



Article

Enhanced Preservation of Bioactives in Wild Garlic (*Allium ursinum* L.) through Advanced Primary Processing

Alena Stupar ^{1,*}, Žarko Kevrešan ¹, Aleksandra Bajić ¹, Jelena Tomić ¹, Tanja Radusin ^{1,2}, Vanja Travičić ³ and Jasna Mastilović ⁴

¹ Institute of Food Technology, University of Novi Sad, Bulevar Cara Lazara 1, 21000 Novi Sad, Serbia; zarko.kevresan@fins.uns.ac.rs (Ž.K.); aleksandra.bajic@fins.uns.ac.rs (A.B.); jelena.tomic@fins.uns.ac.rs (J.T.); tanja.radusin@norner.no (T.R.)

² Norner Research AS, Dokkvegen 20, 3906 Porsgrunn, Norway

³ Faculty of Technology, University of Novi Sad, Bulevar Cara Lazara 1, 21000 Novi Sad, Serbia; vanjaseregelj@tf.uns.ac.rs

⁴ Institute Biosense, University of Novi Sad, Bulevar Cara Lazara 1, 21000 Novi Sad, Serbia; jasna.mastilovic@biosense.rs

* Correspondence: alena.stupar@fins.uns.ac.rs

Abstract: Medicinal and aromatic plants, such as wild garlic (*Allium ursinum*), are valuable sources of bioactive compounds in traditional and modern medicine. However, the challenges in cultivating wild garlic and its seasonality limit its availability primarily to early spring. To maintain the quality of wild garlic, effective postharvest practices are essential, considering the delicate nature of its leaves and their susceptibility to rapid decay. This study focuses on implementing eco-friendly postharvest practices to address the seasonality and perishability of wild garlic. Optimizing storage conditions and drying processes is essential for extending its shelf life and preserving bioactive components. Two postharvest approaches were evaluated, with vacuum packaging at 4 °C demonstrating the most effective preservation of sensory attributes and bioactive composition over a 9-day period. Additionally, different drying methods, including convective and vacuum drying at various temperatures, were investigated. When the best drying temperature was selected, the results revealed that convective drying is more efficient at preserving phenolic compounds in wild garlic leaves at 60 °C. Conversely, vacuum drying shows superior preservation of alliinase activity and total thiosulfinate content at 70 °C. Furthermore, this study explores the utilization of unused wild garlic, which is typically discarded as waste during storage. By employing suitable drying methods, this material can be preserved and provide a valuable source of phenolic compounds (7.17–10.12 g GAE/100 g) and thiosulfinate (9.35–12.72 mg AC/110 g) compounds for various extraction processes. Accordingly, this research presents significant implications for the integration of wild garlic into diverse industries, particularly in the fields of food and pharmaceutical sectors. The findings offer opportunities for sustainable utilization, economic benefits, and a more environmentally friendly and economically viable approach to wild garlic production and processing.

Keywords: *Allium ursinum*; wild garlic; primary processing; postharvest; drying; bioactive components; polyphenolic; thiosulfinates



Citation: Stupar, A.; Kevrešan, Ž.; Bajić, A.; Tomić, J.; Radusin, T.; Travičić, V.; Mastilović, J. Enhanced Preservation of Bioactives in Wild Garlic (*Allium ursinum* L.) through Advanced Primary Processing. *Horticulturae* **2024**, *10*, 316. <https://doi.org/10.3390/horticulturae10040316>

Received: 10 March 2024
Revised: 21 March 2024
Accepted: 22 March 2024
Published: 25 March 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The enduring significance of medicinal and aromatic plants in traditional and modern medicine underscores their global utilization, emphasizing their importance in ethnomedicine and as valuable indicators in the search for novel bioactive compounds [1]. Responding to the escalating demand for natural, value-added, and healthier food options, significant research efforts have focused on integrating various aromatic plants into conventional food products [2].

As a source of health benefit compounds, *Allium* species have been used in traditional medicine and cuisine for many centuries as an edible and medicinal plant. Recently, there has been a growing interest in *Allium ursinum*, commonly known as wild garlic, driven by consumers' preference for natural, nutrient-rich, and seasonally available food. Its inclusion in a healthy diet has shown positive effects on human well-being, further establishing its status as a highly beneficial food choice [3,4]. Its bioactive components help regulate blood pressure, lower cholesterol levels, and enhance blood vessel health, reducing the risk of heart-related ailments [5,6]. Sulfur compounds present in wild garlic, such as allicin, a potent antioxidant and antimicrobial agent, showcasing its potential to boost the body's defenses against oxidative stress and infections, while flavonoids found in wild garlic, such as quercetin and kaempferol, possess anti-inflammatory properties, contributing to overall immune support and health [3,7–9]. Beyond its bioactive properties and its use as a medicinal herb, wild garlic is also present in diverse culinary cosines. The leaves of wild garlic, characterized by their distinctive garlicky aroma, offer a unique and flavorful complement to a variety of culinary preparations. Their addition enriches the taste profile while simultaneously promoting health properties, providing a nutritious enhancement without dominating the overall flavor profile [9,10]. Despite the widespread cultivation of many medicinal and aromatic plants, wild garlic remains largely uncultivated, primary due the specific requirements for shading and weeding during early crop stages, making it less feasible for large-scale cultivation [11]. The natural habitat of wild garlic, typically forests, ensures that its leaves are free from urban pollution, pesticides, or chemical fertilizers, making it an ideal ingredient for dietary use. Accordingly, the availability of wild garlic to consumers is dependent on gathering it from its natural habitat during the early spring months. However, its amount may be limited.

In order to prevent overexploitation, loss of biodiversity, and ecological imbalances, some countries, like the Republic of Serbia, have implemented gathering quotas that regulate the collection of wild medicinal and aromatic plants, including wild garlic, in order to preserve this priceless resource. (Official Gazette of the RS no. 31/05, 45/05—correction, 22/07, 38/08, 9/10, 69/11, and 95/18—dr. The law).

In order to take advantage of all the benefits of consuming this limited nutritionally valuable source, effective postharvest handling is of utmost importance. Quality assurance for medicinal and aromatic plants, especially those not immediately harvested, poses significant challenges in maintaining consistent product quality. Without adequate control measures, there are often variations in the quality of herbal products [12]. These plants undergo physical, biological, and chemical changes during handling, processing, and storage, affecting their quality and nutritional content. Moreover, inadequate practices can lead to the rapid yellowing and wilting of wild garlic leaves. Accordingly, the postharvest management of medicinal and aromatic plants is a crucial phase that significantly influences the quality and bioactivity of plants and their further utilization. To reduce these changes, various postharvest storage techniques have been employed to preserve the quality and nutritional value of these perishable food products without compromising their physical appearance [13]. Preserving bioactive compounds is crucial for medicinal plants, ensuring their therapeutic properties, while maintaining color and a fresh-like aroma is essential for culinary dried herbs [14,15]. Packaging materials and techniques can effectively prevent contamination, delay spoilage, and maintain the integrity of the bioactive substances [16–18], while proper drying techniques for culinary herbs are essential to retain their flavor, aroma, and nutrient content, ensuring high-quality dried herbs for culinary applications.

Although qualitative alterations due to postharvest processes have been extensively studied in other plants, there is a lack of information regarding the impact on wild garlic leaves [17,19,20]. However, there is a current lack of information regarding the impact of these processes on wild garlic leaves.

Addressing the challenges associated with wild garlic's seasonality and perishability, the objectives of this study were (1) to evaluate the changes in the bioactive components

of wild garlic as a consequence of different storage conditions, (2) to identify the most suitable drying method with minimum effect on wild garlic quality, and (3) to explore the utilization of waste generated during the storage phase as a source of bioactive components. Insights gained from this study will open up new challenges and opportunities in the postharvest manipulation of wild garlic, as well as the possible utilization of generated waste for different food purposes.

2. Material and Methods

2.1. Plant Material

The plant material employed in this study was harvested from the Fruška Gora mountain in Serbia during the spring season. To preserve the delicate leaves, harvesting was conducted early in the morning, and the leaves were carefully packed in PVC bags to minimize physical damage, and then they were promptly transported to the laboratory. Subsequent cleaning and sorting processes were implemented to guarantee the purity of the collected material. For the evaluation of storage condition impacts on the characteristics of fresh wild garlic leaves, only healthy and undamaged leaves were carefully selected for further analysis. This described procedure, including the trimming of the lower stem parts, is a standard practice applied to wild garlic to ensure its market readiness.

The moisture content was measured by the gravimetric method, where samples were maintained at 105 °C up to constant weight (24 h).

2.2. Storage of Wild Garlic Leaves

Two storage methods were used for wild garlic leaves: the traditional method, which involves leaves bundling and stalk immersion in water (TP), and a new method with limited vacuum packaging (VP).

For the traditional method, leaf bundles comprising 20 leaves with their stems submerged in water were stored at 4 °C, 11 °C, and 18 °C in temperature-regulated chambers at 90–95% RH. (FrigoŽika, Ruma, Serbia).

To examine the effects of packaging under limited vacuum conditions, groups of 20 wild garlic leaves were arranged in plastic containers. Each container was sealed hermetically using a vacuum packaging machine (Henkelman boxer 42, Henkelman, the Netherlands) along with a high-barrier film (180 × 400 × 0.15 mm) sourced from Blik d.o.o. The vacuum sealing procedure was carried out using the “Liquid control” program, which includes monitoring the water level throughout the vacuum sealing process and terminating the vacuum once evaporation fell below a predefined threshold. The use of containers and packaging bags was specifically chosen to prevent pressure packing on the leaves.

The experimental storage temperature was selected and set up in order to stimulate the conditions in which wild garlic leaves are mostly sold, which is in markets at ambient temperatures during the spring months (18 °C), in markets in open cooling systems (11 °C), and in a cooled storage room (4 °C). Both types of packaging were placed in cooling chambers, and quality monitoring was performed on days 1, 3, 6, and 9. Ten packaging units were prepared for each method to ensure sufficient plant material for subsequent sensorial and chemical analyses.

2.3. Drying Method Optimization

Wild garlic leaves underwent three distinct drying methods: conventional convective drying, vacuum drying, and lyophilization. The operational parameters for each drying method were established through preliminary experimental runs and by adapting the literature recommendations [21]. Prior to drying, healthy and undamaged leaves were carefully selected. Prior to drying, petals were cut and left at about 1–1.5 cm.

2.3.1. Convective Drying

The assessment of the temperature impact on the convective drying (CD) process was conducted using an experimental laboratory dryer chamber at temperatures of 40, 50, 60, and 70 °C [22]. The drying process maintained a constant mass of 300 g for the wild garlic leaves, arranged uniformly on perforated plates. The hot air, with an airflow rate of 1 m/s, and atmospheric pressure were consistently controlled. After reaching a constant mass, the dried wild garlic leaves were carefully packed in polyethylene bags with zip closures and stored in a dry, dark environment at room temperature for further analysis. The drying process was performed in duplicate to ensure reliability.

2.3.2. Vacuum Drying

Vacuum drying (VD) of wild garlic leaves was performed in a vacuum dryer (VC 115, Binder, Germany) at temperatures of 40, 50, 60, and 70 °C. The vacuum level inside the chamber was set to that which is maximum achievable within the vacuum chamber and maintained at 0 (+1) kPa. Prior to activating the vacuum pump, the dryer was preheated to the operating temperature to reach the desired pressure inside the chamber. The initial sample mass was consistent for all drying temperatures and amounted to 300 g. The wild garlic leaves were uniformly arranged in a thin layer on the plates within the chamber and dried until a constant mass was obtained. After drying, the dried wild garlic leaves were packed in polyethylene bags with zip closures and stored in a dry and dark place at room temperature until further analysis. The drying process was performed in duplicate to ensure reliability.

2.3.3. Lyophilization

The freeze-drying process was conducted at −30 °C and a pressure of 0.01 mbar using a freeze drier Alpha 2-4 LDplus (Martin Christ, gefriertrocknungsanlagen GmbH, Osterode, Germany). The leaves were evenly distributed in a thin layer and dried until a constant mass was achieved. Following lyophilization, the leaves were carefully packed in polyethylene bags and stored at room temperature for subsequent analysis. The drying process was performed in duplicate to ensure reliability.

2.4. Color Determination

The color of the wild garlic leaves was assessed in the CIELab* color space using a CR-400 Chroma Meter (Konica-Minolta, Osaka, Japan) at the midpoint of the leaf, excluding the central leaf vessel. Measurements were conducted on 10 randomly chosen leaves, with five readings for each sample.

2.5. Determination of Bioactive Compounds

2.5.1. Total Phenolic Content Determination

The total phenolic content in fresh wild garlic leaves was determined using a modified Folin–Ciocalteu method. Two grams of leaves was extracted with a 70:30 *v/v* ethanol–water mixture using an ultrasonic bath and orbital shaker. The extract was then filtered and diluted to 50 mL. A portion of the extract was combined with the Folin–Ciocalteu reagent and Na₂CO₃ solution. Following incubation, absorbance was measured at 750 nm. The analysis was conducted in triplicate, and the results were expressed as gallic acid equivalent per 100 g of sample (mg GAE/100 g).

2.5.2. Alliinase Activity Determination

Alliinase activity in wild garlic leaves was determined by extracting 2.5 g of crushed leaves with 20 mL of water. After 20 min of orbital shaking, trichloroacetic acid (5 mL) was added to stop the reaction. The resulting extract, diluted to 50 mL, underwent further analysis. A 0.5 mL aliquot was mixed with water (1.5 mL) and 2,4-dinitrophenylhydrazine (1 mL), followed by the addition of 0.6 M NaOH (5 mL). Absorbance at 445 nm was measured after 10 min. To correct for non-specific reactivity, a blank sample (2 mL of distilled

water and 1 mL of DNPH reagent) was employed. Extracts from alliinase-inactivated wild garlic leaves by heating in a microwave oven (NN-E201W, Panasonic, Japan) for 5 min were used for correction, ensuring precise assessment given the reagent's non-specific nature. The analysis was conducted in triplicate, and the results were expressed as mg of pyruvic acid on 100 g of sample (mg PA/100 g)

2.5.3. Determination of Total Thiosulfinates

To determine total thiosulfinates, a modified method by Han et al. was used [23]. Crushed leaves (2.5 g) were shaken in 20 mL of 50 mM pH 7.5 HEPES buffer for 15 min at room temperature. Following centrifugation and filtration, 1 mL of the extract was mixed with 1 mL of 5 mM L-cysteine in HEPES buffer. The resulting mixture was diluted to 50 mL and incubated at room temperature for 15 min. Subsequently, 9 mL of this mixture was combined with 1 mL of 1.5 mM DTNB solution in HEPES buffer. After 15 min, absorbance at 412 nm was measured. The blank sample employed pure HEPES buffer instead of the extract. The analysis was conducted in triplicate, and the results are expressed as allicin equivalent per 100 g of sample (mg AC/100 g), calculated using a specified formula:

$$C_{\text{thiosulfinates}} = (\Delta A * 100) / (2 * 14,150) \quad (1)$$

ΔA —the absorbance difference between the blank sample and the test sample, 14,150—molar extinction coefficient for DTNB, and 2—the number of moles of cysteine required for thiosulfinates formation.

2.5.4. Determination of the Content of L-Ascorbic Acid

The L-ascorbic acid (vitamin C) content was determined through an oxidation method employing DIF reagent. Spectrophotometric measurement of the color change was conducted at 515 nm. The analysis was conducted in triplicate, and the obtained result is expressed as the ascorbic acid content per 100 g (mg AAC/100 g).

2.5.5. Determination of Total Chlorophyll and Carotenoids Content

To determine the chlorophyll content, 2 g of the sample was mixed with 20 mL of 96% methanol, centrifuged, and the resulting supernatant was analyzed spectrophotometrically at 666 nm and 653 nm for chlorophyll a and chlorophyll b, respectively, using the following equations [24]:

$$\text{chlorophyll a (mg dm}^{-3}\text{)} = 9.784 \times A_{662} - 0.990 \times A_{644}$$

$$\text{chlorophyll b (mg dm}^{-3}\text{)} = 21.426 \times A_{644} - 4.65 \times A_{662}$$

$$\text{chlorophyll a + b (mg dm}^{-3}\text{)} = 5.134 \times A_{662} + 20.436 \times A_{644}$$

$$\text{carotenoids (mg dm}^{-3}\text{)} = 4.695 \times A_{440} - 0.268 \times (\text{chlorophyll a + b})$$

2.6. Sensory Analysis of Fresh Wild Garlic Leaves

A sensory evaluation of the intensity of the leaf smell was conducted as part of the experiment. The assessment involved 12 trained panelists, consisting of 6 women and 6 men, with ages ranging from 20 to 65 years. The evaluation methodology followed the guidelines described by Melgarejo et al. [25]. Panelists were tasked with scoring the characteristic smell intensity on a continuous scale ranging from 0 to 5. This evaluation process occurred at room temperature (20 °C) in individual cabins to ensure controlled conditions. All participants were provided with written information about the study and willingly provided signed informed consent.

2.7. Statistical Analysis

A two-way analysis of variance (ANOVA, $\alpha = 0.05$) was performed with STATISTICA 13.1 (TIBCO Software Inc., Hillview Avenue, Palo Alto, CA, USA) to demonstrate statistically significant differences.

3. Results and Discussion

3.1. Storage of Fresh Wild Garlic Leaves

Our research focuses on optimizing processing methods and storage conditions for wild garlic leaves to preserve their bioactive components, sensory attributes, and extend their shelf life in a fresh state.

3.1.1. Effects of Storing Condition on Color and Bioactive Compounds

Consumer preferences for fresh products often rely on visual properties, emphasizing color as a key quality indicator. Through color monitoring using CIELab color space parameters (Table 1), this study provides scientific insights into the interaction of storage conditions, time, and the color profile of wild garlic, essential for consumer preferences. Regarding the lightness (L^*) of wild garlic leaves, despite the significance of all factors and their interactions, the most significant change is an increase in leaf lightness during storage on 11 and 18 °C. On the other hand, the lightness (L^*) of wild garlic leaves stored at 4 °C was at the same level as in the initial material, regardless of the packing type. The change in green color intensity (a^*) was induced only by the days of storage, with the lowest value recorded in leaves stored in bundles at 11 °C for 9 days (−16.4). The intensity of the yellow color (b^*) was not affected by the temperature or the interaction of the type of packaging and the temperature; however, the time of packaging and storage changed the intensity of this parameter. Vacuum packing lowered b^* ; however, the differences were not significant, except at 11 °C after 6 days of storage, where the highest b^* was observed in bundle packaging type ($b^* = 24.5$). All values (L^* , a^* , and b^*) show variations across different storage conditions and time points; however, storage at 18 °C in bundles significantly reduces lightness and increases the intensity of the yellow color, suggesting an intensive reduction in the overall quality of the leaves.

The observed color changes in wild garlic leaves were accompanied by alterations in the total chlorophyll and carotenoid levels (Table 2). Temperature played a significant role in influencing the pigment content, with fluctuations noted across different storage conditions (4 °C, 11 °C, and 18 °C) and durations. For instance, at 11 °C for 6 days, total chlorophylls significantly increased to 132.8 compared to the values after 3 days of storage, and total carotenoids also showed an increase to 22.37, indicating a potential impact of moderate temperature stress on the pigment dynamics. Remarkably, under storage conditions of 4 °C for 9 days with vacuum packaging, the highest levels of total chlorophylls (109.90) and total carotenoids (21.36) were observed. This suggests that vacuum packaging at 4 °C may contribute to maintaining a higher pigment content over an extended storage period.

Table 1. Change in the color parameters of fresh wild garlic leaves depending on the storage conditions.

		Color Properties									
		L*	a*		b*		C*		h*		
Fresh wild garlic leaves		37.0 ^a	−14.6 ^{cd}		17.8 ^{abc}		23.0 ^{abc}		129.5 ^{ef}		
APPLIED PACKING METHOD											
T (°C)	TS (days)	TP	VP	TP	VP	TP	VP	TP	VP	TP	VP
4	3	38.0 ^{abcd}	37.6 ^{abc}	−15.8 ^{abc}	−14.6 ^{cd}	19.4 ^{abcd}	18.0 ^{abcd}	25.0 ^{abcd}	23.2 ^{abc}	129.3 ^{ef}	129.2 ^{cde}
4	6	39.0 ^{bcd}	37.6 ^{abcd}	−14.8 ^{bcd}	−14.3 ^d	18.8 ^{abcd}	16.9 ^a	23.9 ^{abcd}	22.2 ^c	128.4 ^{bcdef}	130.3 ^f
4	9	38.5 ^{abcd}	37.8 ^{abcd}	−15.8 ^{ab}	−14.9 ^{bcd}	20.6 ^{de}	18.9 ^{abcd}	26.0 ^{de}	24.0 ^{abcd}	127.7 ^{bcde}	128.3 ^{bcd}
11	3	38.4 ^{abcd}	39.6 ^d	−15.3 ^{abcd}	−15.0 ^{bcd}	19.3 ^{abcd}	20.1 ^{bcde}	24.6 ^{abcd}	25.1 ^{bcde}	128.6 ^{cdef}	127.1 ^{bcd}
11	6	38.4 ^{abcd}	39.4 ^{cd}	−14.4 ^d	−15.4 ^{abcd}	17.6 ^{ab}	18.8 ^{abcd}	22.7 ^{abcd}	24.3 ^{abcd}	129.5 ^{ef}	129.6 ^{ef}
11	9	39.5 ^{cd}	39.0 ^{bcd}	−16.4 ^a	−15.4 ^{abcd}	22.2 ^e	20.5 ^{cde}	27.6 ^{ab}	25.6 ^{cde}	126.5 ^b	127.0 ^{bc}
18	3	37.9 ^{abcd}	38.2 ^{abcd}	−14.4 ^d	−14.9 ^{bcd}	17.9 ^{abcd}	18.2 ^{abcd}	23.0 ^{abc}	23.6	129.1 ^{def}	129.5 ^{ef}
18	6	45.2 ^e	39.2 ^{cd}	−15.0 ^{bcd}	−14.3 ^d	24.5 ^f	17.5 ^{ab}	29.1 ^f	22.6	123.2 ^a	129.3 ^{ef}
18	9	-	37.9 ^{abcd}	-	−15.2 ^{abcd}	-	19.1 ^{abcd}	-	24.4	-	128.8 ^{cdef}
Packing method		*	NS		**		**		**		
Temperature		**	NS		NS		NS		NS		
Time of storage		*	**		**		**		**		
PM × T		*	NS		NS		NS		*		
PM × TS		**	NS		*		NS		**		
T × TS		**	NS		**		**		**		
PM × T × TS		**	NS		**		**		**		

* $p < 0.5$; ** $p < 0.001$; NS—not significant; T—temperature; TS—time of storage in days; PM—packaging method; TP—traditional packing of bundles; VP—vacuum packing of bundles; L*, a*, b*, color coordinates; C*—color saturation; h*—hue angle; Values with the same letter in a column are not significantly different.

Table 2. Changes in chemical composition of bioactive compounds of fresh wild garlic leaves depending on the storage conditions.

BIOACTIVE COMPOUNDS													
		TCH (mg/100 g)		TC (mg/100 g)		TPC (mg GAE/100 g)		AA (mg PA/100 g)		TTC (mg AC/100 g)		AAC (mg AAC/100 g)	
Fresh wild garlic leaves		106.5 ^{abcde}		20.25 ^{cdef}		162.9 ^{egh}		23.8 ^{bc}		4.04 ^b		4.04 ^b	
APPLIED PACKING METHOD													
T (°C)	TS (days)	TP	VP	TP	VP	TP	VP	TP	VP	TP	VP	TP	VP
4	3	126.6 ^{hi}	103.9 ^{abcd}	22.96 ⁱ	18.32 ^{abcd}	129.3 ^b	139.8 ^{bc}	30.6 ^{bc}	31.8 ^{ijk}	2.75 ^a	4.29 ^b	59.5 ^h	58.8 ^h
4	6	137.5 ^j	108.2 ^{bcdef}	22.92 ⁱ	18.81 ^{abcde}	180.4 ^{ijk}	161.5 ^{efg}	24.5 ^{ghijk}	30.2 ^{ghij}	2.87 ^{ad}	6.09 ^e	65.9 ⁱ	52.1 ^g
4	9	119.2 ^{fgh}	109.9 ^{cdef}	21.36 ^{fghi}	20.70 ^{efgh}	173.1 ^{ghi}	168.5 ^{fgh}	23.2 ^{bcd}	28.5 ^{efghi}	2.85 ^{cd}	4.80 ^b	56.7 ^h	45.9 ^f
11	3	103.1 ^{abcd}	100.4 ^{abc}	18.35 ^{abcd}	18.53 ^{abcd}	129.8 ^b	143.5 ^{cd}	25.6 ^{bcde}	27.5 ^{defg}	3.99 ^{bcd}	6.56 ^e	58.1 ^{g^h}	43.8 ^f
11	6	132.8 ^{ij}	113.7 ^{defg}	22.37 ^{fghi}	19.40 ^{abcd}	186.1 ^{jk}	176.5 ^{hij}	31.0 ^{hijk}	35.0 ^l	5.85 ^e	12.19 ⁱ	46.2 ^f	14.1 ^b
11	9	97.5 ^{ab}	95.3 ^a	17.25 ^a	18.12 ^{bcdef}	158.2 ^{ef}	169.4 ^{fghi}	26.3 ^{bcde}	33.9 ^{kl}	4.58 ^b	14.22 ^j	28.3 ^{gh}	21.6 ^c
18	3	124.1 ^{ghi}	102.0 ^{abcd}	21.28 ^{fghi}	17.80 ^{ab}	152.7 ^{de}	139.3 ^{cd}	31.4 ^{ijkl}	30.6 ^{ghijk}	7.93 ^f	9.51 ^h	55.3 ^c	30.0 ^d
18	6	104.5 ^{abcd}	103.0 ^{abcd}	17.99 ^{bcdef}	17.04 ^a	190.0 ^k	206.8 ^l	33.4 ^{jkl}	27.7 ^{defgh}	8.15 ^{fg}	13.90 ^j	20.3 ^f	5.0 ^a
18	9	-	116.9 ^{efgh}	-	22.46 ^{hi}	-	189.0 ^k	-	29.8 ^{fghi}	-	12.24 ⁱ	-	7.7 ^a
Packing method		**		**		NS		**		**		**	
Temperature		**		**		**		**		**		**	
Time of storage		**		NS		**		**		**		**	
PM × T		**		**		**		NS		**		**	
PM × TS		**		**		NS		**		**		**	
T × TS		**		**		**		**		**		**	
PM × T × TS		**		*		**		**		**		**	

* $p < 0.5$; ** $p < 0.001$; NS—not significant; T—temperature; TS—time of storage in days; PM—packaging method; TP—traditional packing of bundles; VP—vacuum packing of bundles; TC—total carotenoid content; TCH—total chlorophyll content TPC—total phenolic content (mg GAE/100 g); TTC—total thiosulfinate content (mg AC/100 g); AA—alliinase activity (mg PA/100 g); AAC—ascorbic acid content (mg/100 g); Values with the same letter in a column are not significantly different.

The results of the analyzed bioactive compounds in wild garlic leaves under different storage conditions (Table 2) demonstrate that wild garlic leaves have a higher ascorbic acid content compared to lettuce [26] and similar levels to spinach [27]. This suggests that wild garlic can be a potential source of ascorbic acid in the diet [28]. However, Voća et al. noted that the ascorbic acid content depends on the harvesting period and is lower when wild garlic starts flowering [11]. At the optimal preservation temperature of 4 °C, the reduction in ascorbic acid was approximately 2.8%, escalating to 20% at 11 °C and 65% at 18 °C after 6 days of storage. Prolonged storage intensified the reduction, with losses of 20.41% at 4 °C and 47.62% at 11 °C after 9 days. This aligns with studies on lettuce, showing significant reductions in ascorbic acid during storage [26]. To preserve the ascorbic acid content, determining appropriate storage conditions is crucial. While reduced oxygen atmospheres with up to 10% carbon dioxide are suggested to mitigate vitamin C loss, higher CO₂ and lower O₂ levels in packaging may increase ascorbic acid reduction [29]. In our experiment, storing in a vacuum resulted in a higher reduction in ascorbic acid at 11 °C and 18 °C compared to water-immersed bundles (Table 2), emphasizing the importance of assessing the impact of packaging and gas composition for each specific plant product.

Monitoring the total phenolic content in wild garlic is essential for assessing the postharvest antioxidant potential, as it can be influenced by factors like maturity stage, variety, cultivation location, growth conditions, and postharvest storage [30]. The storage of fresh wild garlic resulted in a significant increase in total phenols compared to the control, regardless of temperature or packaging. Higher temperatures and longer durations led to a rise in phenols, with an approximate 20% increase from the initial sample to the last day, depending on storage temperature. The increase in the total phenol content during the storage of wild garlic can be attributed to additional phenol synthesis as a protective response to the potential damage that occurs during storage [31,32]. The values obtained for the total phenol content in this study (ranging from 129.3 to 206.8 GAE/100 g of fresh product) align with the findings of Mahmutović et al. in the Western Balkans region, suggesting favorable conditions for wild garlic rich in bioactive components, including phenols [33]. In a study conducted by Lachowicz et al. [30], the total phenol content in wild garlic samples collected around Rzeszów, Poland, varied from 38.1 to 47.7 mg EGK/100 g of fresh product depending on the stage of maturity (March–June). In the research conducted by Lachowicz et al., the total phenol content in the tested samples ranged from 38.1 to 47.7 mg GAE/100 g of fresh product, while Alexieva et al. [34] detected a total phenol content of 40 mg GAE/100 g in fresh leaf fragrance from Bulgaria. Myhailova et al. [35] found that the highest content of phenols in leaf flies from the area of Bulgaria was during its flowering period (60.9 mg GAE/100 g of fresh product).

The activity of alliinase plays a crucial role in the conversion of alliin into allicin, which is one of the main bioactive compounds found in wild garlic leaves [36]. Therefore, analyzing the activity of alliinase and its changes is an important quality indicator of wild garlic leaves. Our study reveals a noteworthy variability in alliinase activity during storage under diverse conditions (Table 2). The observed range in alliinase activity, from 23.2 to 33.9 mg of pyruvic acid/100 g of fresh product, suggests temperature-dependent fluctuations. Notably, higher alliinase activity is evident in samples stored at 11 °C, with storage temperature exerting a substantial influence, peaking after 6 and 9 days in vacuum-packed samples at 11 °C. This finding suggests a temperature-dependent modulation of enzymatic activity, potentially impacting the bioactive profile of wild garlic leaves during storage. Furthermore, our study demonstrates a consequential link between alliinase activity and the formation of thiosulfinates, providing valuable insights into the biochemical processes underlying the preservation and transformation of bioactive compounds in wild garlic leaves during storage. The observed rise in total thiosulfinates, ranging from 4.04 to 13.37 mg of allicin/100 g of fresh product, in both water-immersed bundles and vacuum-packed leaves, highlights the dynamic synthesis of sulfur compounds during storage. Another research study conducted by [37] which investigated S-alk(en)yl-cysteine sulfoxide content across 58 wild garlic genotypes emphasized the significant impact of

genetic factors and postharvest storage conditions on sulfoxide levels. While climatic conditions during growth exerted a lesser influence, sulfoxide precursors remain integral to thiosulfinate production, as evidenced by the observed increase in thiosulfinate content during storage in our study. These findings support the understanding of the intricate relationship between sulfoxide precursors and the synthesis of bioactive sulfur compounds in wild garlic leaves.

3.1.2. Effects of Storing Condition on Sensorial Attributes

The sensory assessment of stored wild garlic leaves, both in bundles immersed in water and packed in a vacuum, revealed that there was a faster loss of characteristic odor in the garlic stored in the vacuum-packaged samples compared to the wild garlic stored in the bundles immersed in water. This loss of characteristic odor was more pronounced at higher temperatures, regardless of the storage method, as presented in Figure 1. Packaging leafy vegetables in a vacuum and modified atmosphere can slow down decay and the development of yellowing. However, a possible drawback of this storage method is the potential for tissue degradation due to respiration, fermentation, or acid degradation, which can result in the appearance of foreign smells, as was case when rocket was stored in a modified atmosphere [38,39]. In the case of wild garlic, rapid leaf deterioration occurred when stored in a vacuum at 18 °C, which resulted in the inability to conduct sensory evaluations after the sixth day. Wild garlic leaves were disposed of as waste when visual and sensory observations revealed yellowing and/or an unusual odor, indicating that they were unsuitable for consumption. Therefore, appropriate storage time and temperature have to be optimized for each plant.

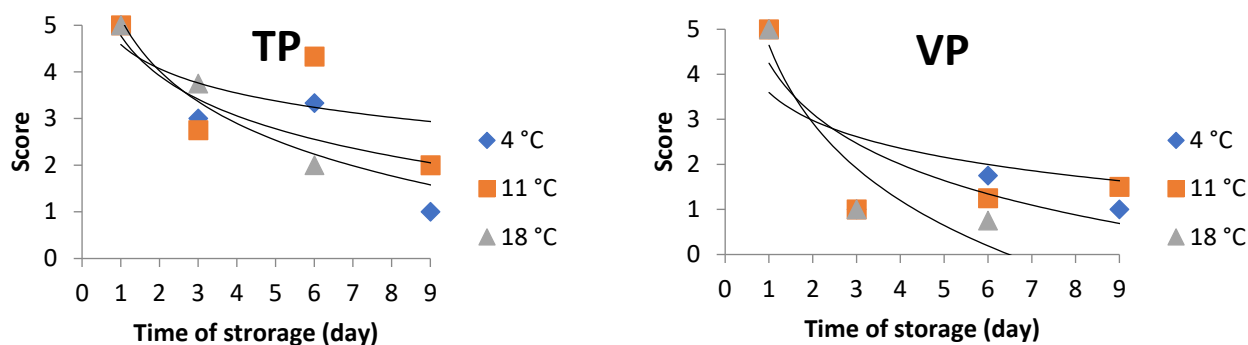


Figure 1. Sensory evaluation of wild garlic leaves depending on the duration and conditions of storage (TP—traditional packing of bundles; VP—vacuum packing of bundles).

3.2. Changes in Selected Parameters after Drying

Preserving bioactive compounds is crucial for medicinal plants, ensuring their therapeutic properties, while maintaining color and a fresh-like aroma is essential for culinary dried herbs [14,15]. As drying significantly impacts costs, the careful selection of temperature and methods was vital for wild garlic leaves drying. Convection drying, commonly used for its simplicity, was compared with vacuum drying and lyophilization, a technique known for bioactive preservation.

During the drying process of wild garlic leaves, various parameters were evaluated to assess the quality of the dried product. These parameters included moisture content, total phenol content, thiosulfinate content, and alliinase activity. In addition to temperature and drying method, the drying time was also analyzed as a parameter in selecting an effective and cost-efficient drying method for wild garlic leaves. The results of these parameters are summarized in Tables 3 and 4.

Table 3. Change in the color parameters of dried wild garlic leaves depending on the drying conditions.

L		Color Properties				b		Moisture Content (%)		Drying Time (h)	
		a									
Lyophilization											
38.03 ^a		−14.50 ^{ab}				17.23 ^{ab}		5.46 ^d		48 ⁱ	
T (°C)	CD	VD	CD	VD	CD	VD	CD	VD	CD	VD	
40	39.33 ^{cd}	38.37 ^{ab}	−15.52 ^a	−14.50 ^{bc}	19.47 ^b	18.21 ^{ab}	9.03 ^d	7.03 ^b	9.0 ^h	6.0 ^g	
50	36.81 ^a	38.12 ^a	−13.21 ^c	−14.22 ^{bc}	15.05 ^a	17.39 ^a	8.20 ^{dc}	6.2 ^a	4.5 ^f	3.75 ^{ef}	
60	37.84 ^{ab}	39.69 ^c	−14.92 ^{ab}	−15.14 ^b	18.04 ^b	19.86 ^c	7.53 ^{bc}	5.76 ^a	2.75 ^d	2.25 ^c	
70	38.53 ^{bc}	41.76 ^d	−15.20 ^{ab}	−17.6 ^a	18.81 ^b	22.42 ^d	7.78 ^b	6.19 ^a	1.75 ^b	1.25 ^a	
Drying method	**		**		**		**		**		
Temperature	**		**		**		**		**		
D × T	**		**		**		**		**		

** $p < 0.001$; T—temperature; D—drying method; CD—convective drying; VD—vacuum drying; Values with the same letter in a column are not significantly different.

Table 4. Changes in chemical composition of bioactive compounds of fresh wild garlic leaves depending on the drying conditions.

	TPC (mg GAE/100 g)		TTC (mg AC/100 g)		AA (mg PA/100 g)	
Lyophilization						
	10.90 ^b		12.96 ^c		7.71 ^f	
T (°C)	CD	VD	CD	VD	CD	VD
40	10.21 ^b	9.81 ^{ab}	12.51 ^c	9.01 ^b	5.62 ^e	3.82 ^{ab}
50	8.71 ^{ab}	9.57 ^{ab}	8.75 ^b	8.45 ^b	4.70 ^c	3.78 ^{ab}
60	9.21 ^{ab}	8.91 ^{ab}	6.25 ^a	9.04 ^b	4.33 ^{bc}	3.67 ^a
70	7.89 ^a	9.17 ^{ab}	5.97 ^a	8.48 ^b	4.98 ^d	3.96 ^{ab}
Drying method	**		**		**	
Temperature	**		**		**	
D × T	*		**		**	

* $p < 0.05$; ** $p < 0.001$; T—temperature; D—drying method; CD—convective drying; VD—vacuum drying; TPC—total phenolic content (mg GAE/100 g); TTC—total thiosulfinate content (mg AC/100 g); AA—alliinase activity (mg PA/100 g). Values with the same letter in a column are not significantly different.

3.2.1. Effects of Drying on Moisture Content and Drying Time

The moisture content of dried plant materials is a critical parameter that can influence their quality and stability. In our study, the moisture content of dried wild garlic samples varied between 5.46% and 9.03%. This variation was attributed to both the drying method employed and the temperature applied during the drying process. Convective drying resulted in a slightly higher moisture content compared to vacuum drying, which can be explained by the differences in the drying mechanisms between the two methods. Convective drying relies on hot air circulation, which may result in slower moisture evaporation and higher moisture retention in the samples. In contrast, vacuum drying creates a low-pressure environment, enabling faster moisture removal and potentially leading to lower final moisture content. These moisture content values align with the moisture content requirements typically observed in similar medicinal and aromatic plant products. For instance, previous studies on *Allium roseum* leaves dried through convective drying reported moisture content values of 8–12% on a dry basis [40]. They have also reported that temperature plays a crucial role in the drying process of *Allium roseum* leaves, with air velocity having no significant impact on drying kinetics or moisture content [40]. Our study yielded similar observations, with convective drying at 40 °C resulting in the

highest moisture content, while higher temperature resulted in lower moisture content in dried wild garlic. Conversely, samples dried using vacuum techniques at 50, 60, and 70 °C, as well as lyophilization, exhibited no statistically significant differences in moisture content. This suggests that higher temperatures in vacuum drying and lyophilization may have enhanced more efficient moisture removal.

According to Table 3, both convective drying and vacuum drying methods show a clear correlation between temperature and drying time. As temperature increases, drying time decreases for both techniques. For instance, in convective drying, the duration decreased from 9.0 h at 40 °C to 1.75 h at 70 °C. Similarly, vacuum drying also exhibited shorter drying times at higher temperatures, with a reduction from 6.0 h at 40 °C to 1.25 h at 70 °C. These findings indicate that vacuum drying may be a more time-efficient option, particularly when rapid drying is necessary to preserve product quality. Conversely, lyophilization, while resulting in the lowest moisture content, requires a significantly longer drying time compared to other methods, with a duration of 48 h observed in this study.

Considering these findings, the choice of a drying method and temperature should factor in the desired moisture content, bioactives content, and the practicality of the drying time, particularly in large-scale production. While freeze-drying (lyophilization) can yield high-quality products, its cost and time requirements make it more suitable for applications where the high value justifies the investment. On the other hand, vacuum drying at higher temperatures offers a time-efficient alternative for achieving a lower moisture content in a shorter duration. These results highlight the need for the careful consideration of both the desired moisture content goals and practical aspects when selecting a drying method and temperature, especially in large-scale production settings.

3.2.2. Effects of Drying on Color Parameters

For culinary dried herbs, factors such as color and maintaining a fresh-like characteristic aroma are key for ensuring their sensory appeal and culinary value. As assumed, the loss of green color was probably caused by chlorophyll decomposition during drying; however, according to visual observation, the dried leaves of wild garlic remained green, an appealing color characteristic for dried herbs with a characteristic garlicky aroma. When analyzing the color parameters, more differences were pronounced. The statistical analysis indicates significant differences in color parameters across different temperature levels and drying methods. For convective drying, the L^* values ranged from 36.8 to 39.3, while the corresponding values for vacuum drying varied from 38.1 to 41.8. The a^* values for convective drying ranged from -15.5 to -14.9 , whereas vacuum drying showed values between -17.6 and -14.2 . The values in the table range from -17.6 to -13.21 for convective drying and -14.22 to -15.14 for vacuum drying, suggesting that the colors observed in the drying process lean towards the greenish side, particularly for convective drying. The b^* values for convective drying ranged from 15.1 to 19.5, while vacuum drying exhibited values between 17.4 and 22.4, suggesting that the colors observed during the drying process tend to have a yellowish tint, especially for vacuum drying.

3.2.3. Effects of Drying on Bioactive Compounds

As expected, the lyophilization method demonstrated superiority in preserving the total phenolic content with a value of 10.90. Among the convective drying temperatures, 40 °C showed relatively high total phenolic content (10.21, indicating its effectiveness in minimizing the degradation of phenolic compounds during drying. As the temperature increased (50 °C, 60 °C, and 70 °C), the total phenolic content decreased (8.71, 9.20, and 7.89, respectively). However, despite some loss compared to the fresh sample, there were no significant differences among the drying samples, suggesting that methods other than lyophilization can still retain a considerable number of phenolic compounds. Convective drying performed slightly better than vacuum drying in this case.

A similar impact of increased temperature on the drying of garlic was observed in the study by Calín-Sánchez et al. and Zhou et al. investigated the influence of temperature

on the drying of garlic using infrared drying as the drying technique [41,42]. Additionally, the impact of the drying method on phenolic compounds has been investigated in various plant materials. For instance, Hossain et al. analyzed the drying of different plants from the *Lamiaceae* family and compared different drying methods and their influence on the content of total phenols [43]. Their research indicated that the highest preservation of phenolic compound content is achieved through convective drying, vacuum drying, and lyophilization, respectively. In the study by Chan et al., where various tea leaf varieties were dried using different drying techniques such as microwave drying, convective drying, sun drying, and lyophilization, the best results in terms of preserving bioactive components (total phenols, vitamin C, antioxidant activity) were obtained through lyophilization, while sun drying drastically reduced the content of bioactive components [44]. Although lyophilization was proved to be the best method for preserving bioactive compounds in tea leaves, the degree of reduction varied depending on the tea variety itself. Based on these results, it can be concluded that besides the drying method and temperature, the type of plant material being dried also affects the content of total bioactive compounds in the dried sample.

Comparing the obtained results, it is evident that the activity of alliinase was highest in the samples dried by lyophilization (7.71 mg PK/100 g dry weight), which is consistent with the content of generated thiosulfinates (Table 4). Comparing the drying methods, higher alliinase activities were observed in samples dried by convective drying compared to vacuum drying. In convective drying, the sample dried at 60 °C exhibited the lowest alliinase activity. Previous studies have also investigated the impact of drying processes and parameters on alliinase activity. For example, the optimal temperature range for pure alliinase enzyme activity has been reported to be around 35–40 °C [45]. During garlic drying, a decrease in the alliinase activity was observed, although the enzyme still retains the ability to convert alliin into allicin [46]. In addition, the inhibition of alliinase has been assessed by monitoring the formation of aroma in garlic through the measurement of pyruvic acid content [47,48]. Interestingly, drying garlic within the temperature range of 45 to 75 °C has been shown to result in the minimal loss of pyruvic acid [49]. By using the chromatographic headspace analysis of volatile sulfur compounds in fresh garlic, the same volatile sulfur compounds were preserved and detected in convectively dried garlic using hot air flow. Authors found that the breakdown of sulfur compound precursors occurs at drying temperatures above 100 °C [49]. This is consistent with the findings of Ben Haj Said et al., who studied the convective drying of *Allium roseum* at temperatures of 40 °C, 50 °C, and 60 °C [40]. They observed that high temperatures, specifically 60 °C, did not impact the potential formation of volatile sulfur compounds in *Allium roseum*.

In terms of the content of total thiosulfinates, expressed as allicin, the samples dried by the convective technique exhibited a range of 5.97 to 12.51 mg/100 g dry weight. On the other hand, in vacuum drying, the range was not statistically different, ranging from 8.45 to 9.04 mg/100 g dry weight. The highest content of total thiosulfinates was achieved through convective drying at 40 °C, and increasing the temperature resulted in a significant reduction in thiosulfinates. These reductions are more pronounced when the convective drying technique was applied, where vacuum drying showed a potential advantage in preserving thiosulfinates. Importantly, there were no statistically significant differences detected in the content of total thiosulfinates with vacuum drying, and drying at 60 °C and 70 °C in vacuum yielded comparable results to convective drying at 50 °C. Therefore, while convective drying at 50 °C excels in the preservation of thiosulfinate content, vacuum drying at higher temperatures can be a viable alternative for achieving similar results with reduced drying times. Similar observations were made when others investigated the effects of convective (50, 60, 80, 90, and 105 °C) and vacuum (50, 60, and 90 °C) drying temperatures on the kinetics and content of allicin, i.e., thiosulfinates, in dried white onion. Mitra et al. (2011) optimized the vacuum drying technique for black onion and determined a recommended drying temperature of 58.66 °C, resulting in the highest content of total thiosulfinates [50]. Zhou et al. found that infrared radiation drying at lower

temperatures (50–70 °C) minimized thiosulfinate degradation, while higher temperatures led to a reduction in thiosulfates due to their thermolabile nature [42].

To achieve the optimal preservation of bioactive compounds (total phenols and thiosulfates) during the drying process of wild garlic leaves, the best results were obtained using convective drying at a low temperature (40 °C). However, drying at this temperature is not the optimal solution due to its long duration (9 h) and inefficient energy utilization. Therefore, vacuum drying with moderate temperatures (50–60 °C) is recommended as the optimal approach for drying wild garlic leaves. This method minimizes the overall drying time and reduces the degradation of heat-sensitive components. As a result, a stable high-quality product, rich in bioactive compounds, can be obtained, which can be used throughout the year.

3.3. Utilization of Wild Garlic Waste Generated during Storage

The postharvest evaluation revealed that wild garlic leaves undergo noticeable visual changes and experience a loss of freshness and, as such, are usually disposed as waste. However, these leaves still possess considerable potential for resource utilization and reducing losses during primary processing. Table 2 indicates that the highest levels of bioactive compounds in wild garlic leaves were observed when they were stored in vacuum packaging at 18 °C for a duration of 9 days. Following storage, the wild garlic leaves underwent a drying process, aiming to conserve the plant material and minimize wastage. The selection of drying parameters was based on a statistical analysis of the data, considering the significant changes that influenced the bioactive compound levels in the wild garlic leaves. Both conventional and vacuum drying methods were employed at temperatures of 60 and 70 °C, respectively. These drying conditions were identified as the most suitable solution for the further preservation of wild garlic through drying.

The results indicate that convective drying is more effective in preserving phenolic compounds in wild garlic leaves (Figure 2). On the other hand, vacuum drying demonstrates the better preservation of alliinase activity and total thiosulfinate content. These findings suggest that the choice of drying method should be based on the specific bioactive compounds of interest. Convective drying is recommended for preserving phenolic compounds, while vacuum drying is preferable for maintaining alliinase activity and total thiosulfates in wild garlic leaves.

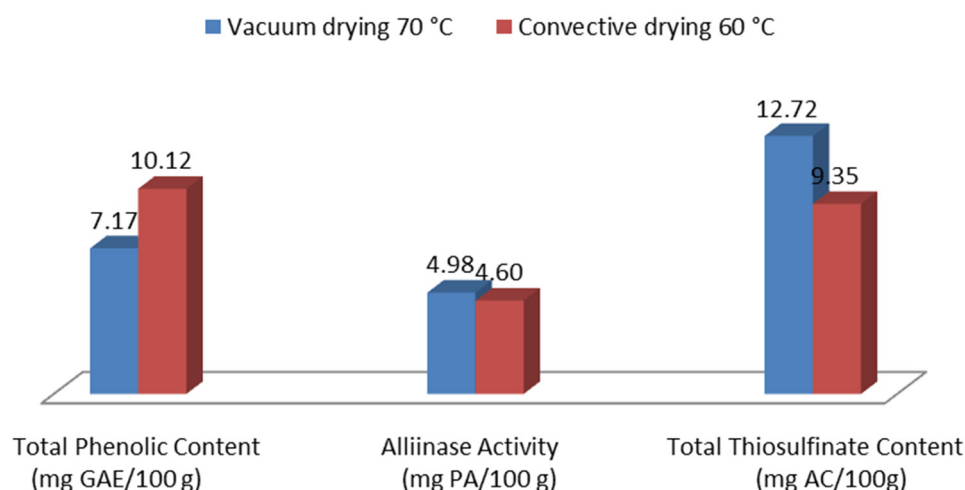


Figure 2. Bioactive composition of dried wild garlic waste generated during storage.

After the postharvest evaluation and drying processes, the effective extraction of bioactive compounds from dried wild garlic using environmentally friendly techniques can reveal their potential applications. Preserved and extracted compounds can be incorporated in the form of liquid or dried extracts into functional food or pharmaceutical products, harnessing their antioxidant, flavor-enhancing, and potential health-promoting properties.

This creates promising opportunities for developing products that offer both nutritional benefits and enhanced well-being.

4. Conclusions

The presented study emphasizes the importance of eco-friendly postharvest practices for wild garlic. By optimizing storage conditions, drying methods, and waste management, we can maximize its utilization efficiently and sustainably, addressing challenges related to availability and perishability. These practices enhance quality, extend shelf life, and minimize waste, contributing to a more environmentally conscious approach to wild garlic production and utilization.

By implementing recommended storage practices, such as storing wild garlic at 4 °C in vacuum packaging, its freshness can be preserved for up to 9 days. Furthermore, to prolong the storage duration of wild garlic leaves under household conditions, it is recommended to immerse them in water and store them at 4 °C. This practice enables a maximum storage period of 3 days while maintaining the quality and freshness of the leaves. By following these guidelines, the shelf life of wild garlic can be effectively extended, minimizing waste and ensuring the availability of flavorful and nutritious produce for a longer period. Additionally, the choice of drying method was shown to be crucial for preserving specific bioactive compounds. The results revealed that convective drying is more efficient at preserving phenolic compounds in wild garlic leaves at 60 °C. Conversely, vacuum drying shows the superior preservation of alliinase activity and total thiosulfinate content at 70 °C.

By utilizing these storage and drying strategies, the utilization of wild garlic can be maximized, ensuring a consistent supply of high-quality products while minimizing waste.

Additionally, this research underscores the potential of utilizing the waste generated after storage and drying processes. When this waste is dried, it yields a material that is rich in bioactive compounds, making it highly suitable for extraction processes and the isolation of valuable bioactive constituents. This approach not only minimizes waste but also unlocks the potential of previously discarded materials, contributing to the development of sustainable and eco-friendly practices. By harnessing bioactive-rich waste material, novel applications and value-added products can be derived, further enhancing the economic and environmental sustainability of wild garlic utilization.

Author Contributions: Conceptualization, A.S. and J.M.; data curation, A.S., A.B. and V.T.; formal analysis, A.S., A.B., J.T., T.R. and V.T.; methodology, Ž.K. and J.M.; supervision, J.M. and Ž.K.; validation, J.M. and Ž.K.; writing—original draft, A.S., J.T. and V.T.; writing—review and editing, Ž.K. and J.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia under the Agreements on the Implementation and Financing of Research (nos. 451-03-66/2024-03/200222).

Data Availability Statement: Data are contained within the article.

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

References

1. Cvetanović Kljakić, A.; Stupar, A.; Terzić, M.; Božunović, J.; Gašić, U.; Zengin, G.; Yildiztugay, E. Chemical Profiling and Biological Activities of *Opopanax Hispidus* Extracts: A Comparative Insight on Conventional and Green Extraction Technologies. *Sustain. Chem. Pharm.* **2023**, *33*, 101122. [\[CrossRef\]](#)
2. Filipčev, B. The Effects of Aromatic Plants and Their Extracts in Food Products. In *Feed Additives*; Academic Press: Cambridge, MA, USA, 2020; pp. 279–294. [\[CrossRef\]](#)
3. Stanisavljević, N.; Soković Bajić, S.; Jovanović, Ž.; Matić, I.; Tolinački, M.; Popović, D.; Popović, N.; Terzić-Vidojević, A.; Golić, N.; Beškoski, V.; et al. Antioxidant and Antiproliferative Activity of *Allium ursinum* and Their Associated Microbiota During Simulated in Vitro Digestion in the Presence of Food Matrix. *Front. Microbiol.* **2020**, *11*, 601616. [\[CrossRef\]](#) [\[PubMed\]](#)
4. Pavlović, D.R.; Veljković, M.; Stojanović, N.M.; Gočmanac-Ignjatović, M.; Mihailov-Krstev, T.; Branković, S.; Sokolović, D.; Marčetić, M.; Radulović, N.; Radenković, M. Influence of Different Wild-Garlic (*Allium ursinum*) Extracts on the Gastrointestinal System: Spasmolytic, Antimicrobial and Antioxidant Properties. *J. Pharm. Pharmacol.* **2017**, *69*, 1208–1218. [\[CrossRef\]](#) [\[PubMed\]](#)

5. Burton, G.P.; Prescott, T.A.K.; Fang, R.; Lee, M.A. Regional Variation in the Antibacterial Activity of a Wild Plant, Wild Garlic (*Allium ursinum* L.). *Plant Physiol. Biochem.* **2023**, *202*, 107959. [[CrossRef](#)] [[PubMed](#)]
6. Rankovic, M.; Krivokapic, M.; Bradic, J.; Petkovic, A.; Zivkovic, V.; Sretenovic, J.; Jeremic, N.; Bolevich, S.; Kartashova, M.; Jeremic, J.; et al. New Insight Into the Cardioprotective Effects of *Allium ursinum* L. Extract against Myocardial Ischemia-Reperfusion Injury. *Front. Physiol.* **2021**, *12*, 690696. [[CrossRef](#)] [[PubMed](#)]
7. Stupar, A.; Šarić, L.; Vidović, S.; Bajić, A.; Kolarov, V.; Šarić, B. Antibacterial Potential of *Allium ursinum* Extract Prepared by the Green Extraction Method. *Microorganisms* **2022**, *10*, 1358. [[CrossRef](#)] [[PubMed](#)]
8. Tomšik, A.; Pavlič, B.; Vladić, J.; Cindrić, M.; Jovanov, P.; Sakač, M.; Mandić, A.; Vidović, S.; Pavli, B.; Vladi, J.; et al. Subcritical Water Extraction of Wild Garlic (*Allium ursinum* L.) and Process Optimization by Response Surface Methodology. *J. Supercrit. Fluids* **2017**, *128*, 79–88. [[CrossRef](#)]
9. Stupar, A.; Vidović, S.; Vladić, J.; Radusin, T.; Mišan, A. A Sustainable Approach for Enhancing Stability and Bioactivity of *Allium ursinum* Extract for Food Additive Applications. *Separations* **2024**, *11*, 81. [[CrossRef](#)]
10. Filipčev, B.; Kojić, J.; Miljanić, J.; Šimurina, O.; Stupar, A.; Škrobot, D.; Travičić, V.; Pojić, M. Wild Garlic (*Allium ursinum*) Preparations in the Design of Novel Functional Pasta. *Foods* **2023**, *12*, 4376. [[CrossRef](#)]
11. Voća, S.; Žlabur, J.Š.; Uher, S.F.; Peša, M.; Opačić, N.; Radman, S. Neglected Potential of Wild Garlic (*Allium ursinum* L.)—Specialized Metabolites Content and Antioxidant Capacity of Wild Populations in Relation to Location and Plant Phenophase. *Horticulturae* **2021**, *8*, 24. [[CrossRef](#)]
12. Rao, K.S.; Haran, R.H.; Rajpoot, V.S. Value Addition: A Novel Strategy for Quality Enhancement of Medicinal and Aromatic Plants. *J. Appl. Res. Med. Aromat. Plants* **2022**, *31*, 100415. [[CrossRef](#)]
13. Ziv, C.; Fallik, E. Postharvest Storage Techniques and Quality Evaluation of Fruits and Vegetables for Reducing Food Loss. *Agronomy* **2021**, *11*, 1133. [[CrossRef](#)]
14. Vallino, M.; Faccio, A.; Zeppa, G.; Dolci, P.; Cerutti, E.; Zaquini, L.; Faoro, F.; Balestrini, R. Impact of Drying Temperature on Tissue Anatomy and Cellular Ultrastructure of Different Aromatic Plant Leaves. *Plant Biosyst.-Int. J. Deal. All Asp. Plant Biol.* **2022**, *156*, 847–854. [[CrossRef](#)]
15. Zaman, F.Q.; Jaffel, K.; Abdelmageed, A.H.A. The Effects of Post-Harvest Drying Period on the Yield and Chemical Composition of Leaf Essential Oil from *Cymbopogon Citratus* (DC.) Stapf. *J. Essent. Oil Bear. Plants* **2022**, *25*, 571–580. [[CrossRef](#)]
16. Erceg, T.; Šovljanski, O.; Stupar, A.; Ugarković, J.; Aćimović, M.; Pezo, L.; Tomić, A.; Todosijević, M. A Comprehensive Approach to Chitosan-Gelatin Edible Coating with β -Cyclodextrin/Lemongrass Essential Oil Inclusion Complex—Characterization and Food Application. *Int. J. Biol. Macromol.* **2023**, *228*, 400–410. [[CrossRef](#)] [[PubMed](#)]
17. Jangi, F.; Ebadi, M.T.; Ayyari, M. Qualitative Changes in Hyssop (*Hyssopus officinalis* L.) as Affected by Cold Plasma, Packaging Method and Storage Duration. *J. Appl. Res. Med. Aromat. Plants* **2021**, *22*, 100289. [[CrossRef](#)]
18. Erceg, T.; Vukić, N.; Šovljanski, O.; Stupar, A.; Šergelj, V.; Aćimović, M.; Baloš, S.; Ugarković, J.; Šuput, D.; Popović, S.; et al. Characterization of Films Based on Cellulose Acetate/Poly(Caprolactone Diol) Intended for Active Packaging Prepared by Green Chemistry Principles. *ACS Sustain. Chem. Eng.* **2022**, *10*, 9141–9154. [[CrossRef](#)]
19. Jyotshna; Nupur, S.; Akhilesh, K.Y.; Karuna, S.; Madan, M.G.; Raj, K.L. Impact of Postharvest Processes on Major Phenolic Constituents and Antioxidant Potentials of Different *Ocimum* Species. *J. Appl. Res. Med. Aromat. Plants* **2018**, *10*, 9–15. [[CrossRef](#)]
20. Marchioni, I.; Pistelli, L.L.; Ferri, B.; Copetta, A.; Ruffoni, B.; Pistelli, L.L.; Najar, B. Phytonutritional Content and Aroma Profile Changes During Postharvest Storage of Edible Flowers. *Front. Plant Sci.* **2020**, *11*, 590968. [[CrossRef](#)]
21. Tomšik, A.; Radojčin, M.; Stamenković, Z.; Kevrešan, Ž.; Mastilović, J.; Pavkov, I.; Vidović, S. Convective Drying Kinetics of and Preservation of Functional Ingredients of Wild Garlic (*Allium ursinum* L.) in Dependence of Drying Temperature. In Proceedings of the III International Congress on Food Technology, Quality and Safety, Novi Sad, Serbia, 25–27 October 2016.
22. Pavkov, I.; Radojčin, M.; Stamenković, Z.; Kešel, K.; Tylewicz, U.; Sipos, P.; Ponjičan, O.; Sedlar, A. Effects of Osmotic Dehydration on the Hot Air Drying of Apricot Halves: Drying Kinetics, Mass Transfer, and Shrinkage. *Processes* **2021**, *9*, 202. [[CrossRef](#)]
23. Han, J.; Lawson, L.; Han, G.; Han, P. A Spectrophotometric Method for Quantitative Determination of Allicin and Total Garlic Thiosulfinates. *Anal. Biochem.* **1995**, *225*, 157–160. [[CrossRef](#)] [[PubMed](#)]
24. Stojanović, Z.S.; Uletilović, D.D.; Kravić, S.; Kevrešan, Ž.S.; Grahovac, N.L.; Lončarević, I.S.; Đurović, A.D.; Marjanović Jeromela, A.M. Comparative Study of the Nutritional and Chemical Composition of New Oil Rape, Safflower and Mustard Seed Varieties Developed and Grown in Serbia. *Plants* **2023**, *12*, 2160. [[CrossRef](#)]
25. Melgarejo, P.; Calín-Sánchez, Á.; Carbonell-Barrachina, Á.A.; Martínez-Nicolás, J.J.; Legua, P.; Martínez, R.; Hernández, F. Antioxidant Activity, Volatile Composition and Sensory Profile of Four New Very-Early Apricots (*Prunus armeniaca* L.). *J. Sci. Food Agric.* **2014**, *94*, 85–94. [[CrossRef](#)] [[PubMed](#)]
26. Serea, C.; Barna, O.; Manley, M.; Kidd, M. Effect of Storage Temperature on the Ascorbic Acid Content, Total Phenolic Content and Antioxidant Activity in Lettuce (*Lactuca sativa* L.). *J. Anim. Plant Sci.* **2014**, *24*, 1173–1177.
27. Toledo, M.E.A.; Ueda, Y.; Imahori, Y.; Ayaki, M. L-Ascorbic Acid Metabolism in Spinach (*Spinacia oleracea* L.) during Postharvest Storage in Light and Dark. *Postharvest Biol. Technol.* **2003**, *28*, 47–57. [[CrossRef](#)]
28. Wang, M.; Xu, J.; Ding, Z.; Xie, J. Prolong the Postharvest Shelf Life of Spinach through the Antioxidative Ability of Melatonin. *Food Chem. X* **2023**, *19*, 100769. [[CrossRef](#)] [[PubMed](#)]
29. Ghidelli, C.; Pérez-Gago, M.B. Recent Advances in Modified Atmosphere Packaging and Edible Coatings to Maintain Quality of Fresh-Cut Fruits and Vegetables. *Crit. Rev. Food Sci. Nutr.* **2018**, *58*, 662–679. [[CrossRef](#)]

30. Lachowicz, S.; Kolniak-Ostek, J.; Oszmiański, J.; Wiśniewski, R. Influence of Maturity on the Content of Phenolic Compounds of *Allium ursinum* L. *J. Food Process. Preserv.* **2016**, *41*, e13089. [\[CrossRef\]](#)
31. Pinto, T.; Aires, A.; Cosme, F.; Bacelar, E.; Morais, M.C.; Oliveira, I.; Ferreira-Cardoso, J.; Anjos, R.; Vilela, A.; Gonçalves, B. Bioactive (Poly)Phenols, Volatile Compounds from Vegetables, Medicinal and Aromatic Plants. *Foods* **2021**, *10*, 106. [\[CrossRef\]](#)
32. Bernaert, N.; De Clercq, H.; Van Bockstaele, E.; De Loose, M.; Van Droogenbroeck, B. Antioxidant Changes during Postharvest Processing and Storage of Leek (*Allium ampeloprasum* Var. *porrum*). *Postharvest Biol. Technol.* **2013**, *86*, 8–16. [\[CrossRef\]](#)
33. Mahmutovic, O.; Tahirovic, I.; Copra, A.; Memic, M.; Ibragic, S.; Karic, L. Correlation of Total Secondary Sulfur Compounds, Total Phenols and Antioxidant Capacity in the Ramsons and Garlic. *Br. J. Pharm. Res.* **2014**, *4*, 2662–2669. [\[CrossRef\]](#)
34. Alexieva, J.; Mihaylova, D.; Popova, A. Antioxidant capacity and thin layer chromatography of ethanol extracts of *Allium ursinum* L. and *Allium bulgaricum* L. *Sci. Bull.* **2014**, *XVIII*, 91–96.
35. Mihaylova, D.S.; Lante, A.; Tinello, F.; Krastanov, A.I. Study on the Antioxidant and Antimicrobial Activities of *Allium ursinum* L. Pressurised-Liquid Extract. *Nat. Prod. Res.* **2014**, *28*, 2000–2200. [\[CrossRef\]](#) [\[PubMed\]](#)
36. Nataša, S. Sekundarni Biomolekuli U Vrstama Allium Sect. Codonoprasum Rchb.—Biološke Aktivnosti, Fitohemijski I Hemotaksonomski Aspekti. Ph.D. Thesis, University of Novi Sad: Novi Sad, Serbia, 2009.
37. Horníčková, J.; Kubec, R.; Cejpek, K.; Velišek, J.; Ovesna, J.; Stavelikova, H. Profiles of S-Alk(En)Ylcysteine Sulfoxides in Various Garlic Genotypes. *Czech J. Food Sci.* **2010**, *28*, 298–308. [\[CrossRef\]](#)
38. Løkke, M.M.; Seefeldt, H.F.; Skov, T.; Edelenbos, M. Color and Textural Quality of Packaged Wild Rocket Measured by Multispectral Imaging. *Postharvest Biol. Technol.* **2013**, *75*, 86–95. [\[CrossRef\]](#)
39. Løkke, M.M.; Edelenbos, M.; Larsen, E.; Feilberg, A. Investigation of Volatiles Emitted from Freshly Cut Onions (*Allium cepa* L.) by Real Time Proton-Transfer Reaction-Mass Spectrometry (PTR-MS). *Sensors* **2012**, *12*, 16060–16076. [\[CrossRef\]](#)
40. Ben Haj Said, L.; Najjaa, H.; Farhat, A.; Neffati, M.; Bellagha, S.; Ben, L.; Said, H.; Najjaa, H.; Farhat, A. Thin Layer Convective Air Drying of Wild Edible Plant (*Allium roseum*) Leaves: Experimental Kinetics, Modeling and Quality. *J. Food Sci. Technol.* **2015**, *52*, 3739–3749. [\[CrossRef\]](#)
41. Calín-Sánchez, Á.; Figiel, A.; Wojdyło, A.; Szarycz, M.; Carbonell-Barrachina, Á.A. Drying of Garlic Slices Using Convective Pre-Drying and Vacuum-Microwave Finishing Drying: Kinetics, Energy Consumption, and Quality Studies. *Food Bioprocess Technol.* **2014**, *7*, 398–408. [\[CrossRef\]](#)
42. Zhou, L.; Guo, X.; Bi, J.; Yi, J.; Chen, Q.; Wu, X.; Zhou, M. Drying of Garlic Slices (*Allium sativum* L.) and its Effect on Thiosulfinates, Total Phenolic Compounds and Antioxidant Activity during Infrared Drying. *J. Food Process. Preserv.* **2017**, *41*, e12734. [\[CrossRef\]](#)
43. Hossain, M.B.; Barry-Ryan, C.; Martin-Diana, A.B.; Brunton, N.P. Effect of Drying Method on the Antioxidant Capacity of Six Lamiaceae Herbs. *Food Chem.* **2010**, *123*, 85–91. [\[CrossRef\]](#)
44. Chan, E.W.C.W.C.; Lim, Y.Y.Y.; Wong, S.K.K.; Lim, K.K.K.; Tan, S.P.P.; Lianto, F.S.S.; Yong, M.Y.Y. Effects of Different Drying Methods on the Antioxidant Properties of Leaves and Tea of Ginger Species. *Food Chem.* **2009**, *113*, 166–172. [\[CrossRef\]](#)
45. Wang, J.; Cao, Y.; Sun, B.; Wang, C.; Mo, Y. Effect of Ultrasound on the Activity of Alliinase from Fresh Garlic. *Ultrason. Sonochem.* **2011**, *18*, 534–540. [\[CrossRef\]](#) [\[PubMed\]](#)
46. Li, Y.; Xu, S.-Y.; Sun, D.-W. Preparation of Garlic Powder with High Allicin Content by Using Combined Microwave–Vacuum and Vacuum Drying as Well as Microencapsulation. *J. Food Eng.* **2007**, *83*, 76–83. [\[CrossRef\]](#)
47. Pezzutti, A.; Crapiste, G.H. Sorptional Equilibrium and Drying Characteristics of Garlic. *J. Food Eng.* **1997**, *31*, 113–123. [\[CrossRef\]](#)
48. Ratti, C.; Araya-Farias, M.; Mendez-Lagunas, L.; Makhlof, J. Drying of Garlic (*Allium sativum*) and Its Effect on Allicin Retention. *Dry. Technol.* **2007**, *25*, 349–356. [\[CrossRef\]](#)
49. Méndez Lagunas, L.L.; Castaigne, F. Effect of Temperature Cycling on Allinase Activity in Garlic. *Food Chem.* **2008**, *111*, 56–60. [\[CrossRef\]](#)
50. Mitra, J.; Shrivastava, S.L.; Srinivasa Rao, P. Process Optimisation of Vacuum Drying of Onion Slices. *Czech J. Food Sci.* **2011**, *29*, 586–594. [\[CrossRef\]](#)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.