoke vary depending on the harvest period (Palma et al., 2023a). Specifically, those harvested during the first and second cuts are generally more favoured by the market.

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With the aim of diversifying production and expanding sales markets, several Sardinian companies have begun a conversion of the artichoke cultivation systems towards organic farming systems.

Thanks to early harvesting season, along with the adoption of organic farming system and for its nutritional and organoleptic properties, the Sardinian-grown 'Spinoso sardo' artichoke is in demand not only in local markets but also in markets far from the production area.

After harvest artichokes are highly perishable due to their high respiratory and transpiration rates, which lead to a rapid loss in water and firmness and to important physiological changes, such as chlorophyll degradation and bract browning, which compromise marketability.

Artichokes are typically sold loose, but their marketing as a packaged product in various ways is becoming increasingly popular for convenience, presentation, and because it can preserve quality, especially when the product is destined to long-distant markets (Izquierdo et al., 2002).

In fact, in recent years, commercialization of artichokes packed in trays sealed with different polymeric films (MAP) has become popular as it offers the advantage of maintaining tissues freshness by preventing water loss thanks to the high in-package humidity that can be maintained all along the distribution chain (Izquierdo et al., 2002). Besides, marketing artichoke heads in units ready-to-use reduces the vegetable material waste compared to marketing artichokes loosely, with leaves and a portion of the stem.

The goal of film-packaging is to preserve produce quality and freshness by creating an optimal in-package modified atmosphere, with steady state levels of water vapor, O₂ and CO₂ that do not cause physiological disorders.

The literature provides contrasting information on the potential benefits of MAP for artichokes; while some studies report positive effects, including reduced mass loss, firmness maintenance, and delayed browning, others report only moderate or no significant advantages (Izquierdo et al., 2002).

Recommended storage atmospheres are composed by 1–6 % O₂ and 2–7 % CO₂, but the response to these atmospheres is strongly dependent on the cultivar (Andre et al., 1980; Escriche et al., 1982; Suslow and Cantwell, 1997; Beaudry, 1999; Sandhya, 2010).

Some artichoke cultivars, such as 'Madrigal', are more sensitive to carbon dioxide: exposure to just 3 % CO₂ leads to increased pappus growth in the receptacle, whereas values higher than 10 % result in browning of internal bracts and blackening of internal core. At the same time, atmospheres with concentration below 2 % of O₂, considered the fermentation threshold, may result in internal blackening of artichokes (Miccolis and Saltveit, 1988; Conesa et al., 2001; Amodio et al., 2020).

Thus, specific formulation of a MAP may be suitable for some cultivars but not for others.

In Sardinia, the 'autumn-winter' production of 'Spinoso sardo' is primarily destined for fresh consumption, both in a non-packaged form with leaves and as a packaged product, whereas the spring harvest is generally processed by industry to produce canned artichokes, artichoke hearts, and other processed artichoke products (Sgroi et al. 2015).

The choice to market artichoke 'Spinoso Sardo' as a packaged product, as an alternative to the loose form with leaves and a portion of the stem, is driven by the potential increase in market penetration, convenience of use and shelf-life. Packaging the artichokes facilitates the handling of the product, reduces the risk of damage, and ensure a longer shelf life. Moreover, by removing the leaves and outer bracts, the artichokes can be prepared more quickly and easily by consumers, making them more appealing to those who may hesitate to purchase whole artichokes with thorns, which are characteristic of 'Spinoso sardo'.

Artichoke manufacturers typically put 4 or 6 artichoke heads per package, arranged in plastic, polystyrene or cardboard trays sealed with a plastic film. However, the choice of plastic film is not based on scientific information but rather on what is available from film retailers. This is due to a lack of scientific information on packaging for this

product.

With this study we pursued the following objectives: a) identify any possible critical step at retail level of packaged artichokes that can compromise the produce quality and self-life; b) identify the best commercial packaging systems; c) compare the postharvest behaviour of conventional and organic 'Spinoso Sardo' artichokes treated with the packing solution we considered as the best among the tested commercial ones. To accomplish objectives number 1 and 2, we did a preliminary study through a survey at retail level followed by observations done in our lab on artichoke packages provided by packinghouses.

2. Materials and methods

2.1. Preliminary study

A preliminary survey was conducted to gain an overview of the "state of art" of postharvest handling of 'Spinoso sardo' by Sardinian packinghouses. We also investigated how the large-scale retail outlets display packaged artichoke and, every time the retail outlets did not display the packages in refrigerated cases, 10 packages were bought, which within 1 hour were transported to our laboratory to determine the in-package atmosphere composition. This to assess if at ambient temperature display of packages could affect negatively the in-package air composition and quality.

From the survey we found that the most used packages were the following:

1. Six artichokes heads per package, without stem and trimmed by removing the external bracts and the apical part of the head (processed artichoke), placed inside cardboard waterproofed trays wrapped with macro-perforated oriented polypropylene film (2 holes per package with 5 mm diameter, Coralife SWAF 400) (PACK1).
2. Six artichokes heads per package, without stem and trimmed by removing the external bracts and the apical part of the head (processed artichoke), placed inside cardboard waterproofed trays wrapped with laser micro-perforated oriented polypropylene film (400 laser perforations per meter square with a diameter of 80 µm, Coralife SWAF 400) (PACK2).
3. Six artichokes heads per package without stem (whole artichoke head), placed inside polystyrene trays wrapped with a polyvinyl chloride stretch film (PVC KOEX 112; Thickness 12 µm; O₂ permeance 17.500 cc/m²/24hBatm; CO₂ permeance 118.000 cc/m²/24 h atm). (PACK3).

After the investigation at retail outlets, we contacted three local packinghouses asking them to provide some samples of un-packaged and packaged artichokes destined to market, to let us carry out some physiological and qualitative determinations. In all cases artichokes were cultivated under conventional agronomic systems. Each packinghouse provided 30 packages of one of the three kinds of packages above described plus 90 non-packaged artichokes. The artichokes were taken from the packinghouses immediately after preparation for packaging (non-packaged samples) or as soon as they were packaged and transported to the ISPA-CNR lab in Sassari within 2 h.

To evaluate the respiratory activity of un-packaged artichokes and the impact of wounds inflicted by processing, half of the samples were destemmed (whole artichokes) whereas in the remaining half besides the stem also the external bracts and the apical part of the head were removed (processed artichokes). Respiration was determined on six heads of each group at day interval over a five-day period during which the temperature was set at 5 °C and 90–95 % RH or 18 °C and 60 % RH.

Packaged artichokes were stored at 5 °C and 90 % RH or at 18 °C and 60 % RH for 7 d. At day 1, 3, 5 and 7 in-package CO₂ and O₂ partial pressure were determined as described below. At day 7 the packages were opened and the quality of individual artichoke (presence of moulds, bracts browning and internal blackening) was evaluated

according to the method below described.

Bract browning refers to the discoloration of the outer bracts, while internal blackening pertains to the darkening or blackening of the internal tissues, both resulting from physiological disorders or environmental stress (Miccolis and Saltveit, 1998).

Plant material

Artichokes (*Cynara cardunculus* L. var. *Scolymus* L.) cv Spinoso sardo grown under conventional practices of local farmers (CONV) or following an organic management system (ORG), were collected in January in a farm located in Uri, Sardinia, Italy (40 ° N, 8 ° E, 128 m a.s.l.).

The CONV grown system was based on a continuous globe artichoke monoculture, treated with conventional fertilizers, where the crop residues were incorporated into the soil at the end of the crop cycle (Spanu et al., 2018; Palma et al., 2023a).

The design and management of the ORG cropping system were based on agroecological principles applied in organic farming. In this system, an inter-row *Pisum sativum* L. var. Enduro cover crop was introduced for the potential positive effects on soil fertility and quality of the artichoke as a result of chopping and incorporating into the soil the residues of the cover crop (Deligios et al., 2017; 2021). The two management systems were 50 m away each other to avoid interaction effects and possible cross-contamination. Details regarding site description and crop management are reported by Palma et al. (2023a). Respiratory tests and chemical-physical determinations were conducted on artichoke heads harvested in January from the second cut, randomly selected from each growing system.

2.2. Packaging and storage conditions

Six artichoke heads without stems and external bracts removed manually, with an average weight of 130 g, were placed in polypropylene trays (volume 0,0026 m³). Half of the trays were left unpackaged and served as control, the other half were film wrapped. A packing machine (Orved VGP sealer, Orved srl, Verona, Italy) was employed to seal a sheet of polypropylene film, 40 µm thick, with two 5 mm holes (surface area 0.131 m²) on top of each tray.

The choice of the film was based on the results achieved from the preliminary tests.

To simulate the marketing chain conditions, both packaged and unpackaged artichokes were stored at 5 °C and 90 % RH for 5, 10 or 15 d (representing the storage period and/or transport to markets in refrigerated conditions). At the end of each storage period, the packages were transferred to 18 °C for 3 d to simulate the marketing conditions.

To monitor the in-package temperature and humidity, a data logger (RHT10 Humidity/Temperature USB Datalogger, Extech instruments, FLIR System, Townsend West, USA) was placed inside three packages for each storage period and set to record the temperature and the RH every six hours. Three additional data loggers were also placed in different points of each storage room to monitor the storage environment temperature and humidity. A total of 216 trays were used: 9 trays for each sampling time and type of artichoke (CONV and ORG) were used for chemical analysis and overall quality evaluation, while 6 trays were used to determine respiration and in-package air composition.

Respiratory activity, in-package CO₂, O₂, C₂H₄, relative humidity and temperature

Respiratory activity was determined in un-packaged heads as well as in packaged heads, which were first conditioned at 18 °C for 12 h and then transferred to 5 °C and stored for 5 d, 10 d or 15 d. At the end of each storage period both un-packaged and packaged artichokes were transferred to SMC at 18 °C. Respiration was initially measured in samples conditioned at 18 °C and then after 1 d at 5 °C, at the end of each storage period at 5 °C and after 1 and 3 d of SMC at 18 °C.

Both for packaged and un-packaged artichokes, individual trays were placed into 10-L jars and closed for 2 h at 18 °C or 4 h at 5 °C. The jars were equipped with an internal fan for air mixing, and the lids were

fitted with two silicone septa for gas sampling. CO₂ and O₂ were determined using a combined CO₂/O₂ analyser (F-940, Felix Instruments, Camas, WA USA) connected to each jar by two tubes. Each tube ended with a needle inserted into one of the two septa, creating a closed system. An incorporated pump in the CO₂/O₂ analyser, continually pumped headspace air through the inlet tube and reinjected, after reading, the same air into the jars through the outlet tube. The analysis continued for approximately 60 s until the CO₂ reading values stabilized. Respiration activity, as release of CO₂, was expressed as mg CO₂ kg⁻¹ h⁻¹.

In-package gas composition was monitored daily both at 5 °C and during the 3 d of SMC using a multi-gas sampling data logger (CM-100, CO2METER.COM, Ormond Beach, FL, USA) for combined measurements of oxygen and carbon dioxide.

Ethylene concentration was determined according to the procedure described by Palma et al. (2015). For each cultivar, sampling time and treatment six packages were used.

2.3. Weight loss and overall acceptability

Weight loss was expressed as the percentage reduction of the initial weight. Trays of both un-packaged and packaged artichokes of CONV and ORG treatments were initially individually weighed; they were re-weighed at the end of each storage period and SMC. For each treatment combination, the number of trays used were 9. The same artichokes were assessed for overall acceptability, which was carried out by six trained laboratory technicians who evaluated for taste and crispiness of the bracts while chewing. Each artichoke was then cut into 8 pieces and all pieces of the 9 artichokes were mixed and placed into a ceramic bowl. Each panelist tasted 2–3 pieces of samples from each bowl. The judgment for both parameters was based on a subjective scale ranging from 1 to 9. In this scale, 1 represented "very poor," 3 represented "poor," 5 represented "good" (limit of marketability), 7 represented "very good," and 9 represented "excellent. From each tray one artichoke was used, for a total of 9 for each treatment combination. Statistical analysis was conducted on the six scores for each treatment combination provided by the panelists.

2.4. Bracts browning, internal core blackening, mould development, texture properties, and fibres content

At the end of each storage period, the same artichokes used for weight loss were assessed for bracts browning, internal blackening and mould development. The severity of bract browning, and internal blackening was visually evaluated using a rating scale with five levels of damage: 1 = none; 2 = mild, 3 = medium, 4 = severe and 5 = very severe. Mold evaluation was conducted by identifying its presence or absence without considering its intensity, and the results were reported as a percentage of packages with mouldy artichokes.

Texture analysis was conducted in the central area of each bract at the point of transition from yellow to green using a testing machine (model DO-FB 0.5 TS, Zwick-Roell, Ulm, Germany) equipped with a 1.2 mm diameter cylindrical plunger with flat face, moving at a speed of 3.3 mm s⁻¹. For each storage time, the first external bracts were discarded, and the next 30 bracts from 18 artichoke heads (2 for each tray) were used for analysis. Texture properties were assessed by measuring two parameters simultaneously: the bracts' resistance to penetration (F Max) and the surface deformation of the bracts before the penetration of the plunger (L at F max). F Max and L at F Max were expressed as newton (N) and millimetres (mm) respectively.

The Ankom Fibre Analyzer (model A200I Ankom Technology, NY, USA) was used to determine the fibre content of the sample. Neutral and acid detergent fibres (NDF and ADF) and acid detergent lignin (ADL) were determined according to Van Soest et al. (1991) procedure. Cellulose (CELL) content was calculated as ADF minus ADL. Fiber content was expressed as percentage of dry weight.

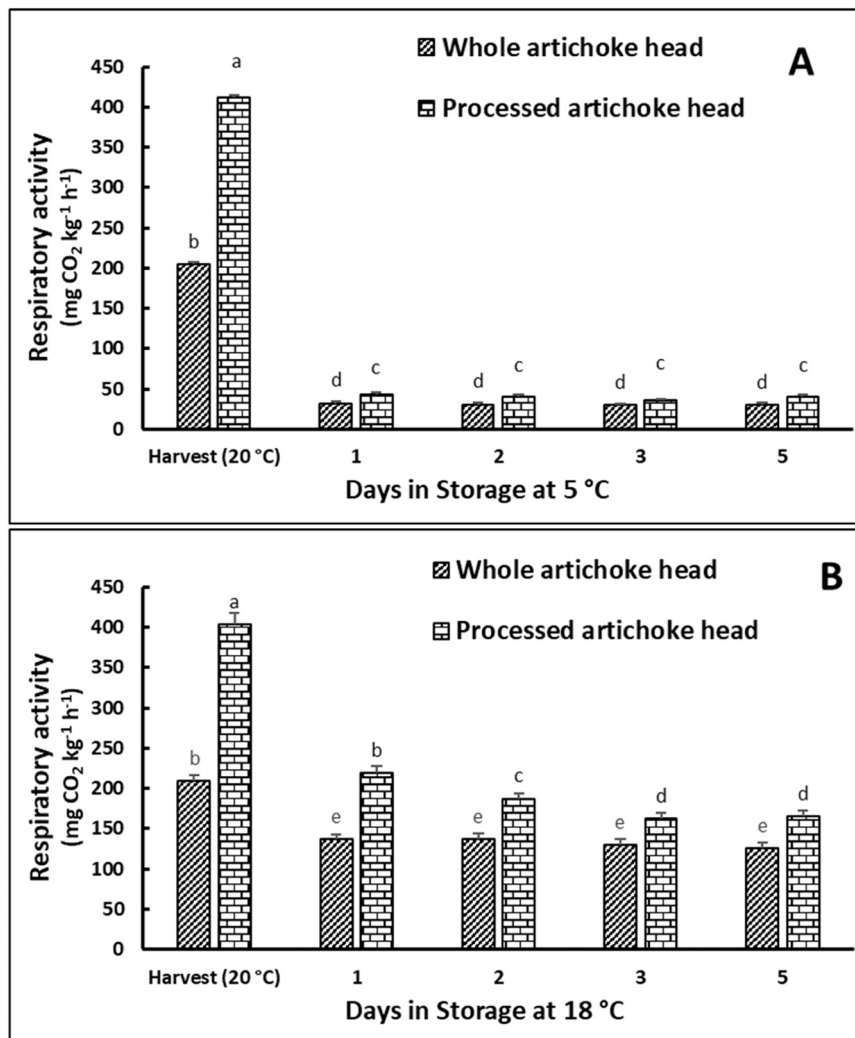


Fig. 1. Respiratory activity as carbon dioxide release in whole and processed ‘Spinoso sardo’ artichoke stored at 5 °C (A) or at 18 °C (B). Columns with different letters are significantly different at $P \leq 0.05$ according to ANOVA analysis. Means separation was accomplished by the Tukey test. Vertical bars represent the standard deviation ($n = 6$).

2.5. Carbohydrates, phenolic compounds, total phenol content, and antioxidant activity analysis

Acetonitrile, trifluoroacetic acid and methanol of HPLC-gradient grade, neochlorogenic acid, chlorogenic acid, apigenin-glucoside, glucose, fructose, and sucrose were purchased from Sigma-Aldrich Co. (Milan, Italy). Other reagents of analytical grade were sodium carbonate; 2,2-diphenyl-1-picryldazyl (DPPH), Trolox (6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid), and Folin–Ciocalteu phenol reagent from Fluka (Buchs, Switzerland). Neutral detergent fiber (NDF), acid detergent fiber (ADF) and sulfuric acid from Carlo Erba Reagents (Milan Italy).

Carbohydrates, phenolic compounds, total phenol content, and antioxidant activity analysis were conducted on extracts obtained following the procedure below: 25 g of sample from each replication, obtained by thinly slicing 3 artichoke heads taken from three different trays (one from each tray), were blended using an immersion blender (model RSCM-350–400P, Royal Catering, Italy) with 50 mL of methanol/water (80/20 v/v) extracting solution until a fine suspension was achieved. After 30 min in agitation at room temperature and in the dark, the suspension was centrifuged for 15 min at 13,000 g (Centurion Scientific Ltd, West Sussex, England) and the supernatant, filtered through a 0.45 mm acetate cellulose filter, was employed for the analyses. Each

analysis was accomplished in triplicates.

Carbohydrates analyses were performed according to the procedure described by Palma et al. (2018). Stock standard solutions of each carbohydrate were prepared in ultrapure water and their quantifications were calculated according to the linear calibration curves of standard compounds. The calibration curves of standards were in the range 0.16–0.042 g 100 mL⁻¹, 0.17–0.042 g 100 mL⁻¹, and 0.08–0.020 g 100 mL⁻¹ with a regression equation of $y = -7E-16 \times 2 + 7E-09X + 0,0022$ ($R^2 = 0.9998$), $y = -E-16 \times 2 + 6E-09X + 0,0024$ ($R^2 = 0.9995$), and $y = -4E-16 \times 2 + 6E-09X + 0,003$ ($R^2 = 0.9999$) for sucrose, glucose, and fructose respectively (Y = analytical signal mV, X = concentration of compounds). Detection limits were 0.006 for sucrose, 0.008 for glucose, and 0.005 g L⁻¹ for fructose.

Phenolics quantification was carried out by the HPLC system (LaChrom Merck-Hitachi liquid chromatograph, Hitachi Ltd., Tokyo, Japan) consisting of a D-7000 system manager, a L-7100 pump and a L-7200 autosampler, was coupled with L-7455 photodiode detector (DAD) and a C18 Prevail column (250 mm x 4.6 mm, 5 μ m, Alltech, Milan, Italy), with a Alltech C18 precolumn (7.5 mm x 4.6 mm I.D.). HPLC elution was carried out at 30 °C. The solvent gradient was performed by varying the proportion of solvent A (H₂O with 0.1 % trifluoroacetic acid) and solvent B (CH₃CN with 0.1 % trifluoroacetic acid) as follows: initial condition 5 % B; at 60 min, 25 % B; at 70 min, 5 % B; with a flow rate of

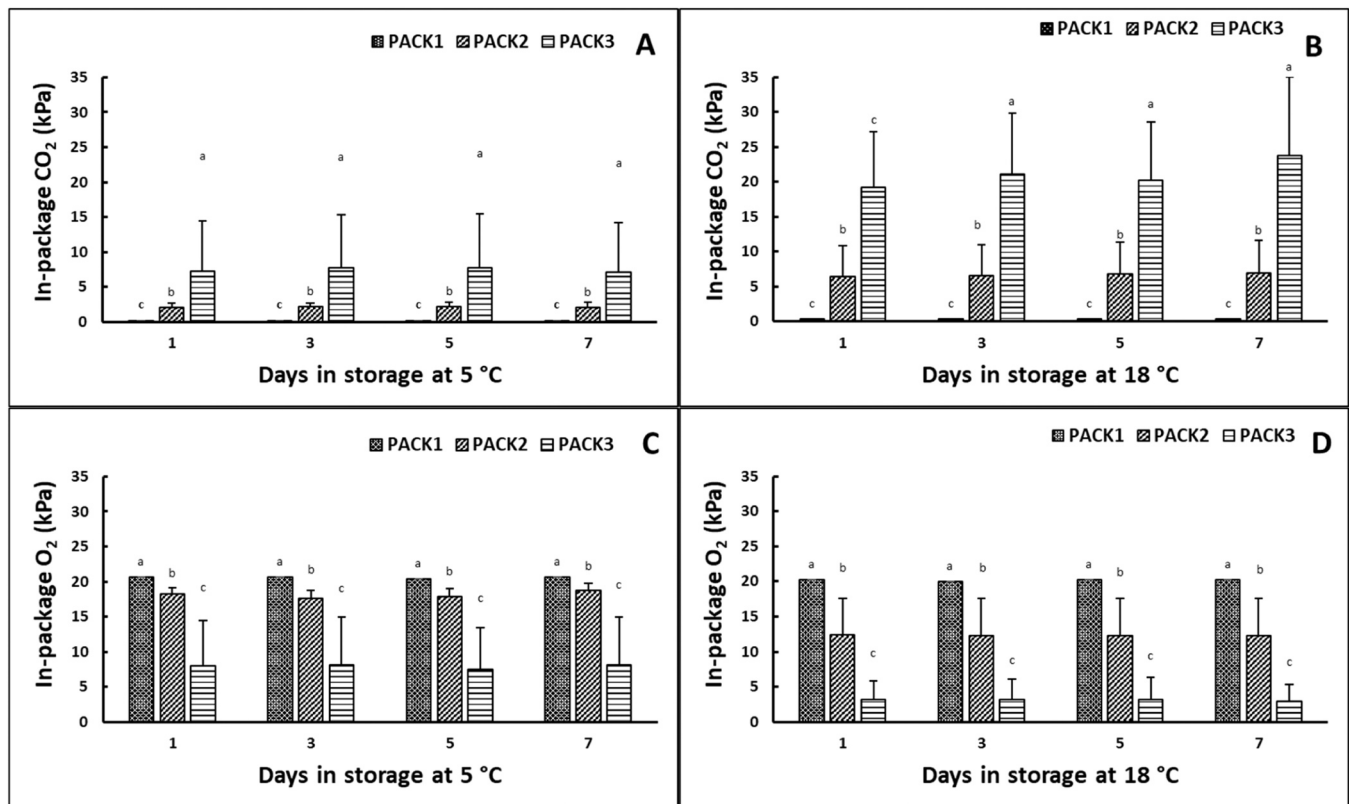


Fig. 2. In-package CO₂ (A, B) and O₂ (C, D) of packages provided by three different packinghouses and stored at 5 °C or 18 °C for 7 d. For each storage time, columns with different letters are significantly different at $P \leq 0.05$ according to ANOVA analysis; means separation was accomplished by the Tukey test. Vertical bars represent the standard deviation ($n = 30$).

1 mL/min. The chromatogram was monitored simultaneously at 280 and 330 nm. Concentrations of neochlorogenic acid, chlorogenic acid, and apigenin-glucoside were calculated using external standards, while the concentration of other detected compounds was expressed as chlorogenic acid equivalent. The calibration curves of standard compounds were linear in the range of 10–100 $\mu\text{g mL}^{-1}$. The regression equation of neochlorogenic acid, chlorogenic acid and apigenin-glucoside, were $y = 10626X - 3696$ ($R^2 = 0.9995$), $y = 14574X + 7047,6$ ($R^2 = 0.9996$), $y = 8304,7X - 2360,4$ ($R^2 = 0.9994$), respectively.

Phenolics compounds were identified by LC-electrospray ionization (ESI) MS analysis using an Agilent Technologies (Palo Alto, CA, USA) 1100 series LC/MSD equipped with a diode-array detector (DAD). A chemstation HP A.10.02 was used for data analysis.

Total phenolic content was determined according to the Folin-Ciocalteu colorimetric method (Singleton and Rossi, 1965). The absorbance was achieved at 760 nm by a UV–vis spectrophotometer (Varian Cary 50, Netherlands). Total phenolic content was expressed as mg kg⁻¹ of gallic acid equivalents. Antioxidant activity was assessed using the free radical DPPH (2,2-diphenyl-1-picrylhydrazyl). The mixture containing 3 mL of a methanol solution of 0.16 mM DPPH and 100 mL of sample, was allowed to react for 15 min in a cuvette. The absorbance of the DPPH solution was determined at 515 nm by a UV–vis spectrophotometer. Antioxidant activity was expressed as mmolKg⁻¹ of Trolox equivalent antioxidant capacity (TEAC).

Quantification of all determined parameters were based on fresh weight (FW).

2.6. Statistical analysis

Statistical analysis was performed using Statgraphics Centurion software (Herndon, VA, USA), version XV Professional statistical

program. Analysis of variance (ANOVA) was carried out for each storage time and mean comparisons among treatments were performed using Tukey multiple range test at $P \leq 0.05$.

3. Results and discussion

3.1. Preliminary study. Respiratory activity, in-packages gas composition, quality evaluation, weight loss and overall acceptability

To preserve quality and freshness of horticultural products, it is necessary to adopt suitable postharvest technologies (Kader 2002a and Kader 2002b). Proper handling and optimal storage conditions, such as refrigeration coupled with effective packaging, play a crucial role in extending the shelf life of produce. The selection of an appropriate packaging system that utilizes materials capable of ensuring adequate exchange of gases and water vapor between the inner packages and the external environment allows for the achievement of optimal levels of CO₂, O₂, and humidity within the package. This helps reduce respiratory activity while preventing anaerobic conditions. The optimal levels of CO₂, O₂, and relative humidity necessary for preserving quality vary depending on type of fruits and vegetables (Beaudry et al., 1999; Sandhya, 2010). In the case of artichoke, unlikely, very few studies have been carried out and none on ‘Spinoso sardo’ cultivar.

The analysis of the in-package gas composition of packages collected from stores displaying the artichokes at room temperature revealed two important aspects: 1) the large variability in gas composition among packages of the same batch; 2) the higher severity of internal blackening (IB) in packages with higher levels of CO₂ and lower of O₂ (data not shown). To understand the cause of this large variability, a trial was conducted using both packaged and un-packaged artichoke heads provided by the packaging house, using the three most common types of packaging, as described in the Materials and Methods section.

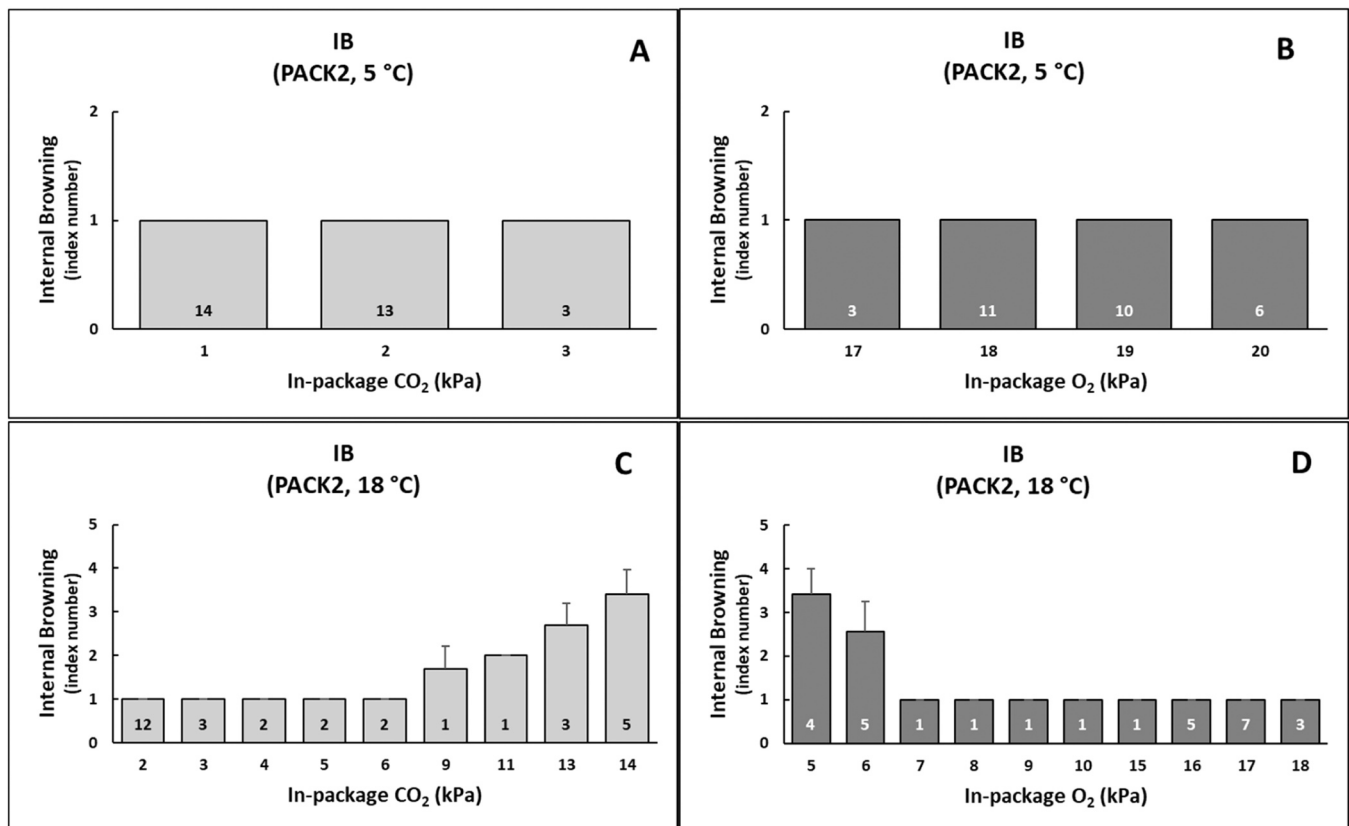


Fig. 3. Internal Browning index (IB) as affected by in-package storage CO₂ (A, C) or O₂ (B, D) in PACK2 samples stored at 5 °C (A, B) or 18 °C (C, D) for 7 d. Each package contained 6 artichokes, and the total number of packages was 30. At the base of each histogram is reported the number of packages whose in-package CO₂ or O₂ partial pressure was the corresponding value reported below in the x-axis. Vertical bars represent the standard deviation of IB of the number of artichokes in the packages reported in each histogram (6 artichokes per package).

The results of this trial (Fig. 1A-B) confirm the high respiratory activity of artichoke heads stored for 5 d at 5 °C or 18 °C as previously reported (Kader, 1992). Processed artichokes showed higher respiration rates than whole artichokes both at 5 °C and at 18 °C. The highest respiration levels were detected at time 0, when the ambient temperature was around 20 °C, thereafter a marked decline occurred both in whole and processed artichokes. At 5 °C differences between processed and whole artichokes, although significant, become very small with storage. On average, at 18 °C respiration rate was around 4-fold higher than at 5 °C in whole artichoke heads and 4.5–5-fold higher than at 5 °C in processed artichokes.

Results of in-package air composition are shown in Fig. 2 A-D. In PACK1 samples, CO₂ partial pressure never exceeded 0.8 kPa (Figs. 2A, 2B), while O₂ levels were always higher than 20 kPa, with negligible differences between packages stored at 5 °C and 18 °C (Figs. 2C, 2D). In PACK2 samples stored at 5 °C CO₂ partial pressure was constantly around 2 kPa (Fig. 2A) while O₂ partial pressure averaged 18 kPa (Fig. 2C); in those stored at 18 °C a slight increase in CO₂ partial pressure occurred over the 7-day storage time (Fig. 2B), while O₂ levels were around 12 kPa (Fig. 2D). In PACK3 stored at 5 °C neither CO₂ (Fig. 2A) nor O₂ (Fig. 2C) showed substantial changes over storage averaging 7 kPa and 8 kPa, respectively, but at 18 °C in-package CO₂ increased markedly with storage, ranging between 19 kPa and 24 kPa (Fig. 2B), while O₂ partial pressure ranged between 3.14 kPa and 2.9 kPa (Fig. 2D). PACK2 and particularly PACK3 in-package air composition showed a very high variability, especially in packages stored at 18 °C.

The high variability encountered in air composition of PACK2 and PACK3 and its effect on the occurrence of IB can be better appreciated in Fig. 3A-D and Fig. 4A-D, where the IB index number is shown as affected by in-package CO₂ or O₂ partial pressures after 7 d of storage at 5 °C or

18 °C. In these figures, packages with CO₂ or O₂ partial pressures differing by no more than 1 kPa were grouped together, and the number of packages in each group is indicated at the base of each histogram.

Data of PACK1 are not shown, as all 30 packages of both storage temperatures had a CO₂ partial pressure always below 0.8 kPa and of O₂ higher than 20 kPa with a very low variation among the individual packages whereas no artichoke head showed symptoms of IB.

In PACK2 samples stored at 5 °C the variability was low; all packages formed 3 groups for CO₂ (1, 2 and 3 kPa with 14, 13 and 3 packages, respectively) (Figs. 3A) and 4 groups for O₂ partial pressure (17, 18, 19 and 20 kPa with 3, 11, 10 and 6 packages, respectively) (Fig. 3B), while no package showed artichokes with IB symptoms, but in samples stored at 18 °C CO₂ partial pressure ranged between 2 and 14 kPa while IB symptoms were detected from 9 kPa on, with IB score peaking to 3.6 in packages with 13–14 kPa (Fig. 3C) combined with O₂ partial pressure of 5–6 kPa (Fig. 3D).

In PACK3 stored at 5 °C CO₂ partial pressure ranged between 1 and 10 kPa (Fig. 4A), whereas O₂ ranged between 2 and 20 kPa (Fig. 4B). IB started to develop at CO₂ partial pressure higher than 6 kPa and O₂ levels below 13 kPa. In PACK3 stored at 18 °C, CO₂ (Fig. 4C) ranged between 9 and 38 kPa while O₂ partial pressure ranged between 0 and 7 kPa (Fig. 4D) with severe IB symptoms appearing even at the lowest levels of CO₂ and highest concentration of O₂ (Fig. 4D). Even when IB symptoms were slight (Fig. 5A) or moderate (Fig. 5B) the appearance of cut heads was compromised. Overall results occasionally showed a slight development of bracts browning in all treatments, whereas in PACK3 samples stored at 18 °C after 4–5 d of storage molds start to develop (Fig. 6).

These results highlight that the cause of this large variability in-package gas composition of PACK2 and PACK3 was mainly due to

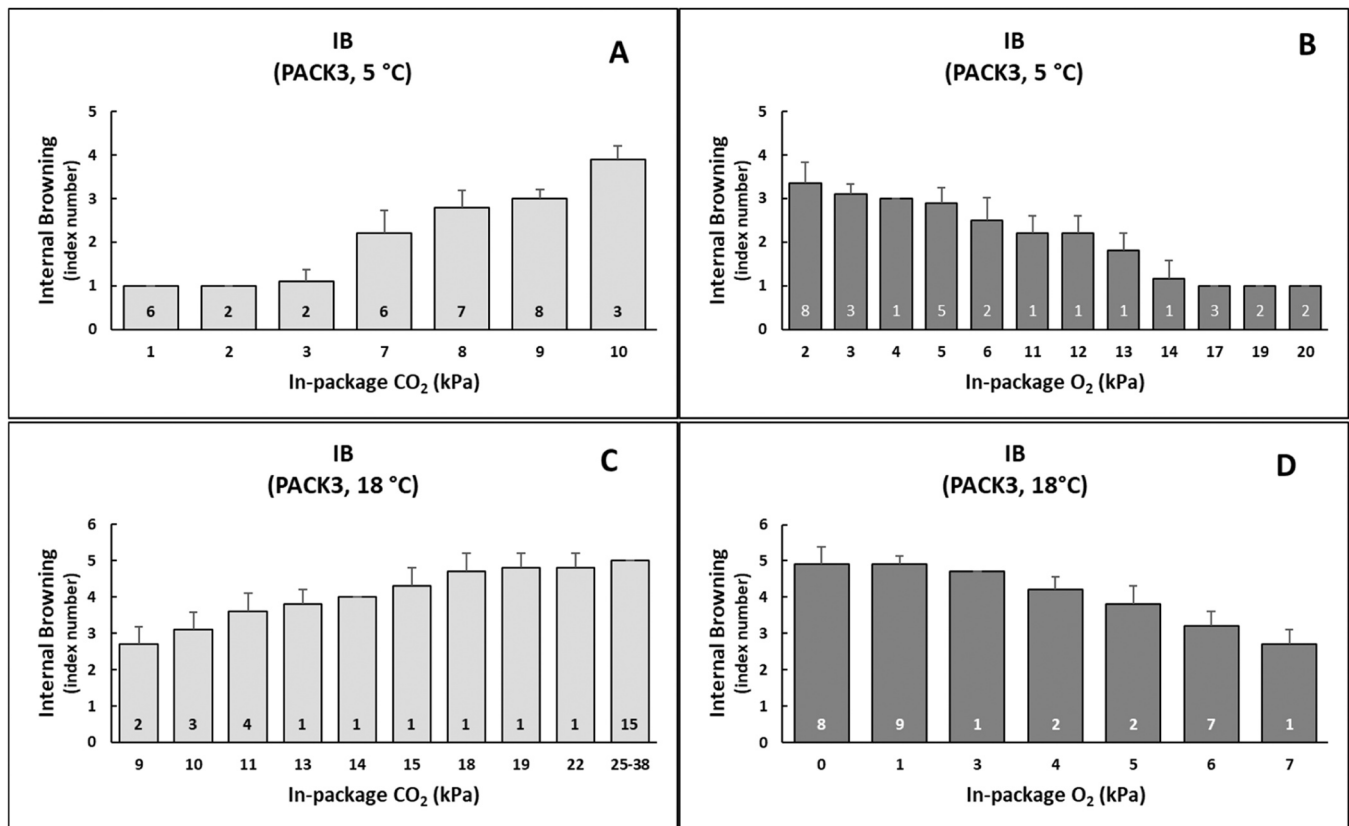


Fig. 4. Internal Browning index (IB) as affected by in-package storage CO₂ (A, C) or O₂ (B, D) in PACK3 samples stored at 5 °C (A, B) or 18 °C (C, D) for 7 d. Each package contained 6 artichokes, and the total number of packages was 30. At the base of each histogram is reported the number of packages whose in-package CO₂ or O₂ partial pressure was the corresponding value reported below in the x-axis. Vertical bars represent the standard deviation of IB of the number of artichokes in the packages reported in each histogram (6 artichokes per package).



Fig. 5. Slight (A) or moderate (B) Internal blackening of 'Spinoso sardo' artichoke packaged with PVC film after 7 d at 18 °C.

imperfections in the sealing process which led to unpredictable results in terms of overall barrier characteristics of individual packaging. In fact, based on results of respiration activity of un-packaged artichokes, size of packages and barrier properties of the used films, the in-package levels of CO₂ and O₂ should have been markedly higher and lower, respectively, than those detected. Consequently, the expected gas exchange of both PACK2 and particularly PACK3 should have not be suitable to match O₂ requirements of packaged artichoke. In fact, in all cases the prediction of in-package air composition would lead to much higher levels of CO₂ and O₂ partial pressures close to 0, especially at 18 °C. Yet, based on the ratio of CO₂ permeance/O₂ permeance of Film1 and Film2,

also the ratio of in-package CO₂ and O₂ should have been quite different. Nevertheless, those imperfections leading to an increase in gas exchange, unexpectedly improved the maintenance of overall quality, as shown by the trend of IB.

These results confirm the crucial role played by packaging design in maintaining the freshness, quality, and extending the shelf life of artichokes during transport and storage (Ruíz-Jiménez et al., 2014; Giménez et al. 2022). In conclusion, neither PACK2 nor PACK3 are suited to match optimal conditions of gas exchange required by artichoke respiration. In fact, at room temperature, all artichokes of PACK2 and PACK3 with less sealing imperfections showed severe symptoms of IB.

For this reason, in the subsequent experiment where we compared the quality of 'Spinoso Sardo' artichoke grown under conventional or organic systems we used Film1, which thanks to the micro-pores guaranteed and optimal in-package RH while maintaining the same in-package gases composition of air.

Therefore, investing in research and development for an effective packaging solution can have a significant impact on the overall success of the artichoke marketability and contribute to companies' profitability.

3.2. Respiratory activity, in-packages gas composition and ethylene production rate

Initially respiration rate of un-packaged organic artichoke was significantly higher than un-packaged conventional ones (Fig. 7A). However, upon transfer to 5 °C differences between CONV and ORG samples were not significant both in un-packaged and in packaged ones, apart the first day (Fig. 7). Similarly, differences between CONV and ORG artichokes were not significant when samples from cold storage



Fig. 6. Mould development in 'Spinoso sardo' artichoke packaged with micro-perforated film after 5 d at 18 °C.

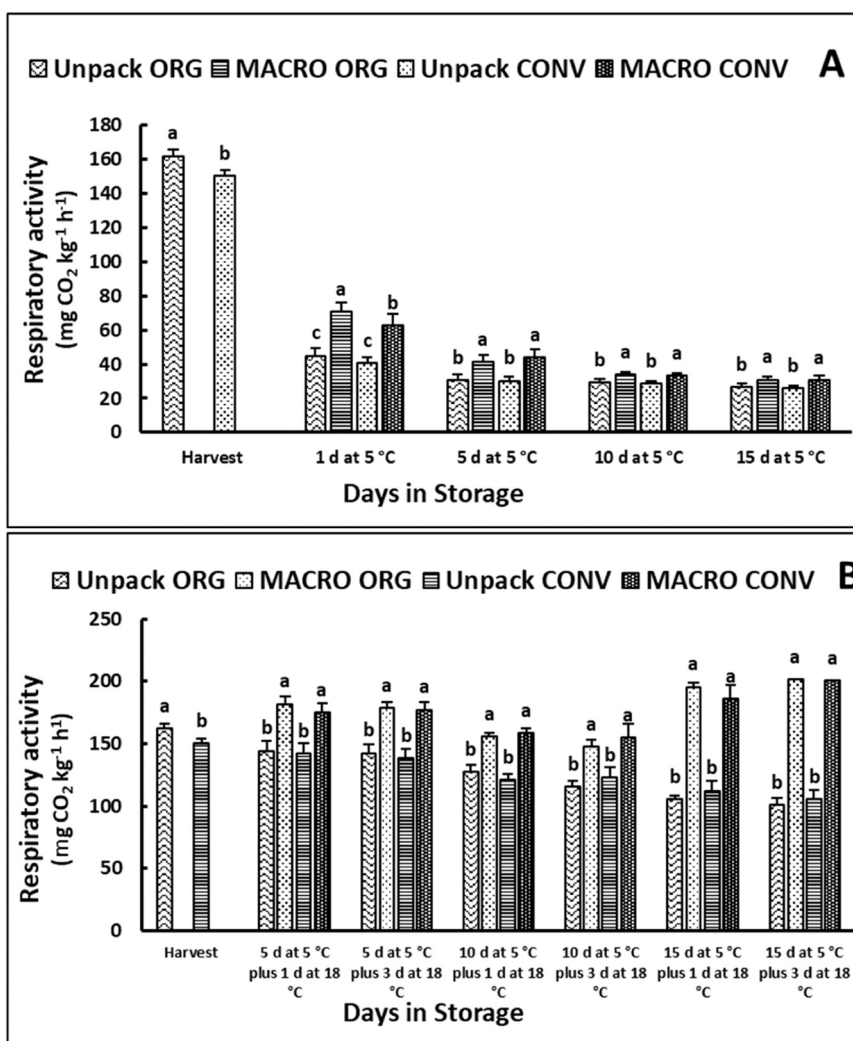


Fig. 7. Respiratory activity as carbon dioxide release in unpackaged or packaged conventional (CNV) or organic (ORG) 'Spinoso sardo' artichoke stored at 5 °C (A) for 5, 10 or 15 d and then transferred to simulated marketing conditions at 18 °C (B). For each storage time, columns with different letters are significantly different at $P \leq 0.05$ according to ANOVA analysis. Means separation was accomplished by the Tukey test. Vertical bars represent the standard deviation ($n = 6$).

were transferred to SMC at 18 °C (Fig. 7B). Respiration of packaged artichoke was always higher than un-packaged ones, although with storage differences become slighter (Fig. 7B). Overall, respiration activity was similar to respiration of 'Blanca Tudela' artichokes harvested in winter (Izquierdo et al., 2002; Gimenez et al., 2022), but slightly higher than those reported by Keder (2002). Transferring artichokes from 18 °C to 5 °C induced an about 5-fold reduction in respiration rate

of un-packaged samples after 1 d and of 9-fold after 15 d (Fig. 7 A).

This decline in respiration rate is common when fruits and vegetables from warmer temperatures are transferred to colder conditions, due to reduction in metabolic processes at lower temperature (Saltveit, 2003; Saltveit, 2019). Gil-Izquierdo et al. (2002) observed a similar pattern of respiration rate during cold storage for the 'Blanca de Tudela' artichoke. In contrast, Gimenez et al. (2022) found that respiration in the same

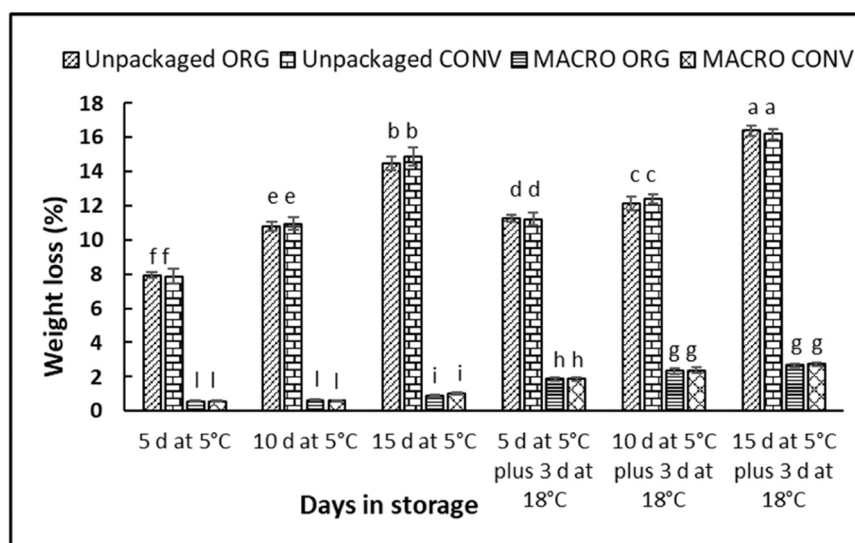


Fig. 8. Weight loss of ORG (organic) and CONV (conventional) un-packaged and packaged with macro-perforated film (MACRO) 'Spinoso sardo' artichokes after 5, 10 or 15 d at 5 °C followed by an additional 3 d at 18 °C. Columns with different letters are significantly different at $P \leq 0.05$ according to ANOVA analysis. Means separation was accomplished by the Tukey test. Vertical bars represent standard deviation ($n = 9$).

cultivar declined after 7 d of storage at 2 °C but then increased slightly during the subsequent 14 and 21 d of storage. A decline in respiration can also occur when tissues undergo to severe water stress. In fact, in packaged samples, exposed to higher levels of humidity compared to un-packaged artichokes, the minor water stress was associated with a delay in senescence and a slighter decrease in respiration with storage (Lyons and Breidenbach, 1990; D'Aquino et al., 2010). This trend was more evident when samples from 5 °C were moved to SMC at 18 °C, with packaged samples showing markedly higher respiration rates than unpackaged samples. On the other hand, the increasing trend in respiration of packaged artichokes after 1 or 3 d following 15 d of cold storage, compared to samples stored for 10 d (Fig. 7B), can result from incipient microbiological infections due to the higher level of humidity associated with the warm temperature.

Similar results have been reported by Palma et al., (2023) who found an increase in respiratory activity in packaged figs when transferred from refrigerated storage to room temperature. D'Aquino et al., (2010) also observed an overall increase in respiratory activity in pomegranate fruit wrapped with polyolefin heat-shrinkable film after being transferred from 8 to 20 °C, but the values were 35–22 % and 44–39 % lower than at harvest after 6 and 12 weeks of cold storage, respectively.

The increase in respiratory activity when fruit are transferred from refrigerated conditions to room temperature represents a crucial aspect for packaged produce that must be considered when designing a package, to prevent potential anaerobic conditions and/or quality losses.

Consistent with preliminary results, the gas composition inside the packages remained similar to atmospheric values during 5 and 10 d of cold storage and in each SMC as well. Palma et al., (2023b) also observed similar slight changes in gas composition inside the packaging during the cold storage period and the following SMC for 'Tondo Nero' figs packaged with a macro-perforated film.

However, after 15 d of cold storage plus 1 and 3 d of SMC at 18 °C, the internal atmosphere inside the packages underwent slight modification, reaching a CO₂ partial pressure of 1.08, and 2.32 kPa (data not shown). The slight changes of the atmosphere composition inside the packaging after 15 d of cold storage, plus 1 and 3 d at 18 °C can be attributed to the increase in respiratory activity associated with the physiological decay of the artichokes and the beginning of root development.

In agreement with the classification of artichoke as very low ethylene producer (Kader, 1992; Gil-Izquierdo, 2002), no detectable production of C₂H₄ was observed during refrigerated storage at 5 °C or under SMC

Table 1

Average values of relative humidity (RH), temperature (T) and dew-point (D.P.) detected in the cold room environment and inside the artichoke packages during cold storage (CS) and in simulated marketing conditions (SMC).

Treatments	% RH	T °C
Storage room environment at 5 °C	91.2 ± 6.35*	5.4 ± 0.40*
Storage room environment at 18 °C	61.5 ± 4.22	18.3 ± 0.21
ORG in-package head space at 5 °C	98.2 ± 1.23	5.2 ± 0.39
CONV in-package head space at 5 °C	98.3 ± 1.28	5.2 ± 0.21
ORG in-package head space at 18 °C	100 ± 0.00	18.2 ± 0.1
CONV in-package head space at 18 °C	100 ± 0.00	18.2 ± 0.1

*Values in column represent the average relative humidity (RH) and temperature (T) over the CS ($n = 120$) and the SMC ($n = 60$) periods.

conditions at 18 °C, except on the third day of SMC after 15 d of storage, when approximately 0.6 ppm of ethylene was detected inside some packages (data not shown). Ethylene was only found in packaged artichokes where degradation or mould development was observed.

3.3. Weight loss and overall acceptability

The primary cause of artichoke deterioration after harvest is water loss due to the high transpiration rate that occurs even under cold storage conditions (Izquierdo et al., 2002; Gimenez et al., 2022). As shown in Fig. 8, no difference was observed in weight loss among artichokes from the two different cropping systems, while significant differences were observed between packaged and unpackaged artichokes. During cold storage, unwrapped artichokes exhibited substantial weight loss, reaching approximately 8 %, 11 %, and 15 % after 5, 10, and 15 d of storage, respectively.

Similar results were obtained by Gil-Izquierdo et al., (2002) and Gimenez et al., (2022). In both studies weight losses of about 15 % were observed in unpackaged heads after 14 d of storage at 2 °C. In contrast, packaged artichokes wrapped with different polymeric films and stored at 5 °C experienced weight loss less than 1.7 % after 8 d of storage (Gil-Izquierdo et al., 2002).

In our study, the packaging played a significant role in reducing weight loss and consequently in the maintenance of artichoke heads freshness. This positive effect is attributed to the packaging's ability to generate and maintain adequate levels of humidity inside the packages during storage, despite did not affect the levels of CO₂ and O₂ compared

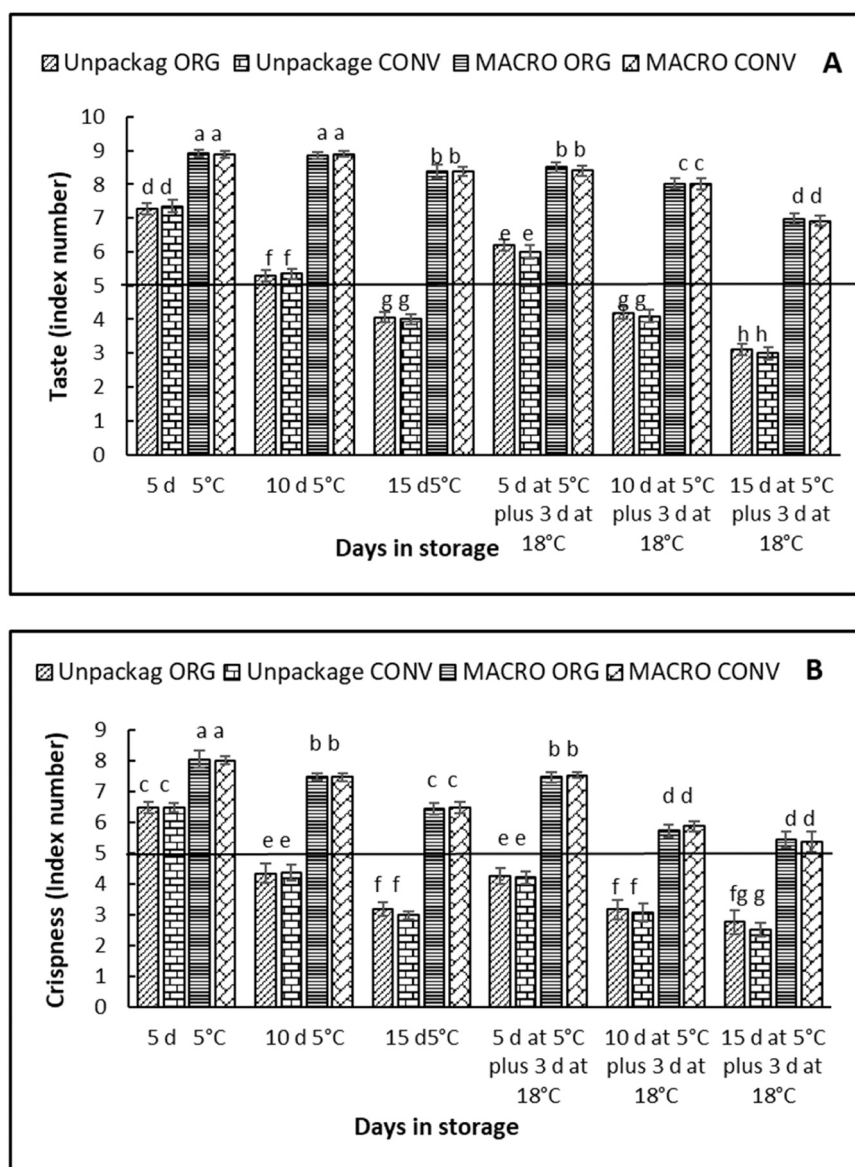


Fig. 9. Taste (A) and perceived crispness (B) of ORG (organic) and CONV (conventional) un-packaged and packaged with macro-perforated film (MACRO) ‘Spinoso sardo’ artichoke after 5, 10 or 15 d at 5 °C followed by an additional 3 d at 18 °C. Columns with different letters are significantly different at $P \leq 0.05$ according to ANOVA analysis. Means separation was accomplished by the Tukey test. Vertical bars represent standard deviation ($n = 6$). Point 5 represents the limit of marketability.

to the ambient atmosphere. In fact, as shown in Table 1 an RH level of approximately 98 % within the packages was achieved both at 5 °C and in SMC at 18 °C. The microenvironment created by the macro-perforated plastic film prevented the artichokes from drying out and extended the shelf life by preserving freshness, taste, and crispness better than the in un-packaged samples (Fig. 9 A, 9 B). Unpackaged artichokes were judged below the marketability limit, identified as an index number of 5, after 15 d of refrigerated storage for taste and 10 d for crispness. After 3 d at 18 °C following 10 d at 5 °C, unwrapped artichokes were rated about 4 for taste and 3 for crispness, while packaged artichokes were scored over 8 for taste and 6.5 for crispness. Following 15 d of cold storage and the subsequent 3 d of SMC, packaged artichokes were rated about 7 for taste and 5.5 for crispness (Figs. 9A, 9B). Despite the panellists’ observation of slight but significant textural differences, the overall quality of packaged artichokes remained appreciable after 15 d of storage. This highlights the effectiveness of the packaging in mitigating the adverse effects of storage on artichoke freshness.

Our results confirm previous reports showing the loss of freshness when most fruits and vegetables lose 3–10 % of the initial weight (Ben-Yehoshua and Rodov, 2002; D’Aquino et al., 2016; Afsah-Hejri et al., 2021). Yet, we found that taste and crispness began to decline when weight loss exceeded 8 %, indicating that artichoke quality is highly dependent on tissue hydration, a condition that is effectively achieved using the macro-perforated film.

3.4. Bracts browning, internal core blackening evaluation, mold development, texture properties and fibres content

No bracts browning or internal core blackening was detected in packaged artichokes of both growing systems during the entire storage period (data not shown). Bracts browning or internal core blackening in packaged artichokes is generally attributed to CO₂ levels above 10 % and/or O₂ concentrations below 2 % (Micolis and Saltveit, 1988; Conesa et al., 2001; Amodio et al., 2020). In our study, the use of macro-perforated film by maintaining CO₂ and O₂ concentrations inside

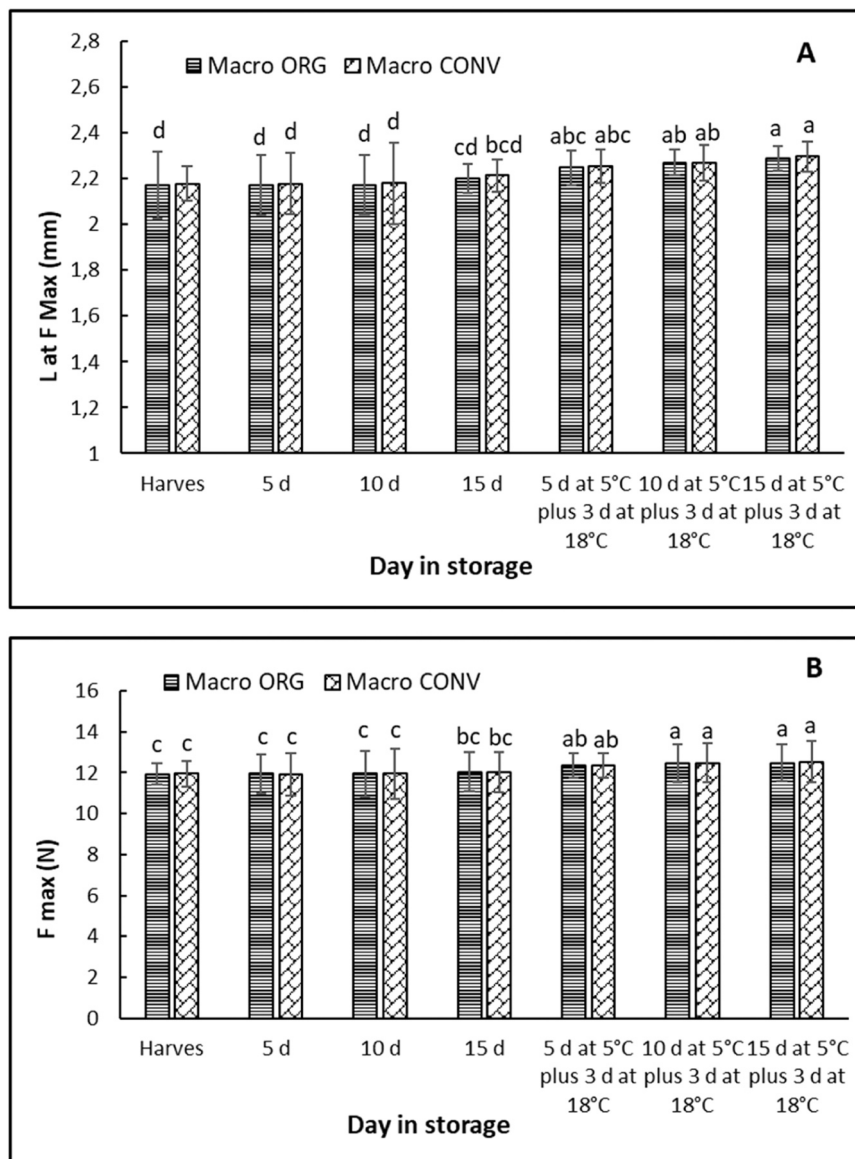


Fig. 10. Texture analysis as surface deformation of the bracts before the penetration (L at F max **A**) and resistance to penetration (F Max **B**) of ORG (organic) and CONV (conventional) packaged ‘Spinoso sardo’ artichoke with macro-perforated film (MACRO) at harvest and after 5, 10 or 15 d at 5 °C followed by an additional 3 d at 18 °C. Columns with different letters are significantly different at $P \leq 0.05$ according to ANOVA analysis. Means separation was accomplished by the Tukey test. Vertical bars represent standard deviation ($n = 18$).

the packages at levels similar to conventional atmosphere, effectively prevented any adverse effect on artichoke’s colour changes.

Similarly, no mould was detected in artichokes of both growing systems after 5 and 10 d of refrigerated storage and during each respective SMC period. However, mould developed in 5 % of packages after 15 d of storage at 5 °C and in 15 % at the end of the subsequent 3 d of SMC at 18 °C (data not shown), likely due to the high in-package level of humidity.

Texture is a crucial quality attribute in artichoke heads, as tissue softening occurs at a very high rate after harvest if not effectively managed through strategies aimed at preventing water loss. Softening can render the artichoke unappealing to consumers, particularly when consumed raw. Among the various factors influencing softening, storage temperature and packaging system assume paramount importance.

Considering the high perishability of un-packed artichoke which just after the 3 d at 18 °C following 5 d of storage at 5 °C lost most of the initial organoleptic quality, being judged below the limit of marketability, from now on we did not show results of un-packed artichokes

and restricted comparison only between packaged CONV and ORG samples.

The results regarding textural evolution are reported in Fig. 10 A as deformation of the bract surface before penetration (L at F max) and in Fig. 10 B as maximum force required for penetration (Fmax), respectively. Negligible changes both in deformation and resistance to puncture were observed during cold storage. In contrast, substantial changes in textural properties occurred during each SMC period, likely due to water loss which drove to a loss of crunchiness and an augmentation of rubberiness of the bracts. The two cropping systems did not affect textural properties neither at harvest nor over the storage period (Figs. 10A, 10B).

Although previous studies investigated the impact of harvest time on textural profile of ‘Spinoso Sardo’ artichoke grown in conventional and organic orchards (Di Salvo et al., 2014; Palma et al. 2023a), to our knowledge, this is the first study to specifically evaluate the texture characteristics of packaged artichokes and their changes during cold storage.

Table 2

Fiber percentage (based on dry weight) as neutral detergent fibres (NDF), acid detergent fibres (ADF), acid detergent lignin (ADL), and cellulose (CELL) in CONV (conventional) and ORG (organic) packaged ‘Spinoso sardo’ artichoke with macro-perforated film at harvest and after 5, 10 or 15 d at 5 °C followed by an additional 3 d at 18 °C.

		Harvest	5 d at 5 °C	10 d at 5 °C	15 d at 5 °C	5 d at 5 °C plus 3 d at 18 °C	10 d at 5 °C plus 3 d at 18 °C	15 d at 5 °C plus 3 d at 18 °C
NDF (%)	CONV	24.4 ± 0.5 A b	24.7 ± 1.0 A b	25.3 ± 0.1 A ab	26.0 ± 0.8 A ab	24.8 ± 0.4 A b	26.0 ± 1.2 A ab	27.9 ± 1.0 A a
	ORG	25.1 ± 0.8 A a	24.3 ± 0.9 A a	24.4 ± 0.9 A a	26.4 ± 0.5 A a	25.2 ± 0.5 A a	26.4 ± 1.6 A a	26.7 ± 0.5 A a
ADF (%)	CONV	19.9 ± 0.3 A a	20.5 ± 0.9 A a	20.0 ± 0.8 A a	19.5 ± 1.2 A a	21.4 ± 0.7 A a	20.2 ± 1.0 A a	19.8 ± 1.6 A a
	ORG	21.5 ± 0.4 A a	21.3 ± 0.6 A a	19.3 ± 0.9 A a	19.7 ± 1.6 A a	21.2 ± 0.6 A a	21.3 ± 0.8 A a	20.7 ± 1.5 A a
ADL (%)	CONV	13.8 ± 0.5 A a	13.3 ± 0.8 A a	9.9 ± 0.8 A c	10.3 ± 1.0 A c	12.5 ± 0.8 A b	10.3 ± 0.9 A c	10.8 ± 0.9 A c
	ORG	13.7 ± 0.4 A a	13.6 ± 0.6 A a	10.5 ± 0.9 A c	10.9 ± 0.8 A c	12.4 ± 0.9 A b	10.0 ± 0.8 A c	10.4 ± 1.1 A c
CELL (%)	CONV	6.1 ± 0.8 A c	7.2 ± 1.0 A bc	8.9 ± 1.4 A ab	10.1 ± 1.1 A a	9.9 ± 0.9 A ab	10.2 ± 0.7 A a	8.9 ± 0.7 A bc
	ORG	7.8 ± 0.9 A b	7.7 ± 1.2 A b	8.7 ± 1.9 A b	9.2 ± 1.5 A b	11.2 ± 0.9 A a	9.4 ± 1.6 A b	10.3 ± 0.7 A ab

Values of each parameter for samples of each growing system over storage at 5 °C or in SMC (5, 10 or 15 d at 5 °C plus 3 d at 18 °C) not followed by lowercase letters (rows) are significantly different at $P \leq 0.05$ according to Tukey’s multiple range test; for each storage time values in columns not followed by the same capital letters are significantly different at $P \leq 0.05$. “±” stands for standard deviation of the mean (n = 3).

Table 3

Sugar content in CONV (conventional) and ORG (organic) packaged ‘Spinoso sardo’ artichoke with macro-perforated film at harvest and after 5, 10 or 15 d at 5 °C followed by an additional 3 d at 18 °C. Values expressed as g 100 g⁻¹ fresh weight.

		Harvest	5 d at 5 °C	10 d at 5 °C	15 d at 5 °C	5 d at 5 °C plus 3 d at 18 °C	10 d at 5 °C plus 3 d at 18 °C	15 d at 5 °C plus 3 d at 18 °C
Sucrose	CONV	0.49 ± 0.01 A b	0.52 ± 0.01 A ab	0.53 ± 0.01 A ab	0.54 ± 0.010 A a	0.53 ± 0.01 A ab	0.54 ± 0.01 A a	0.51 ± 0.01 A ab
	ORG	0.50 ± 0.02 A a	0.51 ± 0.01 A a	0.51 ± 0.08 A a	0.51 ± 0.01 A a	0.51 ± 0.01 A a	0.51 ± 0.01 A a	0.50 ± 0.01 A a
Glucose	CONV	1.35 ± 0.01 A a	1.24 ± 0.01 A a	1.24 ± 0.02 A a	1.10 ± 0.03 A b	1.24 ± 0.01 A a	1.04 ± 0.03 A b	0.81 ± 0.07 A c
	ORG	1.32 ± 0.01 A a	1.23 ± 0.01 A a	1.22 ± 0.01 A b	1.11 ± 0.02 A c	1.23 ± 0.02 A b	1.01 ± 0.08 A c	0.77 ± 0.05 A d
Fructose	CONV	0.65 ± 0.01 A a	0.64 ± 0.01 A a	0.64 ± 0.01 A a	0.64 ± 0.01 A a	0.64 ± 0.01 A a	0.65 ± 0.01 A a	0.65 ± 0.01 A a
	ORG	0.64 ± 0.003 A a	0.64 ± 0.01 A a	0.63 ± 0.01 A a	0.65 ± 0.01 A a	0.65 ± 0.01 A a	0.65 ± 0.01 A a	0.65 ± 0.01 A a
Total	CONV	2.50 ± 0.01 A a	2.41 ± 0.02 A a	2.43 ± 0.03 A a	2.42 ± 0.03 A a	2.24 ± 0.03 A b	2.29 ± 0.01 A b	1.98 ± 0.08 A c
	ORG	2.47 ± 0.03 A a	2.38 ± 0.02 A b	2.40 ± 0.04 A ab	2.37 ± 0.01 A b	2.17 ± 0.07 A d	2.29 ± 0.01 A c	1.93 ± 0.04 A e

Values of each parameter for samples of each growing system over storage at 5 °C or in SMC (5, 10 or 15 d at 5 °C plus 3 d at 18 °C) not followed by lowercase letters (rows) are significantly different at $P \leq 0.05$ according to Tukey’s multiple range test; for each storage time values in columns not followed by the same capital letters are significantly different at $P \leq 0.05$. “±” stands for standard deviation of the mean (n = 3).

Dietary fiber, a non-digestible form of carbohydrate abundant in plant-based foods, plays an important role in promoting overall health and well-being. Its consumption can positively impact digestive health, aid in weight management, enhance heart health, regulate blood sugar levels, and even lower the risk of colon cancer (Tungland and Meyer, 2002; He et al., 2022).

Artichokes are known for their high dietary fiber content, providing remarkable health advantages (Frutos et al., 2019; Fissore et al., 2015). However, studies on artichoke fiber content have predominantly focused on its quantification at harvest time in different growing systems and harvest times (Fateh et al., 2009; Palma et al., 2023a), while, at our knowledge, the changes in fiber content of fresh or packaged artichokes during storage has never been monitored.

Thus, this study for the first time focused on changes occurring in dietary fiber during storage. Table 2 reports the impact of packaging on the fiber content of both CONV and ORG globe artichokes over storage and the subsequent SMC periods at 18 °C.

At harvest, dietary fiber was not affected by the cropping systems. However, both NDF and CELL content increased significantly over storage. Specifically, in CONV artichokes, the NDF values rose by 12 % after 15 d at 5 °C plus 3 days at 18 °C, whereas in ORG artichokes, the increase was about 6 % although not statistically significant. Nonetheless, when considering only the storage period at 5 °C, no significant differences were observed compared to harvest for both ORG and CONV artichokes.

ADL content displayed a significant decrease after 10 d of storage at 5 °C. This decline was consistent for both CONV and ORG artichokes, with approximately 28 % and 23 %, respectively. Subsequently, the ADL content remained stable during the following 5 d of cold storage. Regarding the ADF values, they were not influenced by storage.

The NDF values of the bracts were consistent with those reported by Attia et al. (2016), Salman et al. (2014), and Palma et al. (2023a). However, the ADF, ADL, and CELL values, although in agreement with those found by Palma et al. (2023a), exhibited lower concentrations compared to previous research by Allahdadi et al. (2020).

Based on the overall trend in the fiber content of artichokes from both cultivation systems during the storage period, we can conclude that the packaging successfully preserved their fiber content.

3.5. Carbohydrates, total phenol content, phenolic compounds, and antioxidant activity

Sugars and phenolic compounds play a significant role in characterizing the taste and health properties of fruit and vegetable products.

In Table 3, the changes of sucrose, glucose, fructose, and total sugars are reported. The sugar content was not affected by the cultural system and remained relatively stable during the storage period, except for glucose, which showed a significant reduction during storage.

Since glucose is the most abundant sugar, the evolution of total sugars during storage had a trend similar to glucose, showing a

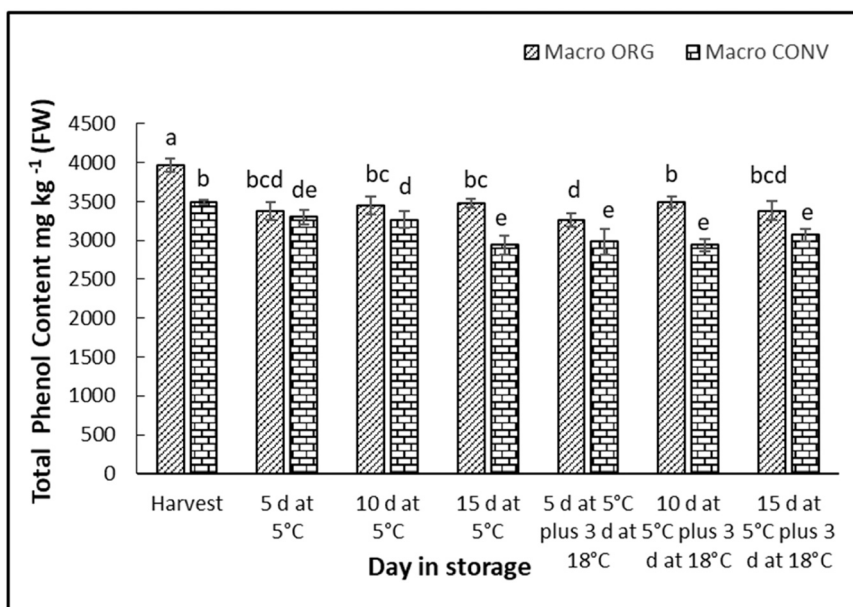


Fig. 11. Total phenolics content, expressed as mg kg^{-1} of gallic acid equivalents on fresh weight (FW), in organic (ORG) and conventional (CONV) ‘Spinoso sardo’ artichokes packaged with macro-perforated film at harvest and after 5, 10 or 15 d at 5°C followed by an additional 3 d at 18°C . Columns with different letters are significantly different at $P \leq 0.05$ according to ANOVA analysis. Means separation was accomplished by the Tukey test. Vertical bars represent standard deviation ($n = 3$).

significant decrease when the artichokes were transferred to SMC.

Similar results regarding the sugar content of ‘Spinoso sardo’ artichoke in both organic and conventional grown systems were obtained by Palma et al. (2023a). However, no published study has yet compared the evolution of sugar changes during storage of packaged artichokes cultivated organically or with conventional grown systems. In other crops, there has been a significant variability in sugar content, with contrasting results between organic and conventional produce. Suja et al. (2017) and Hallmann (2012) reported higher sugar levels in organically produced taro and tomatoes compared to conventional crops, whereas Lombardo et al. (2012) showed opposite results, with higher sugar content in conventionally grown tomatoes. In contrast, Lester et al. (2007), Çandır et al. (2013), and Bach et al. (2015) found no significant difference in sugar content between organic and conventional grapefruits, oranges, and carrots. In our study, at harvest, no significant difference was observed in the sugar content of artichokes from the two cultivation systems. During the SMC, a slight reduction in total sugar content was observed, likely attributed to the enhanced metabolic activity triggered by the temperature change from 5°C to 18°C .

Artichokes are a rich source of polyphenols that contribute to the appearance, taste, and flavour of products, as well as to their health-promoting properties. The polyphenol content can be influenced by various factors, including the variety, the cropping system, and the environmental conditions (Lattanzio et al., 2009; Pandino et al., 2011).

This study found that both the cropping system and storage time significantly impacted the total phenolics content (Fig. 11). At harvest, ORG artichokes exhibited a higher level of phenolic compounds, reaching a value of 3967 mg kg^{-1} , while CONV samples showed values of 3491 mg kg^{-1} (Fig. 11). Similar results were found by Palma et al. (2023a) in ‘Spinoso sardo’ artichokes from organic and conventional growing systems, harvested at different stages of the cultivation cycle.

The evolution of total phenol content during refrigerated storage showed a slight decreasing trend, affecting both samples of CONV and ORG cropping systems. In both cropping systems, the total phenolic compounds declined during storage at 5°C and in SMC, with losses at the end of each storage period accounting for approximately 12%.

Various factors, including genotype, harvest time, growing system,

and extraction methods, can affect the total phenolic content of fruits and vegetables. Researchers have observed fluctuations in the total phenolic content of fresh fruits and vegetables during storage. These fluctuations may involve increases or decreases in response to stress from low temperatures, leading to alterations during the storage period and resulting in chilling injuries or loss of quality. These changes can be attributed to the activity of enzymes such as phenylalanine ammonia-lyase and polyphenoloxidase, which, influenced by the different variety of fruit or vegetables subjected to low temperatures, can activate mechanisms responsible for variations in phenolic content (Lattanzio et al. 2009; Patthamakanokporn et al. 2008). D’Aquino et al. (2010) observed a decreasing trend in total phenols during cold storage in wrapped pomegranate fruit, and Palma et al. (2023b) reported a comparable trend in figs packaged with various packaging solutions. Similarly, Napolitano et al. (2004) and Goluas et al. (2014), in studies involving cold-stored apples, observed a decrease in total phenolic compounds attributed to a combination of factors. These factors included changes in the relative amounts of individual phenolic compounds characterized by different molar extinction coefficients, resulting in a varying contribution to the value of absorbance during spectrophotometric quantification and at the activity of phenylalanine ammonia-lyase and polyphenoloxidase enzymes.

While Gil-Izquierdo et al. (2001), in a study on the effect of storage temperature on the phenolic content of artichoke heads (cv. Blanca de Tudela), found that after 14 d at 5°C , the total phenolic compounds were similar in external bracts and higher in internal bracts compared to harvest time. However, after 14 d at 0°C , no difference was observed. In a study by Gil-Izquierdo et al. 2002, on artichokes cv. Blanca de Tudela packaged with films characterized by a different gas permeability and stored for 8 d at 5°C , the internal head portion of the artichokes exhibited a similar content in total phenolic compounds when packaged with a perforated polypropylene film, a slight increase in a micro-perforated polypropylene film, and a more marked increase in a low-density polyethylene and polyvinyl chloride film compared to harvest time. The different response in the total phenols content is attributed to the different modified atmospheres generated by the plastic films employed. More specifically, in perforated polypropylene film, the concentrations of CO_2 and O_2 within packages were similar to

Table 4

Phenolic compounds detected in CONV (conventional) and ORG (organic) packaged ‘Spinoso sardo’ artichoke with macro-perforated film at harvest and after 5, 10 or 15 d at 5 °C followed by an additional 3 d at 18 °C. Values expressed as mg kg⁻¹ fresh weight.

		Harvest	5 g	10 g	15 g	5 g S.L.	10 g SL	15 g SL
Neochlorogenic acid	CONV	98 ± 2.12 B b	101 ± 5.12 A a	86 ± 3.61 B b	81 ± 6.60 A a	93 ± 4.12 B a	96 ± 7.11 B a	94 ± 5.13 B a
	ORG	116 ± 1.00 A b	123 ± 10.5 A a	142 ± 8.19 A a	128 ± 4.08 A a	129 ± 8.08 A a	136 ± 4.06 A a	134 ± 5.00 A a
Chlorogenic acid	CONV	1380 ± 63 B a	1280 ± 88.4 B b	1229 ± 80.9 A b	1086 ± 38.6 A c	1082 ± 94.5 A c	920 ± 112.3 B d	907 ± 54.3 A d
	ORG	1628 ± 27 A a	1587 ± 19.1 A a	1425 ± 118.2 A b	1327 ± 66.2 A c	1311 ± 105.2 A c	1285 ± 74.1 A c	1079 ± 50.0 A d
1-O-Dicaffeoylquinic acid	CONV	4 ± 0.311 B b	0.9 ± 0.43 A b	4 ± 0.26 A b	5 ± 0.61 A b	4 ± 0.81 A b	5 ± 0.62 A b	5 ± 0.36 A b
	ORG	8 ± 0.222 A a	0.3 ± 0.35 A b	5 ± 0.23 A b	5 ± 0.46 A b	4 ± 0.30 A b	5 ± 0.33 A b	5 ± 0.40 A b
3,5-O-Dicaffeoylquinic acid	CONV	701 ± 40.2 B g	753 ± 27.8 B g f	853 ± 47.6 B e f	913 ± 20.3 B cde	893 ± 7.05 B de	884 ± 2.11 A de	776 ± 33.4 B f g
	ORG	891 ± 22.3 A de	934 ± 24.9 A cde	1057 ± 45.1 A a	1010 ± 51.1 A ab	997 ± 55.3 A ab	943 ± 26.2 A cde	978 ± 21.2 A bcd
1,5-O-Dicaffeoylquinic acid	CONV	1080 ± 50.2 B b	1131 ± 12.6 A ab	861 ± 67.3 B de	812 ± 40.3 B ef	994 ± 84.2 A bcd	788 ± 66.7 B ef	659 ± 38.2 B f
	ORG	1282 ± 43.9 A a	1160 ± 70.1 A ab	1101 ± 30.4 A b	1053 ± 54.7 A bc	1020 ± 68.1 A bcd	1004 ± 84.0 A bcd	897 ± 30.4 A cde

Values of each parameter for samples of each growing system over storage at 5 °C or in SMC (5, 10 or 15 d at 5 °C plus 3 d at 18 °C) not followed by lowercase letters (rows) are significantly different at $P \leq 0.05$ according to Tukey’s multiple range test; for each storage time values in columns not followed by the same capital letters are significantly different at $P \leq 0.05$. “±” stands for standard deviation of the mean ($n = 3$).

atmospheric levels, conditions closely to those observed in our study. Differently, [Gimenez et al. \(2022\)](#) observed a contrasting evolution of the total phenolic content in artichokes stored for 21 d at 2 °C. The changes depended on the order of artichoke head harvest (main, secondary, and tertiary) and the harvest period (winter or spring). Particularly, at the end of the storage period, no difference was found in the total phenolic content in the main and secondary heads collected in the winter period and in the primary heads collected in the spring. However, an increase in the total phenolic content was observed in the tertiary flower heads collected in winter and in both secondary and tertiary heads collected in spring. Regarding the total content of luteolins, they reported an increase independent of the order and period of collection.

The authors attributed the increase to the activation of the phenylpropanoid biosynthetic pathway during cold storage as a defence mechanism against stress induced by low temperatures. However, another important factor in this research that may have contributed to the changes found in the phenolic content could be represented by the stress suffered by the artichokes due to weight loss, reaching values of approximately 25 % after 21 d of storage. Similarly, [Martínez-Esplá et al. \(2017\)](#) observed in artichokes an increase in total phenolic content and individual phenolic compounds after 14 d of storage at 2 °C, attributing these trends to the concentration caused by a weight loss of approximately 15 %.

In addition to the total phenolic content, understanding the evolution of individual phenolic compounds during storage is crucial because their contribution to human health, role in determining antioxidant activity, and the total phenolic content differ based on the type and concentration of individual phenolic compounds ([Rice-Evans, 1999](#); [Napolitano et al., 2004](#); [Goulas et al., 2014](#)).

Table 4 reports the qualitative profile and quantitative content of phenolics detected in packaged ORG and CONV artichokes by chromatographic analysis, and their evolution during cold storage and in SMC.

The chromatography analysis of artichoke extracts, from both growing systems, revealed the presence of five principal phenolic compounds: neochlorogenic acid, chlorogenic acid (5-O-dicaffeoylquinic acid), 1-O-dicaffeoylquinic acid, 3,5-O-dicaffeoylquinic acid, 1,5-O-dicaffeoylquinic acid, and Apigenin 7-O-glucoside. In agreement with previous studies by [Lattanzio et al. \(2009\)](#), [Christaki et al. \(2012\)](#); [Spanu et al. \(2018\)](#) and [Palma et al., \(2023a\)](#), chlorogenic acid, followed by 1, 5-O-dicaffeoylquinic acid and 3,5-O-dicaffeoylquinic acid were identified as the main phenolics compounds in ‘Spinoso sardo’ artichokes (**Table 4**).

At harvest, chlorogenic acid, 1,5-O-dicaffeoylquinic acid and 3,5-O-

Dicaffeoylquinic acid accounted for about 97 % of the total detected phenolic compounds (**Table 4**). Moreover, the phenolic content was significantly influenced by cropping systems and storage time. At harvest, organic artichokes exhibited significantly higher levels of all detected phenolic compounds compared to conventional artichokes, with approximately 16 % more phenolic content. These findings are consistent with a previous study by [Leskovar and Othman \(2018\)](#), who found that organic soil management resulted in higher chlorogenic acid and cynarin levels in artichokes. Additionally, a general decreasing trend of the total sum of detected phenolic compounds was observed over the storage period. For ORG artichokes, there was a decrease of about 3 %, 5 %, and 10 % after 5, 10, and 15 d at 5 °C, respectively. In contrast, CONV artichokes exhibited decreases of 0 %, 7 %, and 11 % over the same respective periods. Individual phenolic compounds, however, showed varying responses to the storage time (**Table 4**).

In CONV artichokes, the concentration of neochlorogenic acid remained nearly constant throughout the refrigerated storage period and in SMC, as did the concentrations of 1-O-dicaffeoylquinic acid and 3,5-O-dicaffeoylquinic acid in both ORG and CONV artichokes. In contrast, neochlorogenic acid in ORG artichokes, showed a slight but significant increase after 5 days at 5 °C, maintaining a constant level during the subsequent storage periods, as well as in SMC.

In contrast to neochlorogenic acid, the contents of chlorogenic acid and 1,5-O-dicaffeoylquinic acid declined during refrigeration and in SMC.

Similarly, [Gimenez et al. \(2022\)](#) documented significant changes in the individual phenolic compounds of artichoke heads during a 21-day storage period at 2 °C. These changes were influenced not only by the harvesting period but also by the specific order in which the artichoke heads were harvested.

[Gil-Izquierdo et al. \(2002\)](#) found that packaging artichoke heads with perforated polypropylene film led to a decrease in chlorogenic acid levels in both the internal and external portions after 8 d of storage at 5 °C. However, for 1,5-O-dicaffeoylquinic acid + 1,5-O-dicaffeoylquinic acid, there were slight changes in the external portion and an increase in the internal portion. No significant change was observed in neochlorogenic acid levels for both the external and internal portions. Meanwhile, they observed a general increase in phenolic compounds when artichokes were packaged with low-density polyethylene and polyvinyl chloride films, where the oxygen concentration inside the packages was below 8 %, and the CO₂ concentration was above 10 %.

In our case, the reduction of detected phenolic compounds, considered as a whole, is likely attributable to the aging of the artichokes due to the storage period, as indicated by tests assessing acceptability, mould

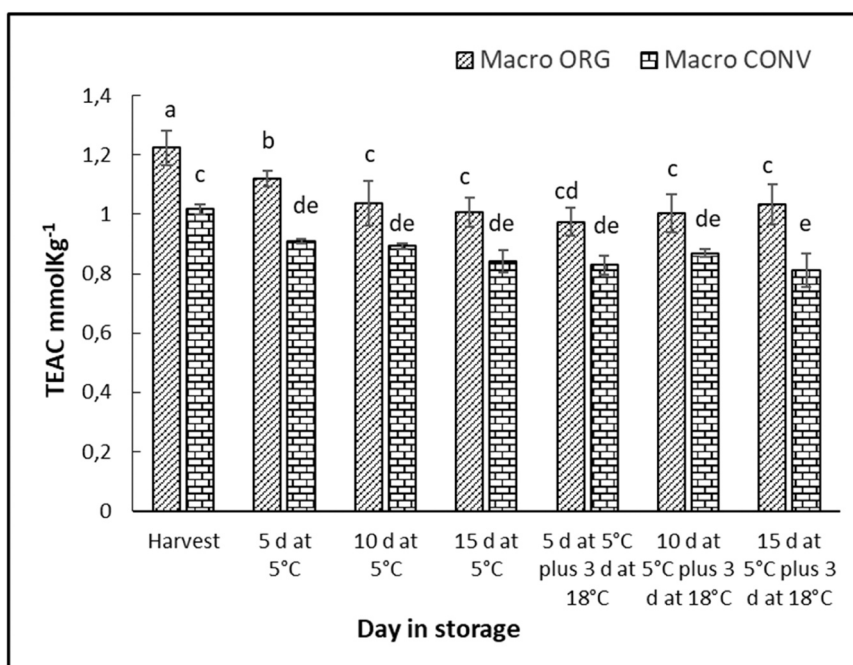


Fig. 12. Antioxidant activity in organic (ORG) and conventional (CONV) 'Spinoso sardo' artichoke packaged with macro-perforated film at harvest and after 5, 10 or 15 d at 5 °C followed by an additional 3 d at 18 °C. Columns with different letters are significantly different at $P \leq 0.05$ according to ANOVA analysis. Means separation was accomplished by the Tukey test. Vertical bars represent standard deviation ($n = 3$).

development, texture evolution, and weight loss. In postharvest, the phenolic content in fruits and vegetables is influenced by various factors affecting their biosynthesis or degradation, primarily through the activities of phenylalanine ammonia-lyase (PAL), polyphenol oxidases (PPO), and peroxidases (POD) enzymes. Storage at low temperatures can have both positive and negative effects on fruit and vegetable phenolics, depending on the specific commodity, the type of phenolic compound involved, and the storage temperature. Generally, storage at low temperatures stimulates PAL activity, leading to the accumulation of phenolics and anthocyanins. However, if alterations occur during storage, such as the development of mold or the senescence of the product,

resulting in the degradation of cell membranes, there may be oxidative degradation of the phenolic component may occur, catalysed by the activity of PPO released from the vacuoles (Tomás-Barberán, and Espín, 2001; Nunes et al., 2005; Lo Piero et al., 2005; Galani et al., 2017).

Several authors have observed a correlation between total phenolic content and antioxidant activity in different artichoke genotypes (Lutz et al., 2011; Cefola et al., 2012; Martínez-Esplá et al. 2017; Gimenez et al., 2022; Palma et al., 2023a).

In this study, the antioxidant activity (Fig. 12) reflected the trend observed in the total phenols (Fig. 11); yet, the antioxidant activity in ORG artichokes was generally higher than in CONV ones, while overall it

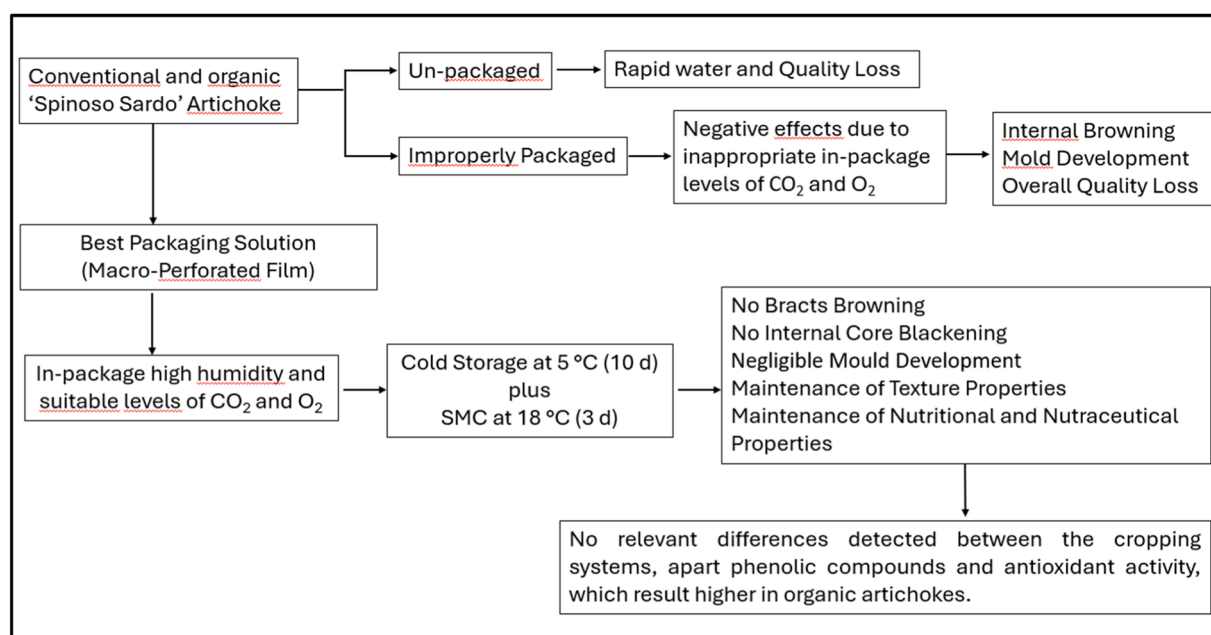


Fig. 13. Schematic representation of an appropriate packaging system on postharvest quality of 'Spinoso Sardo' artichokes.

tended to decrease by about the 16 % during storage, both in ORG and CONV artichokes (Fig. 12).

4. Conclusion

Results of this study show the high perishability of ‘Spinoso sardo’ artichokes, as previously observed for other cultivars. Preliminary studies showed a general poor handling management at retail level, where very often both packaged and un-packaged artichokes are displayed at room temperature, which resulted detrimental for overall quality in the case of un-packaged artichokes for the rapid water loss and tissue wilting whereas in packaged samples led to internal browning for the anaerobic conditions occurring inside the packages. The preliminary study also demonstrated that the type of packaging adopted by the local packinghouses were not driven by a rational design of the packaging but by the kind of films available on the market which better fitted to the kind of packaging machines available. Paradoxically, the frequent imperfections in the sealing process, by increasing the package gas exchange improved the gas requirement of packaged samples mitigating the negative effect deriving by in-package levels of CO₂ and O₂ not matching the tissues requirement for O₂.

The adoption of a macro-perforated film for packaging by assuring a high level of humidity without not substantially affecting the in-package gas composition resulted to be the best packaging solution which allowed to cold store ‘Spinoso sardo’ artichokes both CON and ORG for 10 d plus 3 d of SMC at 18 °C without relevant qualitative loss and microbiological alterations as outlined in Fig. 13.

CRediT authorship contribution statement

A. Palma: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **L. Iedda:** Writing – review & editing, Visualization, Validation, Supervision. **P.A. Deligios:** Writing – review & editing, Visualization, Validation, Supervision. **M.T. Tiloca:** Validation, Supervision, Methodology, Investigation. **M.M. Sass:** Formal analysis. **S. D’Aquino:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

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

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Data Availability

Data will be made available on request.

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