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Original Research Paper

Packaging impacts arugula microgreens quality under retail cold storage

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Abstract: The rapid perishability of microgreens poses a significant challenge to their commercialization, despite their high nutritional value and health benefits. This study addresses the need for effective preservation strategies to extend the shelf-life of arugula (*Eruca sativa* Mill.) microgreens, a particularly perishable product. The objective was to evaluate the impact of different packaging methods on maintaining the sensory, biochemical, and physiological attributes of arugula microgreens during refrigerated storage. Arugula microgreens were grown under controlled conditions. They were then packaged in non-perforated polypropylene bags (PB) or micro-perforated polypropylene bags (MPB), and compared to unpackaged samples (NP) under simulated supermarket conditions (10 °C with alternating 12-hour light/dark cycles). Shelf-life was assessed through sensory evaluation (visual and olfactory quality), headspace gas composition, chlorophyll content, antiradical activity, total phenolic compounds, and carotenoid profiles. Microgreens in MPB exhibited the best preservation, maintaining visual quality and minimizing off-odors for up to 14 days. Unpackaged samples deteriorated within seven days, and those in PB experienced excessive moisture accumulation. MPB packaging also maintained stable oxygen levels and prevented excessive carbon dioxide accumulation. MPB-stored microgreens retained higher chlorophyll and carotenoid content, with only a 15% reduction in chlorophyll after 14 days, indicating slower degradation. MPB bags are superior for preserving the quality and extending the shelf-life of arugula microgreens, offering practical benefits for the fresh produce industry by reducing waste and enhancing nutritional value.

Keywords: *Eruca sativa* Mill.; functional compounds; packaging; physiological attributes; postharvest; shelf-life.

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1. Introduction

Microgreens have emerged as a highly valued category of functional foods due to their rich nutritional profile, diverse flavors, and aesthetic appeal (Bonasia et al., 2024; Xiao et al., 2012; Set et al., 2025). These young seedlings, harvested at the cotyledon stage or when the first true leaves appear, have gained popularity among consumers and the food industry for their concentrated bioactive compounds, including vitamins, minerals, antioxidants, and polyphenols (Kyriacou et al., 2017). However, despite their numerous health benefits, the commercialization of microgreens faces significant challenges, primarily due to their short shelf-life (Di Gioia et al., 2017). Post-harvest degradation, characterized by loss of texture, discoloration, and diminished nutritional quality, limits their availability and increases food waste (Samuolienė et al., 2019). Therefore, understanding and optimizing preservation techniques is essential to ensure their marketability and extended freshness (Mamman Musa et al., 2017).

The shelf-life of microgreens is influenced by various factors, including their high metabolic rate, susceptibility to moisture loss, and sensitivity to microbial growth (Rouphael et al., 2021; Heena et al. 2025). Several preservation strategies, such as refrigeration, modified atmosphere packaging (MAP), and edible coatings, have been explored to maintain their quality post-harvest (Yan et al., 2022; Gunjal et al. 2025). Among these, packaging plays a crucial role in regulating gas exchange, controlling moisture accumulation, and preventing rapid deterioration (Turner et al., 2020). Previous research has demonstrated that packaging conditions can significantly affect sensory attributes, chlorophyll retention, and bioactive compound stability in microgreens (Pannico et al., 2020). Selecting the most effective packaging material is therefore critical to enhancing their commercial potential while minimizing nutritional losses (Ranjitha et al., 2023).

One of the major challenges associated with microgreen preservation is their rapid perishability. Unlike mature vegetables, microgreens have a high respiration rate, which accelerates their metabolic processes and leads to a faster decline in quality (Dubey et al., 2024; Heena et al., 2025). Additionally, their delicate tissues are highly prone to mechanical damage, dehydration, and microbial contamination (Bhaswant et al., 2023). The combination of these factors results in a limited shelf-life, often ranging from a few days to two weeks under refrigeration (Yan et al., 2022). As a result, there is a growing need for innovative post-harvest technologies that can effectively prolong freshness while maintaining the sensory and nutritional properties of these products (Grown and Ledwo, 2023). Research efforts in this direction are crucial for optimizing storage conditions and developing packaging solutions that cater to the needs of both producers and consumers (Du et al., 2025).

An innovative approach involves packaging microgreens along with their growing media, offering a ready-to-harvest vegetable product. (Turner et al., 2020). This approach offers potential advantages in maintaining plant hydration and minimizing mechanical damage during storage (Baghi et al., 2022) under simulated sale conditions such as temperature fluctuations and alternating periods of light and darkness (Rouphael et al., 2021). These conditions reflect real point-of-sales ones where nonoptimal cold storage can accelerate deterioration and impact product quality (Turner et al., 2020).

In the fresh produce supply chain, strict refrigeration (e.g., storage at ~4 °C) is advocated to maintain quality and safety of bagged leafy greens and microgreens, yet retail display temperatures often exceed these recommendations. For example, the FDA mandates that cut leafy greens be stored at 41 °F (≈5 °C) or below (FDA, 2010), since chilling to ~4 °C sharply inhibits pathogens (e.g. *Escherichia coli*) on lettuce (Stein, 2024). However, surveys of supermarket cold rooms and open cases reveal widespread temperature abuse. EFSA notes that even though 7 °C is recommended for marketing salad greens, actual display cases may reach 10–12 °C (EFSA, 2014). In one study of U.S. supermarkets, over 40% of sensors in produce displays recorded >7.2 °C (and 58% of storage sensors did so for ≥5% of the time) (Brown et al., 2016). Similarly, USDA researchers report that produce on open-front cases often exceeds the 5 °C limit (De Frias et al., 2015). Such elevated retail temperatures (7–10 °C or higher) accelerate senescence and favor microbial growth, highlighting a gap between ideal storage (4–5 °C) and real-world practice (EFSA 2024; Brown et al., 2016). Evaluating microgreens under these realistic conditions provides essential insights into their storage behavior and the effectiveness of different packaging techniques (Pannico et al., 2020).

Arugula microgreens (*Eruca sativa* Mill.), a widely consumed species, are particularly prone to rapid degradation due to their delicate structure and high respiration rate (Ranjitha et al., 2023). Studies have shown that changes in headspace gas composition, such as decreased oxygen levels and increased carbon dioxide concentrations, can alter physiological responses and accelerate spoilage (Dubey et al., 2024). Maintaining an optimal balance of oxygen and carbon dioxide within the packaging can help slow down enzymatic reactions and microbial proliferation, thereby extending the shelf-life of microgreens (Bhaswant et al., 2023). Additionally, chlorophyll and carotenoid content serve as key indicators of product freshness, as their degradation is directly linked to quality loss and visual appeal (Yan et al., 2022). Therefore, evaluating these biochemical parameters under different storage conditions provides valuable insights into the effectiveness of various packaging techniques (Grown and Ledwo, 2023).

Starting from all above remarks, this study aims to assess the impact of different packaging strategies on the sensory, biochemical, and physiological attributes of arugula microgreens packaged along with their growing media. Specifically, we evaluated the effectiveness of polypropylene (PB) and micro-perforated polypropylene (MPB) bags in preserving visual quality, chlorophyll content, carotenoid levels, and antioxidant properties of microgreens during cold storage at point-of-sale conditions. By comparing these packaging methods, the general goal was to identify the best approach to optimize shelf-life while maintaining the nutritional and organoleptic properties of microgreens.

2. Materials and Methods

2.1. Chemicals and Reagents

The reagents used for the various methods of analysis and the standards used for the analysis of volatile compounds were: acetone, methanol, 2,2-diphenyl-1-picrylhydrazyl (DPPH), sodium carbonate, gallic acid, butylated hydroxytoluene (BHT), ammonium acetate, methyl t-butyl ether (MTBE), CaCl2, 2-ethyl-2-hexen, 4-methyl-2-pentanol, isopropyl isothiocyanate, 3-octen-2-one, cis-7-decen-1-al, p-tolualdehyde and 2,6-dimethylphenyl isothiocyanate and were purchased from Sigma-Aldrich (Milano, Italy).

2.2. Plant Material and Growth Conditions

Arugula (*Eruca sativa* Mill.) seeds were purchased from Riccardo Larosa Company (Andria, Italy). Microgreens were grown in a growth chamber at controlled temperature (20 °C) and relative humidity (90%), equipped with light emitting diodes (LEDs) modules (Phytofy RL, OSRAM, Munich, Germany) (Palmitessa *et* al., 2022). The seeds were of a high quality, with a 95% germination at a constant temperature of 20 °C. The seed was sown at a density of 3 seeds cm^{-2} in plastic trays. The substrate used was a peat-based substrate (50% white-50% black peat mixture, Brill 3 Special, Brill Substrates, Georgsdorf, Germany). During the first two days, the trays were covered and the seeds were germinated in the dark. Subsequently, the seedlings were exposed to a light irradiance of 200 $\mu mol\ m^{-2}\ s^{-1}$, determined by using LICOR LI-190 (Li-Cor Inc., USA) quantum sensors, for a 12 h photoperiod. All microgreens were daily fertigated by a nutrient solution with the following concentrations ($mg\ L^{-1}$): 105 nitrogen, 15 phosphorus, 117 potassium, 100 calcium, 24 magnesium, 0.25 boron, 0.01 copper, 2.5 iron, 0.25 manganese, 0.025 zinc, and 0.005 molybdenum. Ten days after the germination, arugula microgreens trays were ready for the shelf-life study.

2.3. Microgreens Packaging and Storage

Microgreens trays were stored in three different conditions: not packaged control (NP); packed with polypropylene bags (PB) (25 × 30 cm, OTR 25 °C, 0% RH = 1800 $cm^3 \cdot m^{-2} \cdot 24\ h^{-1}$, WVTR 38 °C, 90% RH = 6 $g\ m^{-2}\ 24\ h^{-1}$); packed with micro-perforated polypropylene bags (MPB). All microgreens trays were stored in conditions simulating the storage in refrigerated shelves: 10 °C with 12 hours of lighting (exposed to a light irradiance of 200 $\mu mol\ m^{-2}\ s^{-1}$, determined by using LICOR LI-190 (Li-Cor Inc., USA) quantum sensors and 12 hours of dark. The storage temperature of 10 °C was deliberately chosen to better represent real point-of-sale conditions, where the recommended 4 °C temperature for fresh produce is often not strictly maintained. By adopting this temperature, we aimed to test the product under more challenging and realistic retail conditions, to evaluate its quality performance and packaging response in a context closer to that encountered by consumers. Sampling was performed after 3, 7, 11 and 14 days of storage (DOS). Three packs were sampled at each time and analyzed as independent replicates for shelf-life evaluation. The shelf-life of arugula microgreens was assessed by sensory analysis (visual and olfactive quality), headspace gas composition, total chlorophylls, antiradical activity and total phenolic compounds, carotenoid profiles and volatile compounds.

2.4. Sensory Evaluation

The evaluation of visual and olfactive quality was performed according to (Paradiso *et al.*, 2018). Sensory evaluation was conducted by five expert members with an extensive experience in sensory evaluation of microgreens. First the visual aspect of the three theses under examination and then the olfactory aspect was evaluated. The sensory evaluation was carried out on three replicates. The descriptors in Table 1 were used for visual quality, while olfactive quality was evaluated using a scale from 5 to 1, where 1 denoted no off odors and 5 denoted very intense off-odors. A score of 3 was considered the limit of acceptability.

Table 1. Visual quality rating of microgreens.

Score	Description	Rating
5	Essentially free from defects, freshly harvested. No profound visible defects.	Excellent
4	Minor defects, not objectionable. Some (<10%) physical damage (i.e. creased cotyledons). Product is turgid (not wilted).	Good
3	Moderately objectionable defects, marketability threshold. Slight chlorosis (yellowing). Areas of dry and wilted microgreens (<25%).	Fair
2	Excessive defects, not saleable – discolored hypocotyls (blue, black). Cotyledon chlorosis (>25%). Dry and wilted (>50%).	Poor
1	Unusable, degraded product. 100% chlorotic. Mold present, foul odor. Extensive rooting. Physical degradation apparent (liquid present).	Very poor

2.5. Headspace Gas Composition

The gas composition of the headspace in individual packages was determined using an O_2/CO_2 gas analyzer (CheckMate II, PBI-Dansensor A/S, Ringsted, DK), by inserting the needle of the measuring assembly through a septum adhered to the packaging film.

2.6. Chlorophylls Content

Total chlorophyll content was determined spectrophotometrically using the method of Lichtenthaler and Buschmann (2001) with minor modifications. Excised leaves (0.5 g) were homogenized with 15 mL acetone (HPLC-UV grade, Pharmco-Aaper, Brookfield, CT, USA) and stirred for 20 min. The mixture was filtered (Grade 413 Filter Paper, Qualitative, VWR International, West Chester, PA, USA) and transferred into spectrophotometric cuvettes. The absorbance was read at 661.6 nm and 644.8 nm with a Cary 60 UV-VIS system (Agilent Technologies, Santa Clara, PA, USA) and total chlorophyll was calculated as the sum of chlorophyll a (chla) and chlorophyll b (chlb) by using the following formulas:

$$\text{chl}_a\ (\text{mg L}^{-1}) = 11.24\ A661.6 - 2.04\ A644.8$$

$$\text{chl}_b\ (\text{mg L}^{-1}) = 20.13\ A644.8 - 4.19\ A661.6$$

where A*n* is the absorbance of the extract at n nm of wavelength. The samples were analyzed in triplicate for each treatment examined.

2.7. Antiradical Activity and Total Phenolic Compounds

Antiradical activity was evaluated by the 2,2-diphenyl-1-picrylhydrazyl (DPPH) stable radical scavenging capacity test according to (Castellino *et al.*, 2020). The samples (1 g) were extracted with 10 mL methanol:water (80:20) for 2 hours in tubes covered with aluminium foil. The extracts were then centrifuged for 15 minutes at 15,000 × g and 24 °C. The supernatant was recovered and filtered with nylon septa (0.45 µm). The extracts (50 µL) were added to 950 µL of 0.08 mM DPPH in methanol. The mixture was shaken and kept at room temperature in the dark for 30 min. The decrease of the ab-sorbance at 517 nm was measured using a Cary 60 Agilent spectrophotometer (Agilent Technologies, Milan, Italy). The results were expressed in µmol Trolox equivalents (TE) g^{-1}. Each sample was analyzed in triplicate.

Total phenolic compounds (TPC) were determined on the same methanolic extract by the Folin–Ciocalteu assay, according to (Paradiso *et al.*, 2016). In particular, 100 µL of the extract were mixed with 100 µL of the Folin–Ciocalteu reagent and, after 4 min, with 800 µL of a 5% (w/v) solution of sodium carbonate. The mixture was then heated in a water bath at 40 °C for 20 min and the total phenol content was determined at 750 nm by using an Agilent Cary 60 spectrophotometer (Agilent Technologies, Santa Clara, USA). The total phenolic content was expressed as mg gallic acid equivalents g^{-1}.

2.8. Carotenoids Analysis

The extraction of carotenoids from microgreens samples was carried out in dim light at ambient temperature. Samples were weighed (1 g) in test tubes covered with aluminium foil and homogenized with 15 mL of pure acetone and 50 µL of 0.1% butylated hydroxytoluene (BHT) in acetone for 24 hours. After centrifugation (3000 g, 5 min) the acetone containing the carotenoids was collected and the pellet was reextracted one more time using pure acetone and 50 µL of 0.1% butylated hydroxytoluene (BHT) in acetone, and agitated for 7 hours. Supernatants were combined, filtered through a 0.45 µm nylon filter and immediately analyzed by HPLC-DAD (Agilent Technologies, 1260 Infinity, USA), according to (Paradiso *et al.*, 2020). Chromatography was carried out on a C30 column (3 µL, 150 mm x 4.6 mm, YMC, Japan). The mobile phase consisted of two components: solvent A, methanol:MTBE:water (95:3:2, by vol-ume, with 1.5% ammonium acetate in water) and solvent B, methanol:MTBE:water (8:90:2, by volume, with 1.0% ammonium acetate in water). The flow rate was 0.4 mL/min, the injection volume was 25 µL and all carotenoids were monitored at 445 nm. The gradient procedure (10 °C), was as follows: start at 100% solvent A; a 22 min linear gradient to 45% solvent A and 55% solvent B; an 11 min linear gradient to 5% solvent A and 95% solvent B; a 4 min hold at 5% solvent A and 95% solvent B; a 2 min linear gradient back to 100% solvent A; a 28 min hold at 100% solvent A. Carotenoid identification was carried out by means of analytical standards (β-carotene and lutein), comparison with retention times in literature, and UV spectra examination.

2.9. Statistical Analysis

One-way analysis of variance (ANOVA) and post-hoc Tukey's HSD test were performed using JASP (Version 0.19.3).

3. Results

3.1. Sensory evaluation

Sensory evaluation gave results related to the different packaging (Figure 1). Samples stored without any packaging (NP) showed a high visual quality up to day 4 of refrigerated storage and then decreased slightly on day 7, when they were still considered marketable, due to the presence of slightly opaque green leaves. Subsequently, a drop in quality was observed, which made marketing unacceptable in the following days, due to an obvious lodging (Figure 1).

Microgreens stored in polypropylene bags showed a high visual quality up to 4 days of preservation which decreased slightly after 7 days, due to the loss of brightness of the leaves and even more after 11 days, showing moderately unpleasant defects and a slight allurement of the plants which made the trays at the limit of marketability. In addition, the presence of water droplets in the pouch, more and more consistent during storage, indicating that formation of water vapor occurred. Microgreens stored in micro-perforated bags showed a good visual quality until the fourth day of packaging, which decreased slightly in the following days, scoring 4 until the eleventh day of storage. After fourteen days microgreens showed a slight decrease in visual quality with a score of 3.5; thus, they could not be considered as saleable in the following days, due to the slight yellowing (Figure 1).

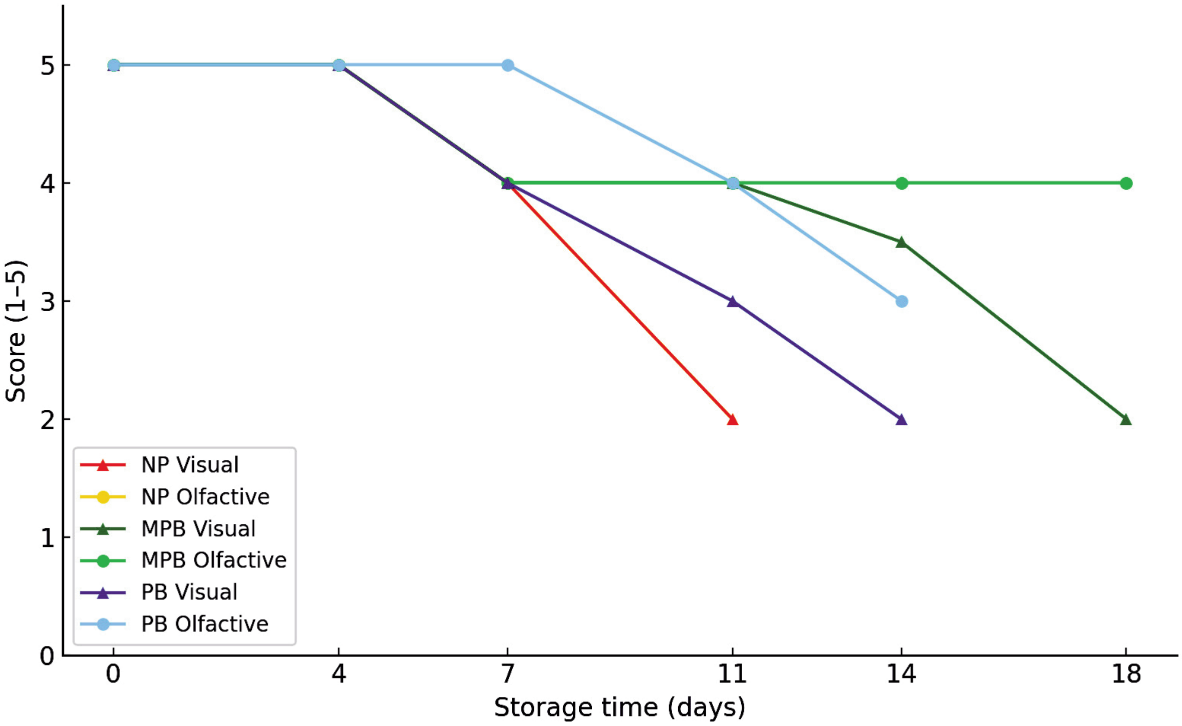

Figure 1. Sensory scores of microgreens during storage at 10 °C. NP: not packaged control; MPB: packaged with micro-perforated polypropylene bag; PB: packaged with polypropylene bag.

3.2. Headspace gas composition

Partial pressures changes of oxygen and carbon dioxide inside packages of microgreens during storage are reported in Table 2. The microgreens packaged with poly-propylene bags showed an oxygen decrease over time with a corresponding increase in carbon dioxide. At the same time, the microgreens packaged with micro perforated bags showed a slight decrease in oxygen over time without changes in carbon dioxide. No difference was observed between microgreens differently packaged until the seventh day while only a very low difference regarding CO_2 concentration was found at eleventh day.

Table 2. Headspace gas composition of packaged microgreens during storage at 10 °C.

	Storage time (days)	PB			MPB		
		kPa	SD		kPa	SD	
O_2	4	20.9	±0.1	A; a	20.9	±0.0	A; a
	7	19.9	±0.4	B; a	20.4	±0.1	B; a
	11	19.2	±1.3	B; a	20.5	±0.0	B; a
	14				20.4	±0.1	B
CO_2	4	0.0	±0.0	B; a	0.0	±0.0	A; a
	7	0.1	±0.1	B; a	0.1	±0.1	A; a
	11	1.0	±0.8	A; a	0.0	±0.0	A; b
	14				0.0	±0.0	A

P <0.001. The upper-case letters indicate microgreens analyzed with the same packaging at different times; while the lower-case letters indicate microgreens analyzed with different packaging at the same time. MPB: packaged with micro-perforated polypropylene bag; PB: packaged with polypropylene bag.

3.3. Chlorophyll Content

The storage of microgreens caused a general decrease of chlorophyll content in both packaged and unpackaged samples. However, microgreens packaged with microperforated polypropylene bags showed highest chlorophyll values over time (Table 3).

Table 3. Chlorophyll content of microgreens during storage at 10 °C.

Storage time (days)	NP			MPB			PB		
	µg/g	SD		µg/g	SD		µg/g	SD	
0	940.0	±11.0	A	940.0	±11.0	A	940.0	±11.0	A
4	767.9	±47.2	B; b	926.3	±20.8	A; a	740.6	±37.2	B; b
7	659.3	±46.3	C; b	820.7	±16.3	C; a	621.6	±31.0	C; b
11				863.9	±5.9	B; a	618.3	±20.1	C; b
14				797.3	±20.1	C			

P <0.001. The upper-case letters indicate microgreens analyzed with the same packaging at different times; while the lower-case letters indicate microgreens analyzed with different packaging at the same time. NP: not packaged control; MPB: packaged with micro-perforated polypropylene bag; PB: packaged with polypropylene bag.

Effectively, while MPB samples showed a chlorophyll reduction of 15% after 14 days, unpackaged microgreens showed a reduction of 30% after only seven days and PB samples showed a reduction of 34% after 11 days (Table 3).

3.4. Antiradical Activity and Total Phenolic Compounds

For all treatments the antiradical activity decreased during the storage (Table 4). At the seventh day of storage the antiradical activity of microgreens packaged with polypropylene bag was lower in comparison with unpackaged microgreens. No difference was observed on the 11th day of storage between the packaged microgreens (Table 4).

Table 4. Antiradical activity (expressed in µmol eq Trolox/g) of microgreens during storage at 10 °C.

Storage time (days)	NP			MPB			PB		
	µmol eq Trolox/g	SD		µmol eq Trolox/g	SD		µmol eq Trolox/g	SD	
0	4.85	±0.16	A	4.85	±0.16	A	4.85	±0.16	A
4	4.05	±0.18	B; a	3.81	±0.11	B; ab	3.73	±0.20	B; b
7	3.12	±0.18	C; a	3.00	±0.23	C; ab	2.84	±0.14	C; b
11				2.83	±0.25	C; a	2.70	±0.01	C; a
14				1.89	±0.32	D			

P <0.001. The upper-case letters indicate microgreens analyzed with the same packaging at different times; while the lower-case letters indicate microgreens analyzed with different packaging at the same time. NP: not packaged control; MPB: packaged with micro-perforated polypropylene bag; PB: packaged with polypropylene bag.

Similar to what reported for the antiradical activity, also for the total phenolic compounds the content in microgreens decreased during the storage (Table 5). Starting from the seventh day of storage the content of total phenolic compounds in microgreens packaged with polypropylene bag was lower in comparison with other samples (Table 5).

Table 5. Content of total phenolic compounds (expressed in mg of gallic acid/g) in microgreens during storage at 10 °C.

Storage time (days)	NP			MPB			PB		
	mg gallic acid/g	SD		mg gallic acid/g	SD		mg gallic acid/g	SD	
0	0.99	±0.09	A	0.99	±0.09	A	0.99	±0.09	A
4	0.75	±0.02	B; a	0.75	±0.02	B; a	0.75	±0.01	B; a
7	0.67	±0.02	C; a	0.67	±0.02	C; a	0.57	±0.02	C; b
11				0.61	±0.01	CD; a	0.58	±0.01	C ;b
14				0.59	±0.03	D			

P <0.001. The upper-case letters indicate microgreens analyzed with the same packaging at dif-ferent times; while the lower-case letters indicate microgreens analyzed with different packaging at the same time. NP: not packaged control; MPB: packaged with micro-perforated polypropylene bag; PB: packaged with polypropylene bag.

3.5. Carotenoids content

For all treatments the lutein content decreased during the storage (Table 6). At the fourth DOS the lutein content of microgreens packaged with polypropylene bag was lower in comparison with the other treatments. At the eleventh DOS the lutein content was highest in microgreen packaged with micro-perforated polypropylene bag (Table 6). Considering β-carotene content, the highest values were found at the beginning of the storage period, independently of packaged strategy and it was on average 72.3 µg/g (Table 6). After 4 DOS the microgreens packaged with micro-perforated polypropylene bag had 18% more β-Carotene than the microgreens packaged with polypropylene bag (Table 6). Instead, at 7 DOS the microgreens not packaged had 18% higher β-Carotene than microgreens packaged with polypropylene bag (Table 6).

Table 6. Carotenoids content in microgreens during storage at 10 °C.

Carotenoids	Storage time (days)	NP			MPB			PB		
		µg/g	SD		µg/g	SD		µg/g	SD	
Lutein	0	77.1	±4.9	A	77.1	±4.9	A	77.1	±4.9	A
	4	62.4	±1.8	B; ab	67.1	±6.3	AB; a	55.7	±0.4	C; b
	7	68.8	±3.4	B; a	64.1	±1.5	AB; a	53.6	±0.4	C; b
	11				69.4	±6.1	A; a	64.6	±0.7	B; a
	14				57.2	±2.5	B			
β-Carotene	0	72.3	±4.9	A	72.3	±4.9	A	72.3	±4.9	A
	4	52.0	±0.4	B; ab	54.5	±5.5	B; a	46.2	±1.1	B; b
	7	51.6	±5.7	B; a	50.7	±0.8	B; ab	43.6	±0.5	B; b
	11				53.4	±3.4	B; a	50.3	±0.0	B; a
	14				44.7	±7.5	B			

P <0.001. The upper-case letters indicate microgreens analyzed with the same packaging at different times; while the lower-case letters indicate microgreens analyzed with different packaging at the same time. NP: not packaged control; MPB: packaged with micro-perforated polypropylene bag; PB: packaged with polypropylene bag.

4. Discussion

The study investigated the impact of different packaging conditions on the shelf-life and quality attributes of arugula microgreens during refrigerated storage. The findings indicate that packaging significantly affects the visual, olfactory, and biochemical properties of microgreens over time (Renna and Paradiso, 2020).

Sensory evaluation was conducted to assess the changes in visual and olfactory attributes throughout the storage period, as consumer perception plays a critical role in marketability (Caracciolo *et al.*, 2020). Unpackaged microgreens (NP) retained an acceptable quality for up to seven days, after which wilting, yellowing, and off-odors rendered them unmarketable (Figure 1). The loss of turgidity and discoloration were key indicators of deterioration (Zhang *et al.*, 2021). In contrast, microgreens stored in polypropylene bags (PB) exhibited a gradual decline in quality, remaining marketable until 11 DOS (Figure 1). However, the presence of condensation led to excessive moisture accumulation, which created an environment conducive to microbial growth and decay (Olaimat and Holley, 2012). Micro-perforated polypropylene bags (MPB) were the most effective, maintaining a fresh visual appearance and minimal off-odors for up to 14 DOS, likely due to an improved balance in gas exchange, reducing excessive humidity and preventing anaerobic conditions that accelerate spoilage (Silveira *et al.*, 2015).

Gas composition analysis provided insights into the internal atmosphere of the packaged microgreens and its role in preservation. In PB packaging, oxygen levels declined over time (Table 2) while carbon dioxide concentrations increased (Table 2), potentially leading to stress-induced metabolic changes that contributed to quality loss (Brecht *et al.*, 2003). MPB packaging, on the other hand, maintained more stable oxygen levels and prevented excessive CO_2 accumulation, which likely contributed to the prolonged shelf-life observed. Maintaining an optimal gas balance is crucial to reducing respiration rates and delaying senescence, thus extending the freshness of microgreens (Renna and Paradiso, 2020).

Chlorophyll content was examined as a critical indicator of freshness and pigment stability in the microgreens, as degradation of chlorophyll leads to visible yellowing and reduced quality (Shakeel *et al.*, 2022). Across all storage conditions, a decrease in chlorophyll levels was observed, but the extent of reduction varied significantly (Table 3). NP and PB samples showed a rapid decline, with PB samples experiencing a 34% reduction after 11 DOS (Table 3), indicating that inadequate gas exchange accelerated chlorophyll degradation (Shakeel *et al.*, 2022). In contrast, MPB-stored microgreens retained higher chlorophyll content, experiencing only a 15% reduction after 14 DOS. This suggests that the controlled moisture and oxygen levels in MPB packaging slowed the breakdown of chlorophyll, maintaining the vibrant green color and prolonging marketability (Gaur and Ahmed, 2008).

The observed decrease in antiradical activity (Table 4) and total phenolic content (Table 5) of microgreens during storage is consistent with previous studies on the post-harvest deterioration of fresh produce. Antioxidant compounds, including phenolics, are highly sensitive to environmental conditions such as oxygen exposure, light, and temperature fluctuations (Morand and Tomás-Barberán, 2019). The degradation of these bioactive compounds over time can be attributed to enzymatic oxidation, where polyphenol oxidases and peroxidases catalyze the breakdown of phenolic compounds, leading to a reduction in their antioxidant capacity (González-De-peredo *et al.*, 2022).

The lower antiradical activity (Table 4) and phenolic content (Table 5) in microgreens packaged with polypropylene bags (MPB) compared to unpackaged samples (NP) by the seventh DOS suggest that the packaging conditions may have influenced oxidative stability. While MPB bags can limit moisture loss and provide a barrier against contaminants, they may also create a modified atmosphere that alters the physiological responses of the microgreens. Limited gas exchange could lead to increased respiration rates, accelerated metabolic activity, and a faster depletion of antioxidant compounds (Fadiji *et al.*, 2023). By 11 DOS, the similar levels of antiradical activity across all packaged microgreens (Table 4 and Table 5) indicate that prolonged storage leads to a general decline in antioxidant properties, regardless of the packaging type.

Carotenoid content was also evaluated to assess the nutritional stability of stored microgreens, as carotenoids such as lutein and β-carotene are essential bioactive compounds with significant health benefits (Darvin *et al.*, 2011). Like chlorophyll, carotenoid levels declined over time, impacting both visual and nutritional quality (Table 6). However, the rate of degradation varied depending on the packaging method. At 4 DOS, MPB-stored microgreens contained 18% more β-carotene than those in PB packaging, and by 11 DOS, MPB samples had the highest retention of carotenoids (Table 6). This highlights the role of packaging strategies in preserving not only the appearance but also the nutritional profile of microgreens (Dayarathna *et al.*, 2023). Micro-perforated bags appeared to provide superior conditions for retaining these bioactive compounds, likely due to optimized moisture and gas exchange that mitigated oxidative stress (Ghidelli and Pérez-Gago, 2018).

5. Conclusions

The study underscores the importance of appropriate packaging in extending the shelf-life of arugula microgreens. While polypropylene bags (PB) provided some protective effect, micro-perforated polypropylene bags (MPB) demonstrated superior performance by balancing moisture control and gas exchange, thereby preserving quality attributes for a longer period. These findings have practical implications for the fresh produce industry, highlighting the need for packaging innovations that optimize both shelf-life and consumer appeal. By improving storage conditions, retailers and consumers can benefit from extended freshness, reduced waste, and enhanced nutritional value in microgreens. The findings of this study will contribute to the development of improved post-harvest handling techniques, benefiting both producers and consumers by reducing food waste and ensuring a higher-quality product reaches the market. Future research should focus on further refining packaging solutions, exploring alternative biodegradable materials that maintain optimal gas exchange and humidity control while reducing environmental impact. Additionally, investigating the interaction between packaging and different storage conditions, including temperature and light exposure, could provide valuable insights for maximizing the post-harvest quality of microgreens.

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