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Storage Temperature-Dependent Changes in Physiology, Bioactive Compounds, Essential Oils, and Antibacterial Activity of Fresh Sage (*Salvia officinalis*)

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Received: 29 June 2026; Accepted: 17 September 2026; Published: 19 October 2026

ABSTRACT: Enhancing the quality and extending the storage of fresh herbs is becoming more and more popular, as their high perishability is often associated with suboptimal storage environments. This study examined the impacts of temperature (2, 6, and 20°C) on the quality attributes of fresh *Salvia officinalis* (sage) after postharvest storage. Greater weight loss, respiration rate, and ethylene production, together with reduced visual quality were observed when sage was stored at room temperature (20°C) compared with lower storage temperatures. This was reflected in the decrease in chlorophyll content observed at the end of the storage. In contrast, sage stored at 2°C exhibited lower phenol content and antioxidant activity but higher flavonoid content during storage. The EO yield was 1.51% and was significantly higher at 6 and 20°C after 5 days of storage, although no differences were detected after 10 and 15 days. The relative abundances of the three major components (α -thujone, camphor, and 1,8-cineole) varied according to storage temperature and duration, with α -thujone exhibiting trends opposite to those of camphor and 1,8-cineole. Higher antibacterial activity against *Escherichia coli* was found with infusions prepared from plants stored for 5 days at 2 and 6°C compared with those stored at 20°C, where *Staphylococcus aureus* was more susceptible to infusions obtained from sage stored at 20°C for 5 days. These findings suggest that fresh sage should be stored at 6°C for up to 5 days, whereas a lower temperature (2°C) is recommended for longer storage periods, such as 10 days.

KEYWORDS: Antioxidant activity; infusions; postharvest quality; temperature; sage

1 Introduction

Sage, or *Salvia officinalis* L., is a perennial round shrub of the Lamiaceae family. With approximately 1000 species, *Salvia* represents the largest genus within this family [1]. Although *Salvia* is widely distributed worldwide, the Mediterranean and Middle East are the natural habitats of *S. officinalis*. Both fresh and dried forms of the plant are widely used in traditional medicine and culinary applications. Sage has long been utilized in meal preparation due to its taste and seasoning qualities. In traditional European medicine, *S. officinalis* has been employed to treat mild dyspepsia disorders, including heartburn and bloating, excessive

sweating, age-related cognitive issues, and skin and throat irritation [2]. Additionally, various sage-derived preparations, including tea, essential oils (EOs), hydrosols, and extracts, are well appreciated for their potential health-promoting properties [3,4]. The primary EO components of *S. officinalis* include camphor, α -thujone, β -thujone, 1,8-cineole, borneol, and caryophyllene [2,5]. These compounds contribute to a range of biological activities attributed to the EO, including antimicrobial [2,3], antioxidant [6,7], insecticidal [8] antiproliferative [7], anti-inflammatory [9], anticancer [2,10], and neuroprotective effects associated with Alzheimer's disease [1]. The biochemical composition and EO profile of *S. officinalis* are impacted by various cultivation-related factors, such as temperature, photoperiod, and light intensity [11], which are themselves associated with seasonal growth, altitude, and cultivation practices [10,12].

The use of medicinal and aromatic plants (MAPs) is growing in popularity as a source of nutrients, minerals, vitamins, flavor, aroma, dietary fiber, and secondary metabolites, representing attractive alternatives or complements to conventional pharmaceutical products [13,14]. The primary function of secondary metabolites is to protect plants from herbivores, insects, and pathogens, and help plants withstand biotic and abiotic challenges during plant growth, transportation, and postharvest phases [15]. Their use in traditional medicine and food applications has increased considerably owing to their low production cost and relatively low risk of negative side effects [12,16]. Various secondary metabolites identified in MAPs are used in the fragrance and cosmetics industries, as well as in pharmaceutical, food, and commercial drug production and natural remedies applications. These bioactive metabolites include phenolic compounds, flavonoids, alkaloids, terpenes, anthraquinones, tannins, and saponins.

The global market demand for MAP raw materials has increased by more than 10% annually over the past 20 years. By 2050, the World Health Organization (WHO) projects that the global market for herbal products will be valued at USD 5 trillion [17]. Previous reports have indicated that approximately 11.5% of MAP products are rejected due to poor quality [18]. Among the primary factors of herbal material deterioration is improper postharvest processing. Inadequate handling of harvested plant material can result in significant losses of bioactive compounds, many of which are highly susceptible to degradation [17]. Consequently, it is difficult to fulfill the growing market demand for herbal plant material without efficient handling and post-harvest processing of MAPs, even if the supply is doubled. According to Bisht et al. [18], postharvest losses can be reduced from 75% to as little as 2.9% through the application of effective postharvest technologies. Therefore, lowering MAP postharvest losses is essential to improve market demands [17]. Various studies have been implemented to determine the best postharvest practices for MAPs [19–22]; however, most findings are species-specific and cannot be generalized across the postharvest sector without prior adjustments.

Postharvest losses are estimated to be 40–45% of production in aromatic and spice crops [23], while limited scientific knowledge regarding their appropriate postharvest handling is available [22]. Existing studies have focused primarily on basil (*Ocimum basilicum* L.) [21,24–26] and more recently on *S. fruticosa* under various temperature and moisture conditions [27]. Temperature is one of the key elements that affects metabolism and senescence of fresh produce. Chilling temperatures can reduce physiological deterioration and extend storage life. The suggested range of temperatures for fresh MAPs storage is generally between 2°C and 8°C. In contrast, exposure to high temperatures breaks down lipid-containing plant tissue and evaporates their EOs, allowing them a bitter or harsh flavor [28]. Since volatile oils can be lost during high-temperature treatments, a spice's flavor and scent might be diminished [27]. Fresh produce deteriorates more quickly at room temperature (20–25°C), leading to phytonutrient degradation, color changes (yellowing, browning, spotting), wilting, decrease in flavor, and increased microbial growth [29–31]. In household kitchens, fresh herbs such as sage, are frequently kept under such conditions for several days.

Cold storage, characterized by low temperature and high relative humidity, is the best way to increase shelf life, as it minimizes respiration and water loss [32,33]. Commercial fresh produce is normally kept at 2–4°C, but in open-display freezers in the market, temperatures can occasionally increase to 6–7°C, which could have an impact on the quality of the product [34].

Sage is typically sold in small bundles, pre-packaged trays or containers and/or modified-atmosphere environments. Although fresh herbs have high nutritional and functional value, they are highly perishable due to rapid deterioration during storage, which typically lasts only a few days to a few weeks. Nevertheless, little is known about how to preserve fresh herbs after harvest, which generally undergoes minimal processing (e.g., washing, cutting, and packaging at low temperatures) to verify safety and to maintain freshness, scent, and green color for a long time [35]. Furthermore, flavor and aroma are important qualities that must be maintained to meet market demands as they have an impact on consumers' perceptions and levels of satisfaction.

Therefore, prior to investigating additional postharvest preservation methods, it is crucial to ascertain the optimal storage conditions that minimize deterioration in nutritional quality, antioxidant capacity, and sensory qualities. The current study's goal was to look at the impact of storage temperature on the quality parameters and EO profile of fresh sage after 15 days of storage. Additionally, the impact of storage environments on tannin content and the antibacterial properties of sage infusions was evaluated. Uncontrolled storage conditions were thought to directly reflect the physiological reactions of sage, as well as alterations in the bioactive profile and antibacterial qualities.

2 Materials and Methods

2.1 Plant Material and Sample Preparation

Sage (*S. officinalis*) seedlings were provided by the Department of Aromatic Plants, Ministry of Agriculture, Cyprus, and were cultivated on a commercial organic farm Limassol, Cyprus (34°38' N, 32°56' E, 7 m above sea level) in soil without any chemical application. Plants were harvested during winter 2024. Following sorting and cleaning, the fresh plant material was prepared into uniform bundles weighing approximately 100 g each.

2.2 Storage Conditions

A total of 80 bundles were used in the experiment. The tested factors consisted of three storage temperatures and four sampling times, with four replicates per treatment. For each replicate, two bundles were enclosed in a polypropylene plastic container with a total volume of 5 L. Inside each container, a moisturized paper (saturated with distilled water and regularly re-moisturized as needed) was placed to maintain high relative humidity levels (approximately 95%). The containers were stored for up to 15 days under refrigerated conditions (2 and 6°C) or at room temperature (20°C). Sampling took place on day 0, 5, 10 and 15. To prevent the buildup of high carbon dioxide (CO₂) levels, the remaining sealed containers were quickly aerated (the lid was opened).

2.3 Measurements

2.3.1 Weight Loss and Macroscopic Evaluation

At each sampling date (day 0, 5, 10, and 15), bundle weight was recorded, and water loss was computed as the percentage (%) of the total weight loss.

A macroscopical evaluation based on visual observation took place (eight people at least; untrained panelists representing consumer perception; age range 18–33 years old; getting an overview of the features and storage conditions of the fresh produce under investigation) on each sampling day using a 5-level scale (1–10), where 1: non-marketable, severe spoilage, 3: non-marketable, extensive browning; 5: slightly marketable, presence of yellow or brown spots, 7: marketable, and 10:excellent marketable quality [36].

2.3.2 Respiration and Ethylene Rate Production

Respiration and ethylene rates were determined on days 0, 5, 10 and 15 (four replications/treatment) as previously described by Xylia et al. [22]. Respiration rates were calculated as mL of CO₂ generated per kilogram per hour (mL CO₂/kg h), and ethylene production rates were expressed as mL of ethylene produced per kg of fresh weight per hour (mL ethylene/kg h) [22].

2.3.3 Leaf Chlorophylls Content

Chlorophyll content (chlorophyll a-Chl a, chlorophyll b-Chl b, total chlorophyll-Total Chl) was determined according to Arnon's equations [37,38] at 470, 653, and 666 nm. The Chl a:Chl b ratio was computed.

2.3.4 Phytochemical Analysis

Total polyphenols and antioxidants of fresh sage were extracted according to Chrysargyris et al. [39] using 50% methanol (v/v) (Merck, Darmstadt, Germany). The polyphenolic content was estimated with the Folin-Ciocalteu method as described by Chrysargyris et al. [40], at 755 nm. Flavonoids were quantified by the aluminum chloride colorimetric method at 510 nm [37].

Antioxidant capacity of sage was implemented with Ferric reducing antioxidant power (FRAP) and 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulphonic acid) (ABTS) assays and the results were presented as mg of trolox per g of fresh weight.

Ascorbic acid (AA) content of fresh sage was quantified by titration with 2,6-dichlorophenol-indophenol (Sigma-Aldrich, Darmstadt, Germany) [41], and results were presented as mg of ascorbic acid per g of fresh weight.

2.3.5 Microbial Load

The microbial load was assessed as part of the sage bundle microbial load, including the total viable count (TVC), as previously mentioned [22]. The log of colony-forming units per gram of fresh weight (log cfu/g Fw) was used to express the results.

2.3.6 Extraction and Composition of Essential Oils

Plant material was collected from each sampling day and dried at 42°C, and then hydrodistilled using a Clevenger apparatus. The EO yield and profile determined according to Chrysargyris et al. [42]. EOs components identified by comparing the retention indices relative to n-alkanes (C8-C20), with the respective from the literature or with the authentic compounds (available at CUT laboratory). Complementary, the mass spectra recorded for each compound was matched with the respective in the NIST08 mass spectra library (GC-MS data system) and/or other published data [43]. Each identified compound was quantified by integrating its peak area normalization without using correction factors and presented as the percentages (%) of total peak area. A representative EOs chromatogram is presented in Supplementary Fig. S1.

2.3.7 Infusions' Tannins Content

For the preparation of infusions, plant material was collected on each sampling day and air-dried as previously mentioned in Section 2.3.5. The dried material was ground into a fine powder, and 4 g was extracted with 200 mL of boiling distilled water [44]. The infusion was allowed to stand for 5 min at room temperature, then filtered under reduced pressure, frozen, and lyophilized to complete dryness [45].

2.3.8 Infusions' Antibacterial Activity

The antibacterial activity of the infusions was investigated *in vitro* using the microdilution method as reported by Xylia et al. [46] for *Escherichia coli* (ATCC 25922) and *Staphylococcus aureus* (ATCC 11632). Streptomycin was used as a reference antibiotic with a starting concentration of 100 µg/mL. Calculations were made to determine the minimum inhibitory concentration (MIC), which is the lowest concentration that prevented bacterial growth, and the inhibitory concentration that reduced bacterial growth by 50% (IC₅₀) [47].

2.4 Statistical Analysis

The current study was based on a Completely Randomized Design (CRD) with four biological replicates for each measurement (n = 4) per temperature per sampling day (except the EO profile with three biological replications; n = 3). One- and two-way analysis of variance (ANOVA) and Duncan's post-hoc range test were implemented using IBM SPSS 31.0. Principal component analysis (PCA) was utilized with MetaboAnalyst 6.0 to classify samples based on the observed parameters and assess the contributions of each variable to the overall variance. Pearson's correlation coefficients were utilized to conduct correlation analysis between metabolite concentrations using the MetaboAnalyst 6.0 program.

3 Results

3.1 Impact of Temperature (T) and Days (D) of Storage for Sage and Their Interactions

The storage period and temperature affected all the tested parameters except chlorophyll a:b and 1,8-cineole for the temperature. Significant effects were also found through their interaction (T × D), except for marketability and ABTS (Table 1).

Table 1: Impact of temperature (T) and days (D) for sage storage and their interactions (T × D).

	T	D	T × D		T	D	T × D
Weight loss	***	***	***	Total viable count	***	***	***
Marketability	***	***	ns	Yeasts and Molds	***	***	***
Respiration rates	***	***	***	Tannins	**	***	***
Ethylene rates	***	***	***	<i>Escherichia coli</i> MIC	***	***	***
Chlorophyll a	**	***	***	<i>Escherichia coli</i> IC ₅₀	***	***	***
Chlorophyll b	***	***	***	<i>Staphylococcus aureus</i> MIC	***	***	***
Total Chlorophylls	**	***	***	<i>Staphylococcus aureus</i> IC ₅₀	***	***	***
Chlorophyll a:b	ns	***	***	Essential oil yield	*	***	***
Phenols	***	***	*	α-Thujone	***	***	***
Flavonoids	***	***	***	Camphor	*	***	***
FRAP	***	***	***	1,8-Cineole	ns	**	***
ABTS	***	***	ns				
Ascorbic acid	***	***	***				

***, **, *: significant at $p \leq 0.001$; $p \leq 0.01$; $p \leq 0.05$; ns: not significant, according to two-way ANOVA.

3.2 Weight Loss and Macroscopical Evaluation

Fig. 1 illustrates the effects of storage temperature on weight loss and visual quality of fresh sage over 15 days of storage. Sage stored at 6 and 20°C presented increased weight loss after 10 and 15 days compared to 2°C (up to 9.27 and 10.49% on day 15, respectively) (Fig. 1a). The visual quality of fresh sage decreased (lower scores during the macroscopic evaluation) during storage with more decay symptoms being more evident at 20°C (Fig. 1b). There were no apparent differences in marketability between storage at 2 and 6°C (Fig. 1b, and Fig. 2).

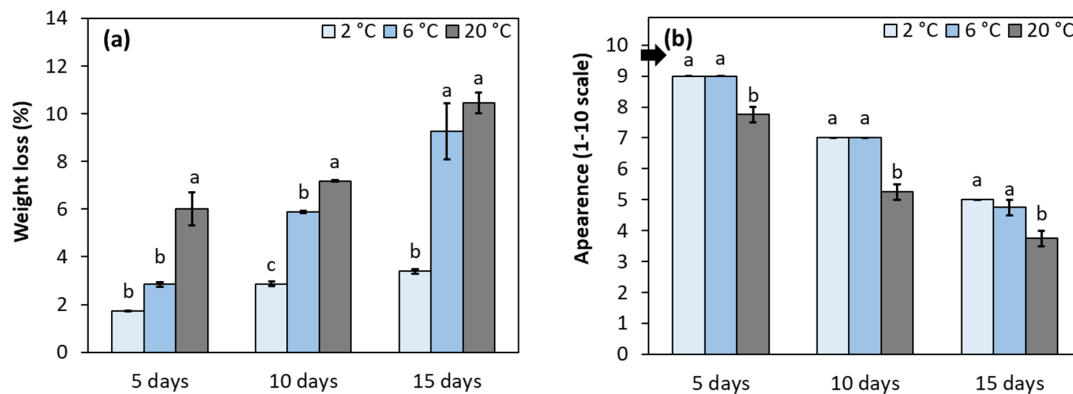


Figure 1: Influence of temperature on fresh sage's (a) weight loss, and (b) appearance when bundles stored at refrigerator (2 and 6°C) and room temperature (20°C) for 15 days. Values are mean ($\pm$ standard error) ($n = 4$). Different letterings indicate statistical differences among storage temperatures on each day ($p \leq 0.05$). The black arrow (→) represents values for the initial day (day 0).

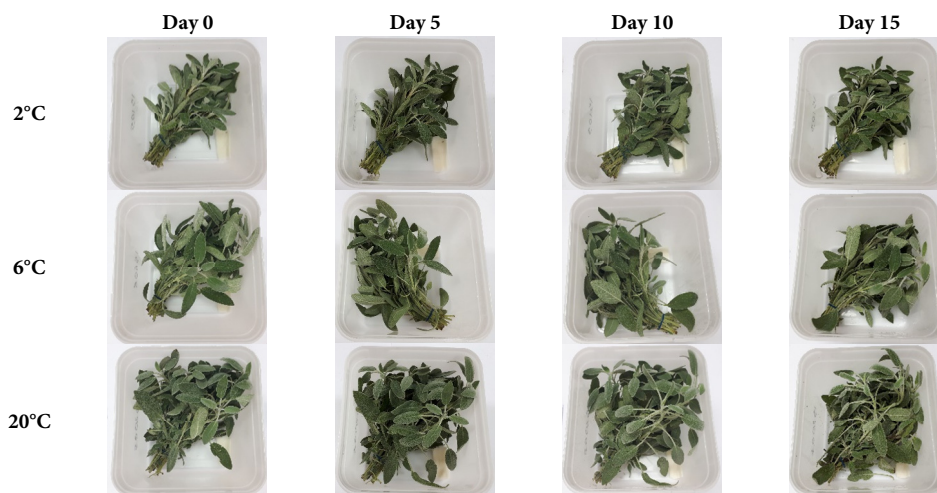


Figure 2: Influence of temperature on fresh sage stored in refrigerator (2 and 6°C) and room temperature (20°C) for 15 days.

3.3 Respiration and Ethylene Rate Production

Respiration rate of sage increased during storage at 20°C on the 5th and 10th day (up to 351.31 and 337.16 mL CO₂/kg h, respectively) compared to lower temperatures on the same days (Fig. 3a). On the last day higher respiration rate was observed at 6°C as opposed to other temperatures on the same day. Ethylene rate increased after 10 days at 20°C reaching up to 0.053 mL ethylene/kg h (Fig. 3b).

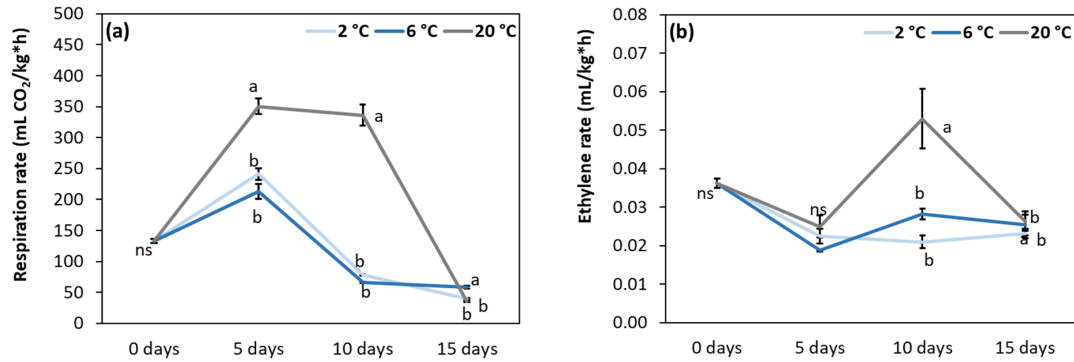


Figure 3: Influence of temperature on (a) respiration and (b) ethylene rate in fresh sage stored at refrigerator (2 and 6°C) and room temperature (20°C) for 15 days. Values are mean ($\pm$ standard error) ($n = 4$). Different letterings indicate statistical differences among storage temperatures on each day ($p \leq 0.05$). ns signifies no statistical differences ($p > 0.05$) between the temperatures on the same day.

3.4 Leaf Pigment Content

The chlorophyll content of fresh sage was affected by storage temperature, as presented in Fig. 4. A decrease in Chl b was reported with storage of fresh sage at 2 and 20°C for five days compared to 6°C (Fig. 4b), while Chl a and Chl b were decreased at 20°C on day 15 (Fig. 4a,b). Total Chl was also decreased on day 15 at room temperature (20°C) (Fig. 4c).

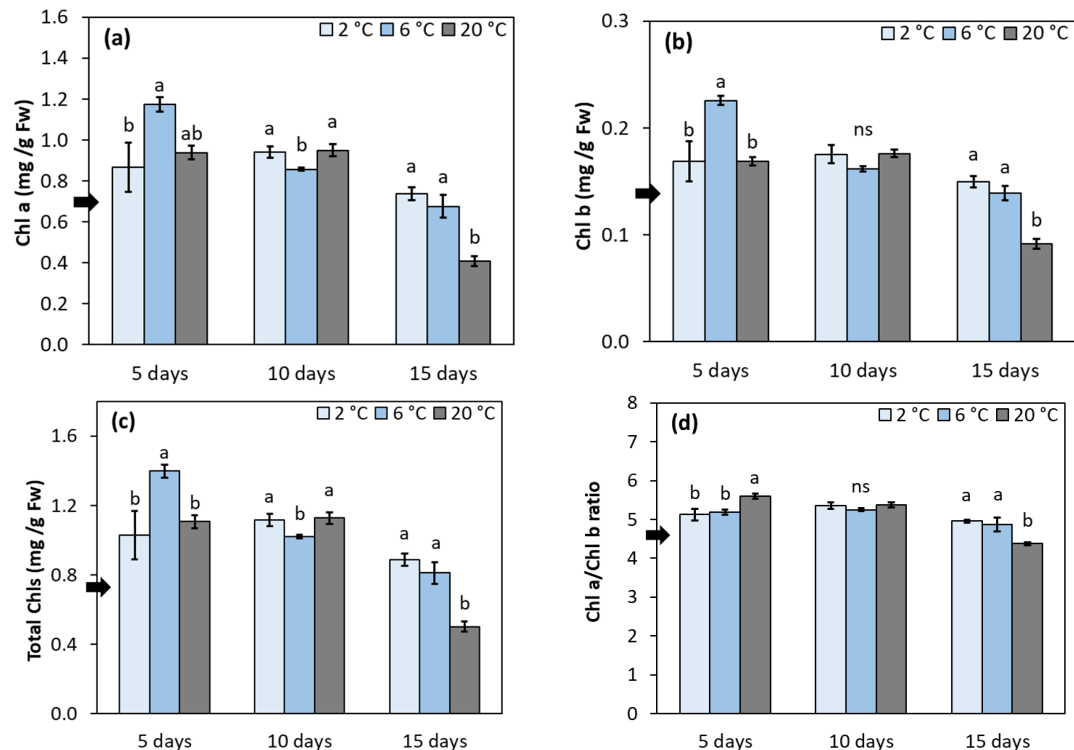


Figure 4: Influence of temperature on fresh sage's chlorophylls [(a) chlorophyll a-Chl a, (b) chlorophyll b-Chl b, (c) total chlorophyll-Total Chl], (d) Chl a: Chl b ratio, following storage at refrigerator (2 and 6°C) and room temperature (20°C) for 15 days. Values are mean ($\pm$ standard error) ($n = 4$). Different letterings indicate statistical differences among storage temperatures on each day ($p \leq 0.05$). The black arrow (→) represents values for the initial day (day 0) whereas ns signifies no statistical differences ($p > 0.05$) between the temperatures on the same day.

3.5 Phenols, Flavonoids, Antioxidant Activity and Ascorbic Acid Content

The effect of 15 days of storage on phenols, flavonoids, antioxidant activity (FRAP and ABTS) and ascorbic acid content of fresh sage kept at different temperatures (2, 6, and 20°C) is shown in Fig. 5. Storage of sage at 6 and 20°C resulted in increased phenolic content on the fifth and 15 days compared to lower temperatures (2°C) (Fig. 5a). In addition, higher phenols content was observed in sage stored for 10 days at room temperature (20°C) as opposed to the ones stored at 2°C (12.46 and 8.46 mg GAE/g Fw, respectively). Flavonoids content decreased as the storage temperature increased for 15 days (Fig. 5b).

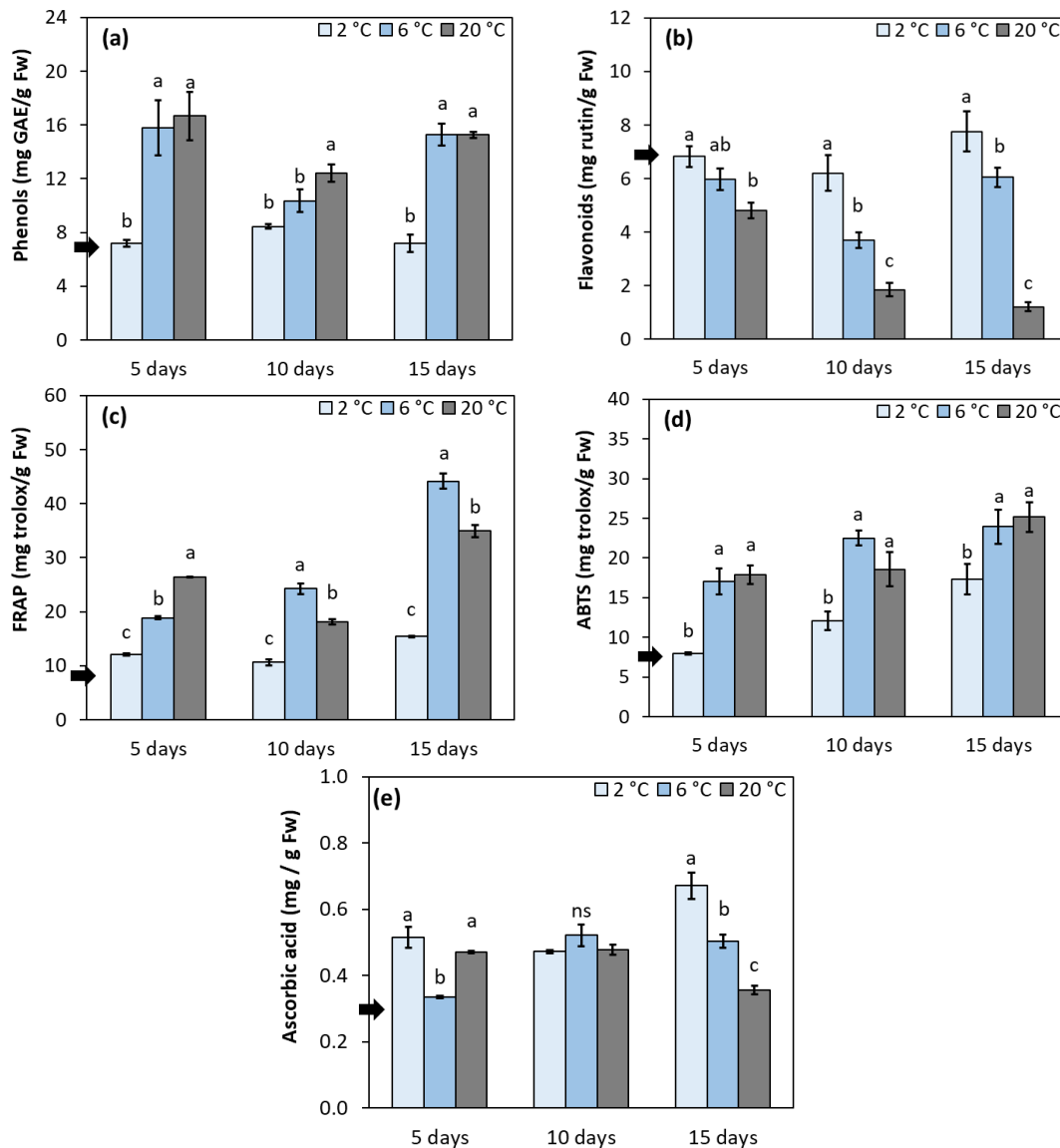


Figure 5: Influence of temperature on fresh sage's (a) phenols, (b) flavonoids, antioxidant activity (c) FRAP and (d) ABTS, and (e) ascorbic acid content stored at refrigerator (2 and 6°C) and room temperature (20°C) for 15 days. Values are mean ($\pm$ standard error) ($n = 4$). Different letterings indicate statistical differences among storage temperatures on each day ($p \leq 0.05$). The black arrow ($\rightarrow$) represents values for the initial day (day 0). ns signifies no statistical differences ($p > 0.05$) between the temperatures on the same day.

As shown by both antioxidant assays (FRAP and ABTS), higher antioxidant activity was observed at 6 and 20°C, particularly toward the end of storage (up to 44.23 and 35.01 mg Trolox/g Fw on day 15, respectively) (Fig. 5c,d). Overall, values were higher at 6°C compared with those at 20°C. In contrast, higher AA content was observed in sage stored for 5 days at 2 and 20°C, whereas after 15 days, refrigerated storage (2 and 6°C) resulted in higher AA levels (0.67 and 0.55 mg AA/g Fw, respectively) compared with storage at 20°C (Fig. 5e).

3.6 Microbial Load

Storage at 2 and 6°C yielded lower TVC levels than storage at 20°C on day 5 and 10. However, on day 15, increased TVC was noted at 6 and 20°C as opposed to 2°C (Fig. 6a). After 5 and 10 days of storage at 20°C, fewer yeasts and molds were observed; however, on the 15 days of storage, elevated temperatures (6 and 20°C) displayed a greater population of yeasts and molds (Fig. 6b).

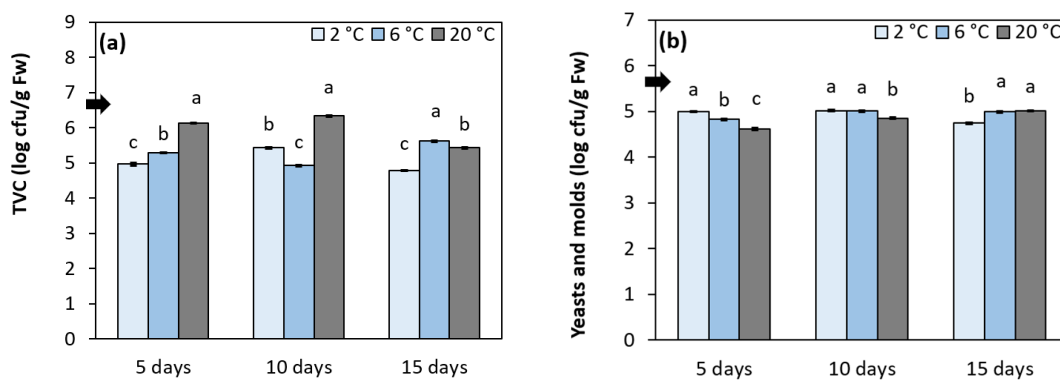


Figure 6: Microbial load (a) total viable count-TVC and (b) yeast and molds, of fresh sage stored at refrigerator (2 and 6°C) and room temperature (20°C) for 15 days. Values are mean ($\pm$ standard error) ($n = 4$). Different letterings indicate statistical differences among storage temperatures in each day ($p \leq 0.05$). The black arrow ($\rightarrow$) represents values for the initial day (day 0).

3.7 Essential Oil Composition

The EO yield was 1.51%, and it was significantly higher at 6 and 20°C than at 2°C after 5 days but remained unaffected after 10 and 15 days of storage (Table 2 and Fig. S2). Twenty-nine components ($>0.05\%$) were identified, with α -thujone (22.50%) being the major compound, followed by camphor (18.42%), 1,8-cineole (18.17%), camphene (6.69%), β -thujone (6.39%), p-cymene (4.37%), borneol (3.40%), from the analysis of plants during day 0, prior the application of the various storage temperatures. The dominant compound (α -thujone) after 5 and 10 days of storage, increased when plants were stored at 20°C (25.51%) and at 6°C (23.39%), respectively, whereas no differences were observed after 15 days of storage at the tested temperatures. The opposite trend was observed for camphor and 1,8-cineole, which decreased after 5 days of storage at 20°C compared with lower temperatures (2°C and 6°C for camphor). After 15 days of storage at 6°C, 1,8-cineole had the higher content, and camphor had the relevant lower content. The various storage temperatures also had an impact on other components that contribute less to the EO profile, such as camphene, β -thujone, p-cymene, and borneol (Table 2).

Table 2: Impact of storage temperature on the essential oil yield and composition (%) of fresh sage stored under different temperatures (2, 6 and 20°C) for 15 days.

Compound	RI	Day 0			Day 5			Day 10			Day 15		
		2°C	6°C	20°C	2°C	6°C	20°C	2°C	6°C	20°C	2°C	6°C	20°C
Tricyclene	922	0.24 ± 0.00	0.23 ± 0.00c	0.27 ± 0.00a	0.25 ± 0.00b	0.24 ± 0.00b	0.27 ± 0.00a	0.25 ± 0.01b	0.30 ± 0.01a	0.30 ± 0.01a	0.26 ± 0.01b		
α-Thujene	926	0.29 ± 0.00	0.23 ± 0.00a	0.17 ± 0.00c	0.19 ± 0.00b	0.14 ± 0.00b	0.15 ± 0.00b	0.16 ± 0.00a	0.16 ± 0.00a	0.14 ± 0.00b	0.15 ± 0.00ab		
α-Pinene	933	4.37 ± 0.05	4.24 ± 0.07c	5.09 ± 0.01a	4.70 ± 0.00b	4.64 ± 0.08b	5.10 ± 0.00a	4.59 ± 0.05b	5.10 ± 0.10b	5.54 ± 0.10a	4.80 ± 0.08b		
Camphene	948	6.69 ± 0.06	6.47 ± 0.10c	7.61 ± 0.02a	6.91 ± 0.01b	6.82 ± 0.12b	7.45 ± 0.03a	6.79 ± 0.04b	7.46 ± 0.12	7.59 ± 0.15	7.17 ± 0.12		
β-Pinene	977	3.05 ± 0.03	2.85 ± 0.05	2.93 ± 0.01	2.87 ± 0.00	2.55 ± 0.05b	2.83 ± 0.01a	2.79 ± 0.05a	2.88 ± 0.05b	3.23 ± 0.06a	2.71 ± 0.05b		
β-Myrcene	989	1.53 ± 0.01	1.65 ± 0.03c	1.90 ± 0.00a	1.78 ± 0.00b	1.97 ± 0.03a	1.70 ± 0.01b	1.95 ± 0.02a	1.73 ± 0.03	1.65 ± 0.03	1.75 ± 0.04		
α-Terpinene	1017	0.25 ± 0.00	0.24 ± 0.00ab	0.23 ± 0.00b	0.24 ± 0.00a	0.20 ± 0.00b	0.19 ± 0.00c	0.24 ± 0.01a	0.22 ± 0.00a	0.17 ± 0.00c	0.19 ± 0.00b		
o-Cymene	1024	2.21 ± 0.02	1.56 ± 0.03c	1.98 ± 0.02a	1.78 ± 0.00b	1.63 ± 0.03b	1.80 ± 0.01a	1.63 ± 0.02b	1.92 ± 0.03a	1.87 ± 0.03a	1.66 ± 0.03b		
Limonene	1028	1.70 ± 0.03	1.82 ± 0.04c	2.13 ± 0.01a	1.94 ± 0.03b	2.01 ± 0.04	2.06 ± 0.02	2.01 ± 0.06	2.20 ± 0.06	2.06 ± 0.04	2.12 ± 0.03		
1,8-Cineole	1031	18.17 ± 0.18	18.66 ± 0.32a	17.67 ± 0.07b	17.77 ± 0.01b	18.24 ± 0.31	17.95 ± 0.04	17.63 ± 0.03	16.64 ± 0.27b	18.25 ± 0.36a	17.62 ± 0.27ab		
γ-Terpinene	1036	0.35 ± 0.00	0.30 ± 0.01a	0.23 ± 0.00c	0.26 ± 0.00b	0.20 ± 0.00b	0.17 ± 0.00c	0.27 ± 0.01a	0.20 ± 0.00b	0.16 ± 0.00c	0.22 ± 0.00a		
Terpinolene	1067	0.08 ± 0.00	0.09 ± 0.00	0.09 ± 0.01	0.08 ± 0.00	0.07 ± 0.00b	0.06 ± 0.00b	0.09 ± 0.00a	0.08 ± 0.00a	0.06 ± 0.00b	0.08 ± 0.00a		
Linalool	1100	0.16 ± 0.00	0.16 ± 0.00a	0.14 ± 0.00b	0.16 ± 0.00a	0.11 ± 0.00c	0.13 ± 0.00b	0.21 ± 0.01a	0.12 ± 0.00b	0.10 ± 0.00b	0.18 ± 0.01a		
α-Thujone	1106	22.50 ± 0.21	23.22 ± 0.36b	21.14 ± 0.01c	25.51 ± 0.01a	22.02 ± 0.38b	23.39 ± 0.03a	21.61 ± 0.08b	21.85 ± 0.36	21.14 ± 0.45	21.55 ± 0.39		
β-Thujone	1116	6.39 ± 0.06	6.36 ± 0.11b	5.95 ± 0.01c	6.84 ± 0.01a	6.18 ± 0.11b	5.91 ± 0.01c	7.55 ± 0.02a	5.87 ± 0.11b	5.45 ± 0.09c	7.14 ± 0.13a		
trans-Sabinol	1136	1.85 ± 0.02	0.61 ± 0.02a	0.53 ± 0.00b	0.25 ± 0.00c	0.12 ± 0.00b	0.17 ± 0.00a	0.17 ± 0.01a	0.20 ± 0.00a	0.17 ± 0.00b	0.21 ± 0.01a		
Camphor	1145	18.42 ± 0.18	20.57 ± 0.38a	20.43 ± 0.02a	18.94 ± 0.01b	19.93 ± 0.86	20.97 ± 0.09	19.73 ± 0.04	19.97 ± 0.34a	18.33 ± 0.36b	20.01 ± 0.30a		
Borneol	1166	3.40 ± 0.04	2.96 ± 0.06b	3.18 ± 0.01a	3.12 ± 0.01a	2.86 ± 0.05c	3.09 ± 0.00b	3.36 ± 0.04a	3.16 ± 0.05	3.20 ± 0.05	3.34 ± 0.09		
Terpinen-4-ol	1178	1.11 ± 0.01	0.94 ± 0.02a	0.87 ± 0.00b	0.88 ± 0.00b	0.75 ± 0.01b	0.84 ± 0.01a	0.84 ± 0.01a	0.88 ± 0.02a	0.83 ± 0.01a	0.77 ± 0.02b		
p-Cymene 8 ol	1186	0.06 ± 0.00	0.05 ± 0.00b	0.07 ± 0.00a	0.05 ± 0.00b	0.07 ± 0.00	0.06 ± 0.00	0.06 ± 0.00	0.07 ± 0.00ab	0.06 ± 0.00b	0.07 ± 0.00a		
α-Terpineol	1191	0.12 ± 0.00	0.14 ± 0.00b	0.16 ± 0.00a	0.11 ± 0.00c	0.13 ± 0.00b	0.14 ± 0.00b	0.16 ± 0.00a	0.15 ± 0.00a	0.15 ± 0.00a	0.13 ± 0.00b		
Bornyl acetate	1287	0.56 ± 0.00	0.61 ± 0.01b	0.66 ± 0.00a	0.42 ± 0.00c	0.54 ± 0.01a	0.53 ± 0.00a	0.36 ± 0.01b	0.66 ± 0.01a	0.48 ± 0.01b	0.17 ± 0.00c		
trans-Sabinyl acetate	1292	1.18 ± 0.01	0.55 ± 0.01a	0.50 ± 0.01b	0.20 ± 0.00c	0.08 ± 0.00c	0.13 ± 0.00b	0.15 ± 0.00a	0.17 ± 0.00a	0.14 ± 0.00b	0.10 ± 0.00c		
β-Caryophyllene	1425	0.55 ± 0.01	0.59 ± 0.01b	0.71 ± 0.00a	0.60 ± 0.00b	0.77 ± 0.01a	0.57 ± 0.00c	0.74 ± 0.00b	0.59 ± 0.01b	0.74 ± 0.01a	0.49 ± 0.01c		
α-Caryophyllene	1462	0.69 ± 0.01	0.74 ± 0.01b	0.91 ± 0.00a	0.71 ± 0.00c	0.96 ± 0.01a	0.66 ± 0.00b	0.95 ± 0.00a	0.72 ± 0.01b	0.96 ± 0.02a	0.71 ± 0.02b		
Caryophyllene oxide	1587	0.16 ± 0.00	0.12 ± 0.00c	0.21 ± 0.00a	0.17 ± 0.00b	0.26 ± 0.00b	0.20 ± 0.00c	0.36 ± 0.00a	0.31 ± 0.00a	0.25 ± 0.02b	0.26 ± 0.01b		
β-Humulene	1592	1.79 ± 0.03	1.39 ± 0.03c	2.55 ± 0.03a	2.03 ± 0.02b	3.21 ± 0.05a	2.19 ± 0.01b	3.30 ± 0.05a	2.84 ± 0.04b	3.20 ± 0.09a	2.67 ± 0.07b		
Humulene epoxide II	1605	0.41 ± 0.01	0.31 ± 0.00c	0.61 ± 0.00a	0.49 ± 0.00b	0.67 ± 0.01b	0.53 ± 0.01c	0.77 ± 0.01a	0.74 ± 0.01a	0.75 ± 0.02a	0.63 ± 0.02b		
Manool	2059	0.19 ± 0.01	0.08 ± 0.00c	0.58 ± 0.03a	0.20 ± 0.01b	0.67 ± 0.03a	0.28 ± 0.00b	0.71 ± 0.10a	0.68 ± 0.01ab	0.91 ± 0.14a	0.59 ± 0.05b		
Total Identified		98.45 ± 1.00	97.76 ± 1.66	99.49 ± 0.06	99.46 ± 0.06	98.03 ± 1.66	99.53 ± 0.07	99.41 ± 0.07	97.85 ± 1.66	97.88 ± 1.67	97.86 ± 1.65		
Monoterpenes		20.67 ± 0.21	19.60 ± 0.33c	22.54 ± 0.01a	20.93 ± 0.04b	20.40 ± 0.35b	21.70 ± 0.07a	20.67 ± 0.26b	22.16 ± 0.40ab	22.72 ± 0.41a	21.02 ± 0.37b		
Oxygenated Monoterpenes		72.24 ± 0.71	73.77 ± 1.25a	70.22 ± 0.10b	73.72 ± 0.05a	70.49 ± 1.22	72.74 ± 0.07	71.40 ± 0.08	68.98 ± 1.16	67.74 ± 1.32	71.23 ± 1.18		
Sesquiterpenes		3.03 ± 0.04	2.73 ± 0.05c	4.17 ± 0.02a	3.34 ± 0.02b	4.94 ± 0.08a	3.42 ± 0.01b	5.00 ± 0.05a	4.15 ± 0.06b	4.90 ± 0.12a	3.86 ± 0.09b		
Oxygenated Sesquiterpenes		0.57 ± 0.01	0.43 ± 0.01c	0.82 ± 0.00a	0.66 ± 0.01b	0.92 ± 0.01b	0.73 ± 0.01c	1.13 ± 0.01a	1.05 ± 0.02a	1.00 ± 0.04a	0.89 ± 0.03b		
Oxygenated Diterpenes		0.19 ± 0.01	0.08 ± 0.00c	0.58 ± 0.03a	0.20 ± 0.01b	0.67 ± 0.03a	0.28 ± 0.00b	0.71 ± 0.10a	0.68 ± 0.01ab	0.91 ± 0.14a	0.59 ± 0.05b		
Others		1.74 ± 0.02	1.16 ± 0.02a	1.16 ± 0.01a	0.62 ± 0.00b	0.61 ± 0.01b	0.66 ± 0.00a	0.51 ± 0.01c	0.83 ± 0.01a	0.62 ± 0.01b	0.26 ± 0.01c		
EO Yield		1.51 ± 0.03	1.47 ± 0.15b	1.87 ± 0.08a	2.13 ± 0.07a	1.95 ± 0.13	2.10 ± 0.06	1.79 ± 0.07	2.17 ± 0.10	2.02 ± 0.06	2.29 ± 0.07		

The values shown are the mean (±standard error; n = 3). Different lowercase letters indicate statistical differences ($p \leq 0.05$) among the treatments on the same day.

3.8 Tannin Content of Infusions

The impact of temperature on the tannin content of sage infusions made from plant material stored at 2, 6, and 20°C is shown in Table 3. Tannin concentration increased at 20°C for the first 5 days but decreased after 10 and 15 days of storage. On the last day of storage, the greatest tannin concentration was found in infusions from sage stored at 2°C (Table 3).

Table 3: Influence of temperature on the tannin's concentration and antibacterial activity of infusions obtained from fresh sage stored at refrigerator (2 and 6°C) and room temperatures (20°C) for 15 days.

Day	Temperature (°C)	<i>E. coli</i>		<i>S. aureus</i>		Tannins Concentration (g/L)
		MIC (mg/mL)	IC ₅₀ (mg/mL)	MIC (mg/mL)	IC ₅₀ (mg/mL)	
0	20	0.500 ± 0.000	3.337 ± 0.657	0.031 ± 0.000	3.420 ± 0.304	1.99 ± 0.99
5	2	0.250 ± 0.000b'	4.693 ± 0.693b'	0.031 ± 0.000a'	2.774 ± 0.071a'	3.53 ± 0.01b
	6	0.500 ± 0.000b'	5.849 ± 0.304b'	0.031 ± 0.000a'	1.876 ± 0.142b'	3.08 ± 0.02c
	20	0.500 ± 0.000a'	9.400 ± 0.068a'	0.031 ± 0.000a'	1.437 ± 0.196c'	4.37 ± 0.06a
10	2	0.500 ± 0.000a''	9.865 ± 0.049b''	0.031 ± 0.000b''	3.065 ± 0.538a''	3.66 ± 0.01b
	6	0.250 ± 0.000b''	8.354 ± 0.465c''	0.031 ± 0.000b''	2.855 ± 0.080a''	3.75 ± 0.02a
	20	0.500 ± 0.000a''	13.006 ± 0.484a''	0.062 ± 0.000a''	1.426 ± 0.316b''	3.09 ± 0.04c
15	2	0.250 ± 0.000b'''	11.300 ± 1.161b'''	0.062 ± 0.000a'''	3.803 ± 0.349a'''	3.44 ± 0.03a
	6	0.500 ± 0.000a'''	16.213 ± 0.555a'''	0.062 ± 0.000a'''	2.665 ± 0.163a'''	2.04 ± 0.01c
	20	0.500 ± 0.000a'''	12.943 ± 0.340b'''	0.062 ± 0.000a'''	3.587 ± 0.677a'''	2.96 ± 0.02b
Streptomycin		0.0015 ± 0.0000c',c'',c'''	0.0063 ± 0.00023c',d'',c'''	0.0008 ± 0.0000b',c'',b'''	0.0002 ± 0.0008d',c'',b'''	

Values are mean (±standard error) (n = 4). Different letterings indicate statistical differences among storage temperatures on each day ($p \leq 0.05$), where: ' refers to differences for day 5; '' refers to differences for day 10; and ''' refers to differences for day 15.

3.9 Antibacterial Activity of Infusions

Five days of storage of sage at 2°C resulted in infusions with higher activity (followed by 6°C) against *E. coli* compared to 20°C. In contrast, infusions from plant material kept at 6 and 20°C showed lower IC₅₀ values (higher antibacterial activity) against *S. aureus* compared to 2°C. Higher activity against both bacteria (*E. coli* and *S. aureus*) was reported with infusions produced from sage stored at 2 and 6°C compared to the ones from room temperature (20°C). At the end of storage (day 15) infusions from sage stored at 2°C revealed lower MIC and IC₅₀ values (higher activity) against *E. coli* compared to higher temperatures (especially 6°C). All sage infusions investigated in this study presented lower antibacterial activity against both bacteria (*E. coli* and *S. aureus*) than the reference antibiotic (streptomycin) (Table 3).

3.10 PCA and Correlation Matrixes

The first eight principal components (PC1 to PC8) were associated with eigenvalues >1, explaining 97.1% of the cumulative variance, as shown in Fig. 7. PC1 to PC8 accounted for 45.2%, 22.6%, 12.8%, 5.6%, 3.6%, 3.1%, 2.7%, and 1.6%, respectively. The loading plot of PC1 and PC2 explained 67.7% of the variance which associated the following variables: the upper left quadrant included TVC, yeasts and molds, and *S. aureus* IC₅₀; the upper right quadrant included EO yield, antioxidants (FRAP, ABTS) and *E. coli* IC₅₀; the lower right quadrant included ascorbic acid, phenols, weight loss, camphor, and Chl a:Chl b ratio; the lower left quadrant included 1,8-cineole, α-thujone, flavonoids, tannins, respiration, macroscopically appearance, and Chl b (Fig. 7). The distinct separation of data throughout the PCA biplot suggested substantial biochemical variations. PC1 separated samples according to quality preservation and storage-induced changes. Positive PC1 scores were associated with antioxidant activity (FRAP, ABTS, and ascorbic

acid), EO yield, antimicrobial activity, and weight loss, whereas negative PC1 scores were associated with flavonoids, tannins, macroscopic quality, and chlorophyll-related parameters. PC2 further discriminated against samples according to respiration, pigment retention, and microbial characteristics. Day 5 treatments clustered closer to chlorophylls, flavonoids, and tannins, suggesting better preservation of quality attributes, whereas the opposite was evidenced for Day 15 treatments.

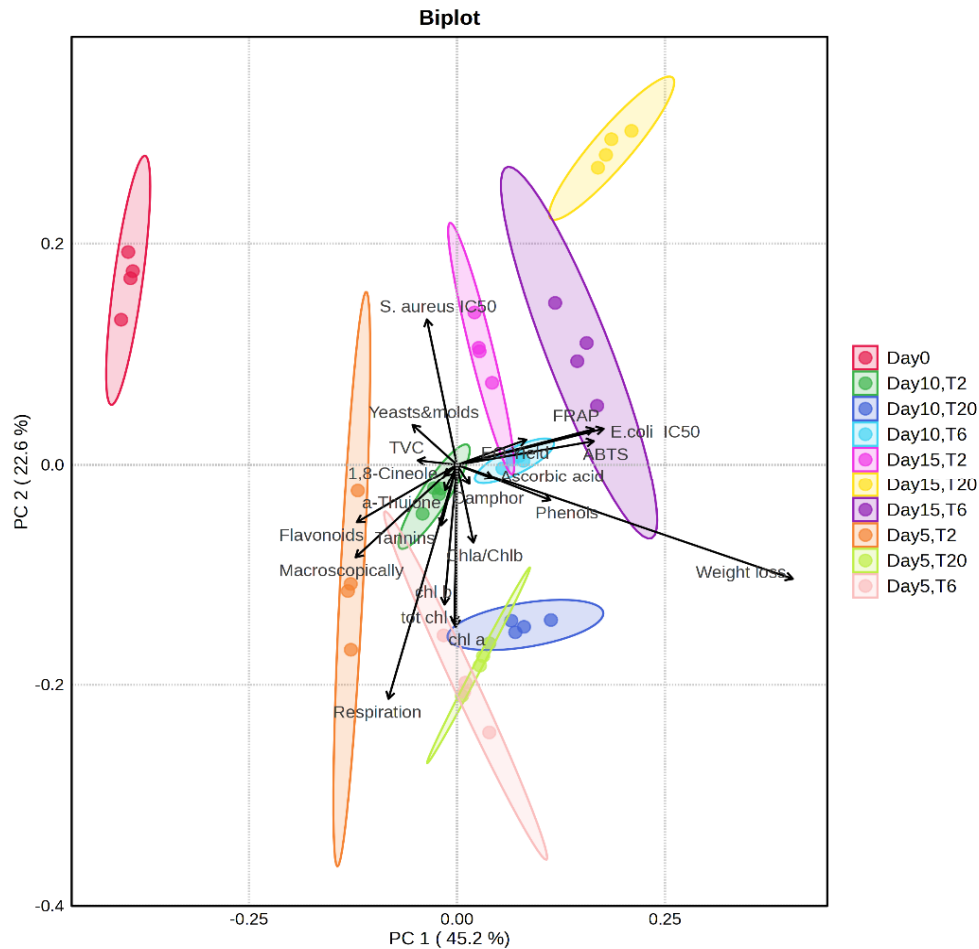


Figure 7: Loading plots of principal components 1 and 2 for different temperatures (T: 2°C, 6°C, and 20°C) and days (Day: 0, 5, 10, and 15) of storage for *S. officinalis*.

Using hierarchical clustering (Fig. S3) and Pearson correlation heatmap analysis (Fig. 8), two significant variable groups were found. The first group comprised chlorophylls, chlorophyll a/chlorophyll b ratio, tannins, flavonoids, ascorbic acid, volatile compounds (α -thujone, camphor, and 1,8-cineole), and macroscopic quality, which were positively correlated and associated with quality preservation. The second group consisted of phenols, antioxidant activity (ABTS and FRAP), EO yield, antimicrobial indicators, microbial counts (TVC and yeasts & molds), and weight loss (Fig. S3). Strong negative correlations between these groups indicate that storage-induced pigment degradation and visual quality loss occurred concurrently with microbial proliferation and changes in antioxidant and antimicrobial properties. The clustering pattern corroborates the PCA results, demonstrating that storage duration and temperature substantially affected physiological, biochemical, and microbiological characteristics.

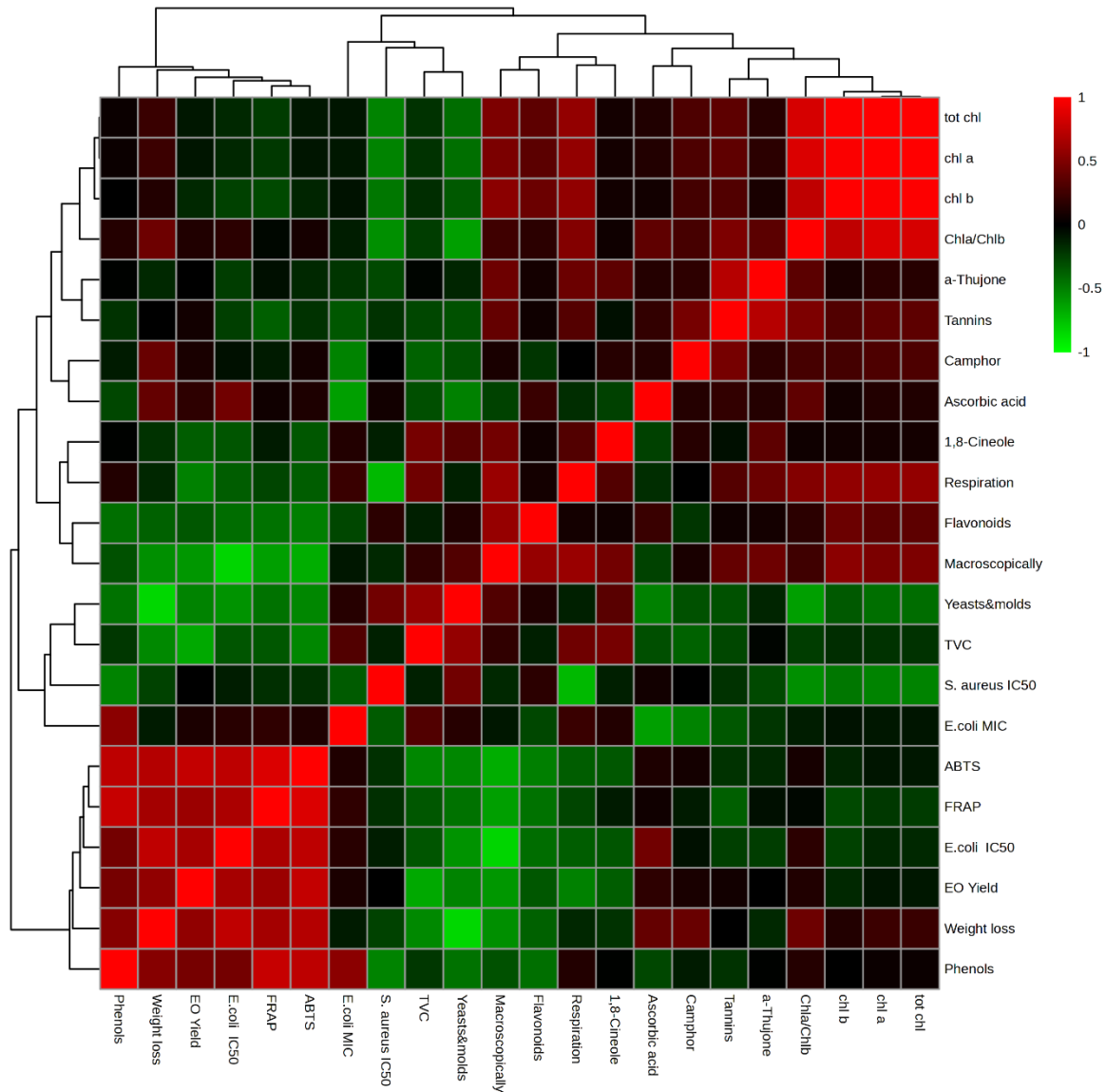


Figure 8: Heat-map matrices of the correlation between growth, physiology, biocidal indices and major essential oil components of *Salvia officinalis*. Each square indicates r (Pearson's correlation coefficient of a pair of metabolites).

4 Discussion

High relative humidity combined with chilled storage temperatures reduces respiratory and enzymatic activity and inhibits disease development, thereby creating favorable conditions for preserving highly perishable fresh products such as herbs. Additionally, these storage conditions reduce the metabolic activity of fresh produce while reducing water loss, respiration, and ethylene emission, thereby delaying and/or inhibiting the growth of spoiling bacteria [32,33]. Once plant tissues are detached from their modular structure, they deteriorate rapidly. The use of refrigerated and controlled atmosphere may help preserve the quality of perishable produce and extend its shelf life [48]. Most vegetables lose between 3–10% of their weight through transpiration during storage, and losses may sometimes be even greater under unfavorable environmental conditions [49]. When leafy vegetables lose more than 3% of their weight while being stored, this is linked to low-quality product, yellowing or browning of the leaves, and a short

shelf life [50]. Furthermore, reduced levels of weight loss have been linked to better visual appearance and storage capacity [36,49,50]. Higher respiration rates are linked to advanced metabolism and quicker senescence in leafy greens and herbs, manifested by leaf wilting and yellowing [51]. In the present study, sage stored at 20°C exhibited up to 10.5% weight loss after 15 days of storage, corresponding to an average daily loss of 0.7%. In contrast, the average daily weight losses at 2 and 6°C were 0.23% and 0.62%, respectively. These observations were consistent with the decreased sage appearance at higher storage temperatures. Considering the commonly accepted threshold limitation of 3% weight loss for maintaining acceptable quality in leafy greens [50], fresh sage could be stored up to 5 days at both 2 and 6°C; however, for longer storage periods, a target temperature of 2°C would be preferable. It is recommended to maintain the relative humidity (RH) in the storage room at a high level, as in the vegetable storage conditions, to avoid excessive water loss and reduce quality losses [52].

The increased weight loss found at 20°C was likely linked to the elevated respiration and ethylene production rates recorded during the first 10 days of storage. An increase in respiration, measured through CO₂ production, and ethylene emission are directly related to the increased storage temperature. This may be exhibited and obviously contributes to senescence, the degradation of leaf green pigments, and an increase in plant metabolism [49,51]. Furthermore, several biological processes, including respiration, ethylene production, and microbial growth, are temperature-dependent and may result in product spoiling, underscoring the need for appropriate postharvest storage conditions.

Higher water loss has been linked to increased color abnormalities, particularly under increased temperatures and reduced relative humidity, potentially due to the membrane breakdown and chlorophyll's green color loss [49,52]. Chlorophyll degradation may be further hastened by mechanical damage occurring during harvesting and/or processing during storage and packing [53]. The main strategy used for avoiding browning in leafy greens is to control storage conditions and to that sense to postpone the chlorophyll oxidation and degradation [54]. Leaf browning has also been associated with the activities of phenylalanine ammonia-lyase (PAL) and polyphenol oxidase (PPO) [55]. PAL participates in the production of phenolic compounds in reaction to environmental stressors, whereas PPO catalyzes the oxidation and polymerization of phenolic compounds, which results in the creation of brown or black pigments, particularly o-quinones [56]. The current study found that storing sage at high temperatures of 20°C, reduced its chlorophyll content, suggesting a low-quality product. According to Manolopoulou and Varzakas [57], the lettuce chlorophyll content remained relatively constant during the initial three days of storage at 5°C, whereas at increased temperatures (10 and 20°C), it was associated with storage duration. It is widely accepted that the last step of senescence is the breakdown of chlorophyll. The observation that chlorophyll catabolic enzymes are activated by plant hormones that control senescence, such as ethylene, abscisic acid, and jasmonic acid, and that chlorophyll breakdown takes place during the latter stage of plant growth, lends credence to this hypothesis [58]. Considering that chlorophyll degradation also serves as a signal to accelerate senescence, one cannot depend on the idea that the chlorophyll degradation is only one of the effects of leaf senescence [59].

Sage is one of the culinary herbs known to be an excellent source of phytochemicals particularly antioxidant compounds. According to a number of studies, a diet rich in polyphenols may help to prevent or to protect against chronic diseases, such as neurological disorders, cancer, and heart problems, among others [60]. A significant amount of enzymatic (catalase, ascorbate peroxidase, etc.) and non-enzymatic (phenols, flavonoids) antioxidant molecules that are activated to reduce oxidative stress are found naturally in sage [61]. Enhancing these natural antioxidant systems through postharvest treatments may help extend shelf life and maintain product quality. Nevertheless, the existence of other chemicals, including vitamin C,

which is often evaluated with the ascorbic acid level, could provide insight into the general stability of the phenolic and flavonoid composition throughout storage [62]. In an effort to alleviate the stress, the plants may produce more polyphenols and other antioxidants like vitamins (E, C), flavonoids, and carotenoids when fresh produce is stored in adverse environments (such as excessively high or low temperatures and low relative humidity) [35,63]. For example, Fratianni et al. [35] found that when sweet basil plants were kept at 12°C for nine days instead of 4°C, they were able to maintain their polyphenol level and antioxidant properties. In the present study, sage stored at higher temperatures (6 and 20°C) presented higher phenolic and antioxidant activity (FRAP, ABTS) opposed to 2°C during storage. In contrast flavonoids and partially AA, remained in high content at low temperature storage of sage. These findings provide credence to the theory that physiological and morphological differences, such as surface area of the leaf and structure, may cause individual herbs and leafy vegetables to perform differently throughout storage [64].

According to Sui et al. [54], storage under adverse conditions may trigger processes like enzymatic activity that might result in polyphenols oxidation and the creation of colorless o-diphenols, which subsequently form brown colored polymers. This mechanism might help to explain why fresh sage kept at 20°C showed a drop in flavonoid levels but not in total phenolic content; however, further investigation is required to validate this hypothesis. Sui et al. [54], also documented same findings throughout the postharvest storage of baby mustard at both low and high storage temperatures (4 and 20°C), whereas the low temperatures delaying the product's antioxidant capability and polyphenol loss. Even though storage-related stress is generally associated with fresh produce deterioration, a rise in antioxidants paired with high visual quality is acceptable as it boosts the product's nutritional value. Because aromatic herbs contain substantial amounts of phenolic compounds and their antioxidant capacity varies little over time, adding a few grams or portions of these herbs to a meal might increase the daily diet's antioxidant capacity with possible health advantages [17]. Furthermore, several phenolic compounds have demonstrated antibacterial properties. When aromatic plants are introduced to various food products, they may act as stabilizers, greatly extending their shelf life [62].

Microbial load has a significant impact on the shelf life of fresh foods, as products stored under high relative humidity conditions and with low to moderate microbial loads may deteriorate more rapidly [53]. In the present study, storage at 2 and 6°C resulted in lower total viable counts on days 5 and 10, while yeast and mold counts were higher at 20°C. Because of their antibacterial activity, higher concentrations of phenols, flavonoids, and ascorbic acid may lower microbial populations and improve preservation [60]. Herbs like rosemary and sage have inherent antibacterial qualities that can reduce microbial loads and prolong shelf life [22]. Increased microbial loads in fresh produce enhance the risk of quality loss, including browning of the leaves due to spoiling microbes such *Pseudomonas* spp. [65,66]. Thus, by reducing microbial activity, low-temperature storage (2–5°C), either alone or in conjunction with other preservation techniques (also known as “hurdle technology”), aids in maintaining quality.

After five days of storage, the EO yield was higher at 6 and 20°C than at 2°C. This difference may be related to the substantial weight loss (up to 6.01%), which may artificially concentrate (dehydration) the EO content on a dry-weight basis without actual *de novo* biosynthesis. However, this was not reflected in the similar EO yield observed after 15 days of sage storage, despite the substantial weight loss (up to 10.5% by Day 15) and may include different physiological responses, and warrant further investigation. The scent of fresh herbs, which is mostly due to their EO content, is one of their primary qualities. EOs are blends of substances that are kept in different parts of plants, such as trichomes on leaves. It is known that younger leaves contain more glandular trichomes than older leaves, which might explain why the composition of EOs varies [67]. In addition to their sensory importance, EOs include components with strong biological

activities, such as antioxidants and antimicrobials. The presence of secondary metabolites produced by plants is necessary for the antibacterial activity of EOs [68]. The primary constituents of sage EO are the monoterpenes 1,8-cineole, α - and β -thujone, and camphor, which are produced by 1,8-cineole synthase, (+)-sabinene synthase and (+)-bornyl diphosphate synthase, respectively [11]. In line with other research, the primary EO components in this investigation were α -thujone, camphor, and 1,8-cineole [69]. The main component, α -thujone, seems to have decreased at 20°C during the storage period. Increased camphor and 1,8-cineole levels were found at refrigerator temperatures, and this is of great importance because of their well-established antimicrobial, antioxidant [70,71], anti-inflammatory [72], and anticancer properties [10].

In addition to EOs, the antibacterial properties of various plant preparations such as infusions and decoctions have been investigated [73]. In the present study, higher activity against both bacteria (*E. coli* and *S. aureus*) was reported with infusions prepared from sage stored at refrigerator temperatures (2 and 6°C) compared to the ones from room temperature (20°C). It became apparent that *S. aureus* was more vulnerable to the infusions' effects than *E. coli*. In *S. aureus*, the higher antibacterial activity (lower IC₅₀ values) was found at lower temperatures (2 and 6°C) during the first five days, which persisted for the 2°C after ten days, and effects eliminated after 15 days. Several hypotheses on the antibacterial activity of plant extracts have been proposed, but they are all predicated on the assumption that particular chemical groups (such as phenols and flavonoids) may target particular cell structures and/or cellular parts including proteins and DNA [74]. *S. aureus* was more susceptible to the infusions obtained during the first five days of storage than *E. coli*. This difference may be attributed to variations in their cell wall structure: Gram-negative bacteria such as *E. coli* possess an additional outer membrane composed of a double lipid layer, which can serve as a supplementary defense towards EOs and other plant-derived extracts [75]. This double lipid layer is absent in Gram positive bacteria such as *S. aureus*. Similar findings regarding the antibacterial properties of *S. officinalis* infusion against these bacteria species have been reported previously [3]. The major EO compounds found in the current research, namely α -thujone, camphor, and 1,8-cineole, have been widely proven to have antibacterial activity [76,77]. The presence of these compounds may therefore explain, at least in part, the antibacterial activity observed in the present study. The examined infusions exhibit promise as antimicrobial agents while having less antibacterial properties than the common antibiotic streptomycin. In particular, these infusions may be useful in combination with antibiotics to reduce required doses and help limit the development of antibiotic resistance. For example, the blend of hydroethanolic (70%) extracts and infusions of clove, cinnamon, and thyme with tetracycline, ciprofloxacin, and erythromycin shown promising effects towards *E. coli*, *S. aureus* and *Pseudomonas aeruginosa* [74].

A broad spectrum of plant-based foods and drinks include tannins, a diversified family of polyphenolic substances that greatly enhance taste, astringency, and a number of health advantages [78]. Tannins concentrations were increased at the 20°C for the first 5 days, and then progressively decreased as the temperature and storage duration were progressed. The stability of tannins is known to be influenced by storage temperature in different fresh produce, whereas the tannin compounds may interact with other components in the sage infusion, such as metal ions [79], which may affect the color and quality changes. However, the specific reasons need to be further investigated.

5 Conclusions

It is crucial to maintain the freshness of herbs and increase their shelf life. Storage under unfavorable conditions may result in quality deterioration and reduced marketability. In an effort to determine the best preservation conditions for sage, this study evaluated the effect of temperature on the postharvest quality of fresh sage. The findings demonstrated that, in comparison to reduced temperatures (2 and 6°C), storing sage

at ambient temperature (20°C) resulted in increased weight loss, greater respiration and ethylene emission rates, and poorer visual quality. Sage stored at 2°C exhibited higher content of phenols and antioxidant capacity but lower flavonoids during storage, while bundles stored at 2°C had the lowest weight loss. After five days of storage, fresh sage stored at 6 and 20°C had considerably higher EO yield than the ones stored at 2°C. However, after 10 and 15 days of storage, the yield stayed the same. Three primary components: α -thujone, camphor, and 1,8-cineole were subjected to temperature and storage duration fluctuations, with α -thujone exhibiting opposite effects compared to camphor and 1,8-cineole. Furthermore, infusions from sage stored at low temperature obtained higher antibacterial activity, compared to the sage stored at higher temperatures. Overall, the findings of this study suggested that storage of fresh sage at 6°C for 5 days, with increased relative humidity, could be considered as favourable conditions for sage preservation. For a longer storage period, i.e., 10 days, a lower temperature of 2°C is recommended.

Acknowledgement: Not applicable.

Funding Statement: The authors received no specific funding for this study.

Author Contributions: Conceptualization, Nikolaos Tzortzakakis; methodology, Antonios Chrysargyris, Jovana Petrovic and Nikolaos Tzortzakakis; software, Antonios Chrysargyris and Gokhan Zengin; validation, Marina Sokovic and Gokhan Zengin; formal analysis, Antonios Chrysargyris; investigation, Antonios Chrysargyris, Jovana Petrovic and Nikolaos Tzortzakakis; resources, Marina Sokovic and Nikolaos Tzortzakakis; data curation, Antonios Chrysargyris and Jovana Petrovic; writing—original draft preparation, Antonios Chrysargyris and Nikolaos Tzortzakakis; writing—review and editing, Antonios Chrysargyris, Marina Sokovic, Gokhan Zengin and Nikolaos Tzortzakakis; visualization, Antonios Chrysargyris; supervision, Nikolaos Tzortzakakis; project administration, Nikolaos Tzortzakakis; funding acquisition, Nikolaos Tzortzakakis. All authors reviewed and approved the final version of the manuscript.

Availability of Data and Materials: The datasets generated during and/or analyzed during the current study are available from the corresponding authors on reasonable request.

Ethics Approval: This study involved a non-interventional consumer sensory survey. All participants provided informed consent, and their personal data were anonymized and kept confidential.

Conflicts of Interest: Given their role as Associate Editors of this journal, Antonios Chrysargyris and Nikolaos Tzortzakakis had no involvement in the peer review of this article and had no access to information regarding its peer review. Full responsibility for the editorial process for this article was delegated to another journal editor. The authors declare no other conflicts of interest.

Supplementary Materials: The supplementary material is available online at <https://www.techscience.com/doi/10.32604/phyton.2026.088145/s1>. Figure S1: Representative *Salvia officinalis* chromatogram. Figure S2: Impact of storage temperature on the main components profile (%) of fresh sage stored under different temperatures (2, 6 and 20°C) for up to 15 days (Day 0-D0; Day 5-D5; Day 10-D10; Day 15-D15). Figure S3: Metabolite changes in *Salvia officinalis*. Heat map representing relative expression of growth, physiology and biocidal features elicited in plant tissue under different temperatures and days of storage.

References

1. Jakovljević M, Jokić S, Molnar M, Jašić M, Babić J, Jukić H, et al. Bioactive profile of various *Salvia officinalis* L. preparations. *Plants*. 2019;8(3):55. [CrossRef].
2. Ghorbani A, Esmaeilzadeh M. Pharmacological properties of *Salvia officinalis* and its components. *J Tradit Complement Med*. 2017;7(4):433–40. [CrossRef].
3. Silva BN, Cadavez V, Caleja C, Pereira E, Calhella RC, Añibarro-Ortega M, et al. Phytochemical composition and bioactive potential of *Melissa officinalis* L., *Salvia officinalis* L. and *Mentha spicata* L. extracts. *Foods*. 2023;12(5):947. [CrossRef].

4. Al-Sarraj F, Alotibi I, Al-Zahrani M, Albiheyri R, Alghamdi MA, Nass NM, et al. Green synthesis of chitosan-capped gold nanoparticles using *Salvia officinalis* extract: biochemical characterization and antimicrobial and cytotoxic activities. *Molecules*. 2023;28(23):7762. [[CrossRef](#)].
5. Cvetkovikj I, Stefkov G, Karapandzova M, Kulevanova S, Satović Z. Essential oils and chemical diversity of southeast European populations of *Salvia officinalis* L. *Chem Biodivers*. 2015;12(7):1025–39. [[CrossRef](#)].
6. Tounekti T, Munné-Bosch S, Vadel AM, Chtara C, Khemira H. Influence of ionic interactions on essential oil and phenolic diterpene composition of Dalmatian sage (*Salvia officinalis* L.). *Plant Physiol Biochem*. 2010;48(10–11):813–21. [[CrossRef](#)].
7. Kontogianni VG, Tomic G, Nikolic I, Nerantzaki AA, Sayyad N, Stosic-Grujicic S, et al. Phytochemical profile of *Rosmarinus officinalis* and *Salvia officinalis* extracts and correlation to their antioxidant and anti-proliferative activity. *Food Chem*. 2013;136(1):120–9. [[CrossRef](#)].
8. Bedini S, Guarino S, Echeverria MC, Flamini G, Ascrizzi R, Loni A, et al. *Allium sativum*, *Rosmarinus officinalis*, and *Salvia officinalis* essential oils: a spiced shield against blowflies. *Insects*. 2020;11(3):143. [[CrossRef](#)].
9. Mansourabadi AH, Sadeghi HM, Razavi N, Rezvani E. Anti-inflammatory and analgesic properties of salvigenin, *Salvia officinalis* flavonoid extracted. *Adv Herb Med*. 2015;1(3):31–41.
10. Russo A, Formisano C, Rigano D, Senatore F, Delfino S, Cardile V, et al. Chemical composition and anticancer activity of essential oils of Mediterranean sage (*Salvia officinalis* L.) grown in different environmental conditions. *Food Chem Toxicol*. 2013;55:42–7. [[CrossRef](#)].
11. Grausgruber-Gröger S, Schmiderer C, Steinborn R, Novak J. Seasonal influence on gene expression of monoterpene synthases in *Salvia officinalis* (Lamiaceae). *J Plant Physiol*. 2012;169(4):353–9. [[CrossRef](#)].
12. Chrysargyris A, Evangelides E, Tzortzakis N. Seasonal variation of antioxidant capacity, phenols, minerals and essential oil components of sage, spearmint and *Sideritis* plants grown at different altitudes. *Agronomy*. 2021;11(9):1766. [[CrossRef](#)].
13. Aksoy A. Areas of use of medicinal and aromatic plants: literature-supported compilation. *Eur J Public Health Stud*. 2025;8(2):180–5. [[CrossRef](#)].
14. Lytra K, Tomou EM, Chrysargyris A, Drouza C, Skaltsa H, Tzortzakis N. Traditionally used *Sideritis cyprica* post.: phytochemistry, nutritional content, bioactive compounds of cultivated populations. *Front Pharmacol*. 2020;11:650. [[CrossRef](#)].
15. Kumar A, Jnanesh A, Venugopal S, Nagaraju S. Post-harvest and value additions of important medicinal crops. In: Hussain M, editor. *Research trends in medicinal plant sciences*. New Delhi, India: AkiNik Publications; 2020. p. 53–75.
16. Hazrati S, Mousavi Z, Nicola S. Harvest time optimization for medicinal and aromatic plant secondary metabolites. *Plant Physiol Biochem*. 2024;212:108735. [[CrossRef](#)].
17. Thakur A, Thakur B, Kumar R. Post-harvest management of medicinal and aromatic plants: current trends and recent advances. *J Essent Oil Bear Plants*. 2025;28(1):1–23. [[CrossRef](#)].
18. Bisht VK, Uniyal RC, Sharma SM. Reasons for rejection of herbal raw material traded in Indian market and its possible solution. *J Appl Res Med Aromat Plants*. 2022;26:100360. [[CrossRef](#)].
19. Sui X, Liu T, Ma C, Yang L, Zu Y, Zhang L, et al. Microwave irradiation to pretreat rosemary (*Rosmarinus officinalis* L.) for maintaining antioxidant content during storage and to extract essential oil simultaneously. *Food Chem*. 2012;131(4):1399–405. [[CrossRef](#)].
20. Hassan FAS, Ali EF, Mostafa NY, Mazrou R. Shelf-life extension of sweet basil leaves by edible coating with thyme volatile oil encapsulated chitosan nanoparticles. *Int J Biol Macromol*. 2021;177:517–25. [[CrossRef](#)].
21. Tzortzakis N. Short-term ozone-enriched atmosphere impacted quality-related attributes during postharvest storage of basil. *Int J Food Sci Technol*. 2025;60(2):vvaf173. [[CrossRef](#)].
22. Xylia P, Fasko KG, Chrysargyris A, Tzortzakis N. Heat treatment, sodium carbonate, ascorbic acid and rosemary essential oil application for the preservation of fresh *Rosmarinus officinalis* quality. *Postharvest Biol Technol*. 2022;187:111868. [[CrossRef](#)].
23. Benkeblia N. Recent advances in postharvest technologies, Volume 2: Postharvest applications. Cham, Switzerland: Springer Nature; 2024. [[CrossRef](#)].
24. Brindisi LJ, Simon JE. Preharvest and postharvest techniques that optimize the shelf life of fresh basil (*Ocimum basilicum* L.): a review. *Front Plant Sci*. 2023;14:1237577. [[CrossRef](#)].

25. Rodeo AJD, Mitcham EJ. Chilling temperatures and controlled atmospheres alter key volatile compounds implicated in basil aroma and flavor. *Front Plant Sci.* 2023;14:1218734. [[CrossRef](#)].
26. Elshafie HS, de Martino L, Formisano C, Caputo L, de Feo V, Camele I. Chemical identification of secondary metabolites from rhizospheric actinomycetes using LC-MS analysis: in silico antifungal evaluation and growth-promoting effects. *Plants.* 2023;12(9):1869. [[CrossRef](#)].
27. Tzortzakis N, Goumenos C, Chrysargyris A. Optimizing the postharvest storage conditions for high quality fresh sage. *Open Agric.* 2026;11:20250489. [[CrossRef](#)].
28. Malik S, Sharma K, Kanaujia A. Harvest and post harvest management for ensuring quality of medicinal plants. *Int J Adv Res.* 2021;9(5):602–6. [[CrossRef](#)].
29. Xiao Z, Luo Y, Lester GE, Kou L, Yang T, Wang Q. Postharvest quality and shelf life of radish microgreens as impacted by storage temperature, packaging film, and chlorine wash treatment. *LWT Food Sci Technol.* 2014;55(2):551–8. [[CrossRef](#)].
30. Kirigia D, Winkelmann T, Kasili R, Mibus H. Development stage, storage temperature and storage duration influence phytonutrient content in cowpea (*Vigna unguiculata* L. Walp.). *Heliyon.* 2018;4(6):e00656. [[CrossRef](#)].
31. Sahu P, Sharma SP, Singh J, Paikra MS, Nishad DD, Kumar A. Effect of different storage condition on storage behavior of primary processed leafy vegetables. *Int J Res Agron.* 2024;7(11S):314–24. [[CrossRef](#)].
32. Ronoh EK, Kanali CL, Ndirangu SN. Effectiveness of an evaporative charcoal cooler for the postharvest preservation of tomatoes and kales. *Res Agric Eng.* 2020;66(2):66–71. [[CrossRef](#)].
33. Hettiarachchi WABH, Sandarenu KMSD, Gamage SNW, Attanayaka RMTD, Dassanayaka YMHM, Galahitiyawa DDK, et al. Evaluation of clay pot cooler storage for preserving postharvest quality of leafy vegetables. *J Hortic Postharvest Res.* 2024;7(1):45–58. [[CrossRef](#)].
34. Bonanno L, Bergis H, Gnanou-Besse N, Asséré A, Danan C. Which domestic refrigerator temperatures in Europe?—Focus on shelf-life studies regarding *Listeria monocytogenes* (Lm) in ready-to-eat (RTE) foods. *Food Microbiol.* 2024;123:104595. [[CrossRef](#)].
35. Fratianni F, Cefola M, Pace B, Cozzolino R, De Giulio B, Cozzolino A, et al. Changes in visual quality, physiological and biochemical parameters assessed during the postharvest storage at chilling or non-chilling temperatures of three sweet basil (*Ocimum basilicum* L.) cultivars. *Food Chem.* 2017;229:752–60. [[CrossRef](#)].
36. Xylia P, Chrysargyris A, Tzortzakis N. *Origanum dubium* boiss. (Cypriot oregano) use for the preservation of fresh spearmint quality and safety. *Agronomy.* 2024;14(6):1252. [[CrossRef](#)].
37. Chrysargyris A, Nikolaidou E, Stamatakis A, Tzortzakis N. Vegetative, physiological, nutritional and antioxidant behavior of spearmint (*Mentha spicata* L.) in response to different nitrogen supply in hydroponics. *J Appl Res Med Aromat Plants.* 2017;6:52–61. [[CrossRef](#)].
38. Arnon DI. Copper enzymes in isolated chloroplasts. polyphenoloxidase in beta vulgaris. *Plant Physiol.* 1949;24(1):1–15. [[CrossRef](#)].
39. Chrysargyris A, Michailidi E, Tzortzakis N. Physiological and biochemical responses of *Lavandula angustifolia* to salinity under mineral foliar application. *Front Plant Sci.* 2018;9:489. [[CrossRef](#)].
40. Chrysargyris A, Petrovic JD, Tomou EM, Kyriakou K, Xylia P, Kotsoni A, et al. Phytochemical profiles and biological activities of plant extracts from aromatic plants cultivated in Cyprus. *Biology.* 2024;13(1):45. [[CrossRef](#)].
41. AOAC International. Official methods of analysis. 18th ed. Gaithersburg, MD, USA: AOAC International; 2007.
42. Chrysargyris A, Panayiotou C, Tzortzakis N. Nitrogen and phosphorus levels affected plant growth, essential oil composition and antioxidant status of lavender plant (*Lavandula angustifolia* Mill.). *Ind Crops Prod.* 2016;83:577–86. [[CrossRef](#)].
43. Adams RP. Identification of essential oil components by gas chromatography/mass spectrometry. 4th ed. Carol Stream, IL, USA: Allured Publishing Corporation; 2007.
44. Tomou EM, Karioti A, Tsirogiannidis G, Krigas N, Skaltsa H. Metabolic characterization of four members of the genus *Stachys* L. (Lamiaceae). *Agronomy.* 2023;13(10):2624. [[CrossRef](#)].
45. Zairi A, Nouir S, M Hamdi N, Bennani M, Bergaoui I, Mtraoui A, et al. Antioxidant, antimicrobial and the phenolic content of infusion, decoction and methanolic extracts of thyme and *Rosmarinus* Species. *Curr Pharm Biotechnol.* 2018;19(7):590–9. [[CrossRef](#)].

46. Xylia P, Chrysargyris A, Tomou EM, Goumenos C, Skaltsa H, Tzortzakakis N. Quality characteristics and essential oil properties of *Thymus capitatus*, *Mentha piperita*, and *Sideritis cypria* dried under different conditions. *Plants*. 2024;13(22):3150. [[CrossRef](#)].
47. Kant R, Tilford H, Freitas CS, Ferreira DAS, Ng J, Rucinski G, et al. Antimicrobial activity of compounds identified by artificial intelligence discovery engine targeting enzymes involved in *Neisseria gonorrhoeae* peptidoglycan metabolism. *Biol Res*. 2024;57(1):62. [[CrossRef](#)].
48. Shomodder A, Imaizumi T, Nagata M, Kasai E, Shiina T, Tsuta M, et al. Existence of circadian rhythm and its response behavior under different storage conditions of soybean sprouts. *J Plant Physiol*. 2023;281:153906. [[CrossRef](#)].
49. Changsawake K, Krusong W, Laosinwattana C, Teerarak M. Retarding changes of postharvest qualities of sweet basil (*Ocimum basilicum* Linn.) by vapor-phase vinegar. *J Herbs Spices Med Plants*. 2017;23(4):284–98. [[CrossRef](#)].
50. Xylia P, Chrysargyris A, Thussagunpanit J, Boonruang K, Zengin G, Tzortzakakis N. Influence of postharvest storage conditions on physiological responses, bioactive compounds, and antibacterial activity of fresh thyme (*Thymus vulgaris*). *Eur Food Res Technol*. 2026;252(9):316. [[CrossRef](#)].
51. Poimenidou SV, Bikouli VC, Gardeli C, Mitsi C, Tarantilis PA, Nychas GJ, et al. Effect of single or combined chemical and natural antimicrobial interventions on *Escherichia coli* O157: H7, total microbiota and color of packaged spinach and lettuce. *Int J Food Microbiol*. 2016;220:6–18. [[CrossRef](#)].
52. Yang C, Xu Y, Xie X, Wu Y, Gao Z, Li K, et al. Post-harvest physiology of vegetable crops and its regulation. In: *Growth regulation and quality improvement of vegetable crops: physiological and molecular features*. Singapore: Springer; 2025. p. 495–557. [[CrossRef](#)].
53. Iakimova ET, Ty AJ, Hertog MLATM, Nicolai BM, Woltering EJ. Programmed cell death and postharvest deterioration of fresh horticultural products. *Postharvest Biol Technol*. 2024;214:113010. [[CrossRef](#)].
54. Sui X, Meng Z, Dong T, Fan X, Wang Q. Enzymatic browning and polyphenol oxidase control strategies. *Curr Opin Biotechnol*. 2023;81:102921. [[CrossRef](#)].
55. Doğan S, Diken ME, Turhan Y, Alan Ü, Doğan M, Alkan M. Characterization and inhibition of *Rosmarinus officinalis* L. polyphenoloxidase. *Eur Food Res Technol*. 2011;233(2):293–301. [[CrossRef](#)].
56. Tonto TC, Cimini S, Grasso S, Zompanti A, Santonico M, De Gara L, et al. Methodological pipeline for monitoring post-harvest quality of leafy vegetables. *Sci Rep*. 2023;13(1):20568. [[CrossRef](#)].
57. Manolopoulou E, Varzakas T. Effect of temperature in color changes of green vegetables. *Curr Res Nutr Food Sci*. 2016;4:10–7. [[CrossRef](#)].
58. Kuai B, Chen J, Hörtensteiner S. The biochemistry and molecular biology of chlorophyll breakdown. *J Exp Bot*. 2018;69(4):751–67. [[CrossRef](#)].
59. Tanaka A, Ito H. Chlorophyll degradation and its physiological function. *Plant Cell Physiol*. 2025;66(2):139–52. [[CrossRef](#)].
60. Arfaoui L. Dietary plant polyphenols: effects of food processing on their content and bioavailability. *Molecules*. 2021;26(10):2959. [[CrossRef](#)].
61. Kalisz A, Sękara A, Pokluda R, Jezdinsky A, Neugebauerová J, Slezák KA, et al. Sequential response of sage antioxidant metabolism to chilling treatment. *Molecules*. 2019;24(22):4087. [[CrossRef](#)].
62. Santos J, Herrero M, Mendiola JA, Oliva-Teles MT, Ibáñez E, Delerue-Matos C, et al. Fresh-cut aromatic herbs: nutritional quality stability during shelf-life. *LWT Food Sci Technol*. 2014;59(1):101–7. [[CrossRef](#)].
63. Curutchet A, Dellacassa E, Ringuet JA, Chaves AR, Viña SZ. Nutritional and sensory quality during refrigerated storage of fresh-cut mints (*Mentha × piperita* and *M. spicata*). *Food Chem*. 2014;143:231–8. [[CrossRef](#)].
64. Bonasia A, Lazzizera C, Elia A, Conversa G. Pre-harvest strategy for improving harvest and post-harvest performance of kale and chicory baby leaves. *Plants*. 2025;14(6):863. [[CrossRef](#)].
65. Xylia P, Botsaris G, Skandamis P, Tzortzakakis N. Expiration date of ready-to-eat salads: effects on microbial load and biochemical attributes. *Foods*. 2021;10(5):941. [[CrossRef](#)].
66. Nousiainen LL, Joutsen S, Lunden J, Hänninen ML, Fredriksson-Ahomaa M. Bacterial quality and safety of packaged fresh leafy vegetables at the retail level in Finland. *Int J Food Microbiol*. 2016;232:73–9. [[CrossRef](#)].
67. Majdi M, Malekzadeh-Mashhady A, Maroufi A, Crocoll C. Tissue-specific gene-expression patterns of genes associated with thymol/carvacrol biosynthesis in thyme (*Thymus vulgaris* L.) and their differential changes upon treatment with abiotic elicitors. *Plant Physiol Biochem*. 2017;115:152–62. [[CrossRef](#)].

68. Jackson-Davis A, White S, Kassama LS, Coleman S, Shaw A, Mendonca A, et al. A review of regulatory standards and advances in essential oils as antimicrobials in foods. *J Food Prot.* 2023;86(2):100025. [[CrossRef](#)].
69. Khammar AA, Moghaddam M, Asgharzade A, Sourestani MM. Nutritive composition, growth, biochemical traits, essential oil content and compositions of *Salvia officinalis* L. grown in different nitrogen levels in soilless culture. *J Soil Sci Plant Nutr.* 2021;21(4):3320–32. [[CrossRef](#)].
70. Ivanov M, Kannan A, Stojković DS, Glamočlija J, Calhelha RC, Ferreira ICFR, et al. Camphor and eucalyptol-anticandidal spectrum, antivirulence effect, efflux pumps interference and cytotoxicity. *Int J Mol Sci.* 2021;22(2):483. [[CrossRef](#)].
71. Boutebouhart H, Didaoui L, Tata S, Sabaou N. Effect of extraction and drying method on chemical composition, and evaluation of antioxidant and antimicrobial activities of essential oils from *Salvia officinalis* L. *J Essent Oil Bear Plants.* 2019;22(3):717–27. [[CrossRef](#)].
72. Boukhary R, Raafat K, Ghoneim AI, Aboul-Ela M, El-Lakany A. Anti-inflammatory and antioxidant activities of *Salvia fruticosa*: an HPLC determination of phenolic contents. *Evid Based Complement Alternat Med.* 2016;2016:7178105. [[CrossRef](#)].
73. Xylia P, Chrysargyris A, Christou C, Kotsoni A, Gkretsi V, Tzortzakis N. Postharvest storage of fresh spearmint as influenced by the application of spearmint essential oil and ascorbic acid. *Postharvest Biol Technol.* 2025;227:113583. [[CrossRef](#)].
74. Seukep AJ, Ojong OCG, Mbuntcha HG, Matieta VY, Zeuko'o EM, Kouam AF, et al. *In vitro* antibacterial potential of herbal beverage extracts from cinnamon, clove, and thyme and their interactive antimicrobial profile with selected antibiotics against drug-resistant clinical pathogens. *J Trop Med.* 2025;2025(1):9916282. [[CrossRef](#)].
75. Chen C, Chen L, Mao C, Jin L, Wu S, Zheng Y, et al. Natural extracts for antibacterial applications. *Small.* 2024;20(9):2306553. [[CrossRef](#)].
76. Hou T, Sana SS, Li H, Xing Y, Nanda A, Netala VR, et al. Essential oils and its antibacterial, antifungal and anti-oxidant activity applications: a review. *Food Biosci.* 2022;47:101716. [[CrossRef](#)].
77. Bajalan I, Rouzbahani R, Pirbalouti AG, Maggi F. Antioxidant and antibacterial activities of the essential oils obtained from seven Iranian populations of *Rosmarinus officinalis*. *Ind Crops Prod.* 2017;107:305–11. [[CrossRef](#)].
78. Cosme F, Aires A, Pinto T, Oliveira I, Vilela A, Gonçalves B. A comprehensive review of bioactive tannins in foods and beverages: functional properties, health benefits, and sensory qualities. *Molecules.* 2025;30(4):800. [[CrossRef](#)].
79. Li X, Zhang L, Gu J, Chen F, Fan Y, Fan Y, et al. Changes of five tannin compounds in the *T. chebula* juice at different storage temperatures. *Cogent Food Agric.* 2025;11(1):2505014. [[CrossRef](#)].