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Assessment of Lycopene Levels in Dried Watermelon Pomace: A Sustainable Approach to Waste Reduction and Nutrient Valorization

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Abstract: Watermelon suffers substantial post-harvest losses owing to strict quality standards, resulting in 20–30% of the crop being left unharvested. This study investigated the potential of valorizing dried watermelon pomace (DWP), a byproduct of watermelon juice extraction, focusing on its lycopene content—a potent antioxidant. This study assessed lycopene stability in DWP from four watermelon cultivars (Perla Nera®, Gavina®, Crimson Sweet, and Asahi Miyako) under different storage conditions (vial-sealed and vacuum-sealed). The lycopene content in freshly prepared DWP samples ranged from 0.734 to 1.572 mg/g db. The results indicated that vacuum-sealed samples exhibited significantly slower lycopene degradation than vial-sealed samples, highlighting the impact of air exposure on lycopene stability. After 90 days of storage, lycopene content in vacuum-sealed samples ranged from 0.214 to 1.234 mg/g db, while that in vial-sealed samples ranged from 0.013 to 0.731 mg/g db. Furthermore, this study assessed the effect of pretreatments with ascorbic acid (pretreatment A) and a mixture of ascorbic and citric acids (pretreatment B) on lycopene stability. Pretreatment B showed superior effectiveness, yielding higher lycopene levels than pretreatment A ($p < 0.05$). The stabilizing effects of ascorbic acid and citric acid were attributed to their antioxidant properties and their roles as pH regulators and chelators.

Keywords: watermelon; lycopene; UV-Vis; sustainability; dietary fibers; recycle; nutrient recovery; biorefinery

Citation: D'Eusanio, V. Assessment of Lycopene Levels in Dried Watermelon Pomace: A Sustainable Approach to Waste Reduction and Nutrient Valorization. *Analytica* **2024**, *5*, 311–321. https://doi.org/10.3390/analytica5030020

Academic Editor: Marcello Locatelli

Received: 17 June 2024
Revised: 5 July 2024
Accepted: 7 July 2024
Published: 9 July 2024

1. Introduction

The climate crises represents an unprecedented threat to our planet by affecting ecosystems, weather patterns, and agricultural productivity. Greenhouse gas emissions are intricately linked to ongoing changes in our climate, with food waste being a significant contributor, accounting for 8–10% of total global emissions [1]. When food is wasted, all the resources invested in its production—including water, land, energy, and labor—are wasted. Moreover, as organic matter decomposes in landfills, it releases methane, a potent greenhouse gas that contributes to climate change [2]. Additionally, it emits significant amounts of methanol and ethanol, which are toxic compounds that can sterilize agronomic soils and harm the biosphere.

Watermelon is one of the most important melon crops worldwide [3], and is prized for its refreshing taste and high nutritional value. Europe alone consumes approximately 3 million tons of watermelon annually, along with more than 2 million tons of other melon varieties [4]. Despite this significant demand, an alarming 20–30% of watermelons are left in fields each year [5,6]. This waste stems from the stringent standards imposed on fresh watermelon consumption, leading to the rejection of any fruit with visible defects. To address these challenges, there is an urgent need to explore value-added products derived from watermelon, leveraging the rejected crops effectively. Watermelon biomass can be categorized into three main components: flesh/pulp, seeds, and rinds. The flesh

constitutes approximately 40% of the total weight [7,8], while the rind and seeds represent about 60%. Since only half of the watermelon fruit is edible, researchers are seeking alternative solutions to valorize the waste fraction, particularly rind and seeds [7–10]. Watermelon byproducts have a high nutritional value and potential for inclusion in the human diet. They are low-cost and have demonstrated significant potential in the food sector for producing additives [11,12], extruded products [13], confectionaries, and snacks [14]. Additionally, they can find applications in the cosmeceutical [15] and pharmaceutical [16] sectors because of their valuable antioxidant and biological activities. Given that watermelons are often discarded as a whole, it is important to also convert the flesh into something valuable. Pomace, the solid residue left after juice extraction, contains insoluble carbohydrates, proteins and minerals, along with residual juice and soluble components, such as sugars [5]. Previous studies have shown that watermelon pomace is a concentrated source of lycopene, containing 110% of the lycopene found in the juice [17,18]. Lycopene, a naturally occurring pigment and powerful antioxidant [17,19], belongs to the carotenoid family and is responsible for the red color in certain fruits and vegetables, notably tomatoes and watermelon. Its series of conjugated double bonds contributes to its potent antioxidant properties, which help neutralize harmful free radicals and protect cells and tissues from oxidative damage [20]. This oxidative stress is linked to the development of various chronic diseases [20–23], including cancer [24,25], cardiovascular disease [26], and age-related degenerative conditions [27].

However, the high-water content of pomace prevents its long-term storage. Drying, a widely used preservation method, can extend the storage life of watermelon pomace, making it more available throughout longer periods and versatile for various applications [5]. Since the drying method and conditions significantly affect the properties of pomace, evaluating the quality of the dried products is essential. During storage, food products undergo transformations that can affect their quality, including chemical reactions, microbial growth, and physical changes, which can alter their taste, texture, color, and nutritional value. In the case of watermelon, which is rich in lycopene, this study focused on lycopene quantity because of its high sensitivity to light, heat, and oxygen [28–30]. During the storage of processed products containing lycopene, degradation follows a complex pattern influenced by factors such as cultivar type, processing methods, water activity, moisture content, and storage conditions. Lycopene content is crucial not only for its antioxidant properties, but also for the color it imparts to dried watermelon pomace (DWP). Color is an important quality attribute for food acceptability, and it is crucial to study how processing and storage affect it.

Previous studies have investigated the lycopene content in dried watermelon pomace by evaluating different drying methods such as spray drying [18,31,32], cabinet and drum drying [5,33], solar drying [34], and freeze-drying [31]. However, as far as we know, no studies have determined lycopene content in DWP under different storage conditions. For this reason, in this study, the effect of air contact with DWP powders was assessed by studying two storage conditions: vial-sealed, and vacuum-sealed. Moreover, the effect of a pre-treatment added to the pomace before drying on the lycopene content of DWP was assessed. Pre-treatments have been previously applied to other food matrices containing lycopene, such as tomato [35,36], but, as far as we know, have never been applied to watermelon.

The composition of watermelon pomace was evaluated across four different watermelon cultivars: Perla nera® (PN), Gavina® (G), Crimson Sweet (CS), and Asahi Miyako (AM). PN and G are seedless, whereas CS and AM are seeded. Lycopene content can vary significantly between cultivars and between seedless and seeded cultivars. Moreover, some of these are unique Italian varieties that have not been studied previously (PN and G). All the samples were dried under the same conditions using an oven-drying process at 40 °C for 24 h. The watermelon pomace powder was then stored in a dark atmosphere, vials-sealed or vacuum-sealed, at room temperature. The lycopene content was assessed

at intervals of 7, 14, 21, 28, 90 days of storage to evaluate both short-term (0–28 days) and long-term (90 days) storage periods.

This study enriches the existing literature, which has primarily focused on other byproducts of watermelon, by including valorization aspects related to DWP. By evaluating the effects of storage conditions and pre-treatments on the lycopene content of DWP, this research provides valuable insights into maximizing the utility and nutritional value of watermelon waste. Consequently, this contributes to broader efforts to reduce food waste and promote sustainable agricultural practices.

2. Materials and Methods

2.1. Sample Preparation

All watermelons investigated in this study were purchased at local supermarkets in Modena, Italy. The watermelon cultivars included Perla Nera® (PN), Asahi Miyako (AM), Gavina® (G), and Crimson Sweet (C). Gavina® is a registered mark from Agricola Campadinese (Tarralba, Italy) and Perla Nera® from a consortium of several producers exclusively from Italy. A total of 8 whole watermelons, 2 for each cultivar, were used to prepare 12 homogenized watermelon pomace (HWP) samples, with 3 samples for each cultivar. After separating the rind and the seeds, the flesh was chopped into small cubes and homogenized for 2 min in a blender. Each HWP sample weighed ~300 g. The pre-treatments followed the procedure proposed by Hasturk Sahin et al. [35], with some modification. One HWP sample for each cultivar was treated with 10 mL of a 20% ascorbic acid solution (Solution A), another with 10 mL of a 20% solution of ascorbic acid and citric acid in a 1:1 ratio, while the third HWP sample remained untreated. The pH of pre-treated HWP sample was 5 for "A" pre-treatment, and 4.5 for "B" pre-treatment.

The HWP samples were then vacuum-filtered to remove most of the water content, spread in a thin layer, and oven-dried at 40 °C for 24 h. This temperature was chosen to mitigate thermally activated reaction, such as the Maillard reaction. The dried samples were then ground using a grinding mill equipped with titanium blades to a fine powder with an average grain size of 0.5 mm. The final product (DWP, dried watermelon pomace, Figure 1) was a slightly sticky red powder.

Figure 1. DWP sample from Gavina® cultivar.

In this study, 6 storage times (0, 7, 14, 21, 28, 90 days) and 2 storage conditions (in a sealed glass vial in the dark at room temperature (RT), and vacuum-stored in the dark at RT) were considered. For each DWP sample, 3 replicates were analyzed. The names of each

sample, along with a description of the pre-treatment and of the storage conditions, are reported in Table 1.

Table 1. Summary of the analyzed DWP samples.

Sample Name	Cultivar	Pre-Treatment	Storage Condition
PN	Perla Nera®	No	Vial-sealed, RT, dark
PN_A	Perla Nera®	Solution A	Vial-sealed, RT, dark
PN_B	Perla Nera®	Solution B	Vial-sealed, RT, dark
AM	Asahi Miyako	No	Vial-sealed, RT, dark
AM_A	Asahi Miyako	Solution A	Vial-sealed, RT, dark
AM_B	Asahi Miyako	Solution B	Vial-sealed, RT, dark
G	Gavina®	No	Vial-sealed, RT, dark
G_A	Gavina®	Solution A	Vial-sealed, RT, dark
G_B	Gavina®	Solution B	Vial-sealed, RT, dark
C	Crimson Sweet	No	Vial-sealed, RT, dark
C_A	Crimson Sweet	Solution A	Vial-sealed, RT, dark
C_B	Crimson Sweet	Solution B	Vial-sealed, RT, dark
PNV	Perla Nera®	No	Vaacum stored, RT, dark
PN_AV	Perla Nera®	Solution A	Vaacum stored, RT, dark
PN_BV	Perla Nera®	Solution B	Vaacum stored, RT, dark
AMV	Asahi Miyako	No	Vaacum stored, RT, dark
AM_AV	Asahi Miyako	Solution A	Vaacum stored, RT, dark
AM_BV	Asahi Miyako	Solution B	Vaacum stored, RT, dark
GV	Gavina®	No	Vaacum stored, RT, dark
G_AV	Gavina®	Solution A	Vaacum stored, RT, dark
G_BV	Gavina®	Solution B	Vaacum stored, RT, dark
CV	Crimson Sweet	No	Vaacum stored, RT, dark
C_AV	Crimson Sweet	Solution A	Vaacum stored, RT, dark
C_BV	Crimson Sweet	Solution B	Vaacum stored, RT, dark

Each sample was extracted through a conventional solvent extraction (CSE) procedure. Hexane was chosen because it is a non-polar solvent and thus is able to solubilize the analyte of interest. In total, 300 mg of each sample was extracted with 10 mL of n-hexane for 1 h at room temperature, under constant stirring and subdued light to prevent lycopene degradation and isomerization. The same procedure was repeated with fresh solvent on the previous solid residue until the fiber no longer yields dye to the hexane (3 times). For each sample, the various aliquots of extract were collected and diluted to the final volume of 100 mL.

2.2. Proximate Analysis

Moisture, ash, crude protein, and total fat were determined following the methods recommended by the Association of Official Analytical Chemists [37]. Moisture content was determined by drying the sample at 105 °C to a constant weight. The ash content was determined using a laboratory furnace at 550 °C, and the temperature was gradually increased. The Dumas method was used to determine nitrogen content, which was converted to protein content multiplying by a factor of 6.25. The Soxhlet method was used to determine the residual fat fraction, using petroleum ether (boiling point range 40–60 °C) as the extractant solvent.

Glucose, fructose, and sucrose were analyzed through the method proposed by Arocho et al. [5] using HPLC analysis. The system was composed of a Waters 2690 Separation Module (Waters, Milford, MA, USA) and a differential refractometer (Waters 2410, Waters, Milford, MA, USA) as a detector. The column was an Aminex Carbohydrate HPX-87 (Bio-Rad, Richmond, CA, USA).

The determination of carbon, hydrogen, nitrogen, and sulfur was performed using a Thermo-Scientific CHNS Analyzer mod. Flash2000 (Thermo-Scientific, Waltham, MA USA) after calibration with thiourea as standard.

Each measurement was performed in triplicate, and the results were averaged.

2.3. Lycopene Analysis

The lycopene determination was conducted using a spectrophotometric method. The UV-Vis spectra of the extracts, previously filtered with a 0.2 µm filter, were measured with a UV-Vis spectrophotometer JASCO V-570 (Jasco International Co., Ltd., Tokyo, Japan), in the wavelength range 200–800 nm, at room temperature, and using quartz cells with optical path of 0.2 cm. Fresh n-hexane was used as blank. The quantitative determination of lycopene content in each solution was determined using Lambert Beer's law at 503 nm, the least interfered by the presence of other carotenes [38]. The concentration of lycopene in the samples was calculated using the following equation (Equation (1)):

$$C = \frac{\frac{A}{17{,}200} \cdot \frac{V}{1000\ mL} \cdot 536.85 \frac{g}{mol} \cdot 1000 \frac{mg}{g}}{S} \quad (1)$$

where C is the concentration of lycopene in mg/g sample, A is the absorbance reading, S is the amount of sample used (g), 17,200 mol/cm is the lycopene coefficient of extinction, V is the extraction volume (hexane), and 536.85 g/mol is the molecular weight of lycopene [5].

2.4. Statistical Analysis

The experimental data were compared by conducting an analysis of variance (one-way ANOVA) with Tukey–Kramer honestly significant difference (HSD) post-hoc testing, by using the Matlab® 2023a environment (Mathworks Inc., Natick, MA, USA). The level of significance was determined at $p < 0.05$ to see whether there were statistical differences between the mean values.

2.5. Reagents and Standards

n-Hexane was purchased from Carlo Erba Reagents (Milano, Italy). Trans-lycopene standard (>98%) was purchased from Merck KGaA (Darmstadt, Germany).

3. Results and Discussion

3.1. Proximate Analysis of DWP Samples

The results of the proximate chemical analysis are reported in Table 2. Data are expressed as mean ± standard deviation of three replicates. Means in the same row followed by the same letter are not significantly different (Tukey–Kramer HSD test, at $p < 0.05$).

Proximate analysis (Table 2) served as a crucial starting point for evaluating the compositional differences among the various DWP samples and their potential applications. Proximate composition is influenced by factors that are challenging to regulate, such as cultivation practices [39–42], light exposure, atmospheric conditions during cultivation, and soil type. These variables can significantly affect the nutritional profile of the samples and must be carefully considered when interpreting the results. The DWP samples were predominantly composed of carbohydrates, with a sugar content of approximately 50%. The protein content was modest (8–15%), whereas the lipid content was negligible (<1%). Among the different cultivars, significant differences were observed in most components, except for total lipids and ash, for which no significant differences ($p > 0.05$) were detected. Some differences between the samples from different cultivars were found in carbohydrate content, including both sugar and total fiber levels. These variations can be attributed not only to the cultivar, but also to the degree of ripeness [40]. For instance, the Crimson Sweet cultivar exhibited a lower sugar content, whereas the Asahi Miyako cultivar had the highest. This suggests that the presence or absence of seeds in the cultivars does not significantly influence sugar levels, or is a secondary factor compared to the degree of ripeness and other variables that are difficult to control in the present study, such as cultivation conditions. The high sugar content was responsible for the sticky nature of the samples. Upon vacuum

packing and storage, the samples tended to cake together, necessitating the use of a mortar to obtain a flowable powder. This highly hygroscopic nature suggests that DWP powder should be stored properly in an airtight container and kept in a cool, dry place. The DWP samples had a significantly lower sugar content than that reported in previous studies [43], which found that dried watermelon pomace contained 68.6% sugars on a dry matter basis. This difference could be due to losses during the drying process or incomplete recovery during the juice extraction, as well as different cultivars or degree of ripeness. It is likely that sugars participate in browning reactions during prolonged heating, contributing to their loss, even at low temperatures. The protein content was higher in the seeded cultivars (AM and CS). Seeds contain storage proteins that support seedling growth [44,45], and their presence may contribute to the overall protein content of the pomace. The moisture content was below 10%, which is sufficient to ensure the microbiological safety of the food powder [46]. Maintaining this low water content effectively inhibits the growth of microorganisms, including bacteria, yeast, and molds, which require higher moisture levels to thrive. Throughout the storage period, no mold formation was observed, further confirming the effectiveness of maintaining a moisture content below 10%.

Table 2. Proximate chemical composition of the DWP samples.

	PN	AM	G	C
Moisture content (%)	6.14 ± 0.12 a	6.68 ± 0.14 b	5.93 ± 0.11 a	6.91 ± 0.16 b
Total fat (%)	0.66 ± 0.08 a	0.59 ± 0.11 a	0.46 ± 0.09 a	0.62 ± 0.10 a
Ashes (%)	3.10 ± 0.02 a	2.91 ± 0.03 a	4.65 ± 0.02 a	3.59 ± 0.04 a
Carbohydrate (%) *	82.1 ± 0.7 a	75.1 ± 0.4 b	80.9 ± 0.5 a	78.6 ± 0.8 d
Total dietary fiber (%)	16.2 ± 0.6 a	15.3 ± 0.5 ab	13.3 ± 0.5 c	14.1 ± 0.6 bc
Glucose (%)	10.4 ± 0.14 a	10.6 ± 0.11 a	9.17 ± 0.13 b	10.4 ± 0.14 a
Fructose (%)	30.9 ± 0.8 a	31.9 ± 0.6 a	33.6 ± 0.5 b	29.4 ± 0.4 a
Sucrose (%)	8.53 ± 0.41 a	8.85 ± 0.40 a	8.01 ± 0.39 a	6.89 ± 0.37 b
Total Sugars (%)	49.8 ± 0.6 a	51.3 ± 0.7 a	50.8 ± 0.8 a	46.7 ± 0.4 b
Proteins (%)	8.04 ± 0.68 a	14.7 ± 0.8 b	8.04 ± 0.45 a	10.3 ± 0.6 c
C%	40.0 ± 0.6 a	42.3 ± 0.5 b	38.9 ± 0.9 a	39.6 ± 0.8 a
H%	6.44 ± 0.12 a	6.33 ± 0.22 a	6.49 ± 0.17 ab	6.92 ± 0.17 b
N%	1.34 ± 0.10 a	2.41 ± 0.11 b	1.35 ± 0.14 a	1.73 ± 0.11 c
S%	<0.1%	<0.1%	<0.1%	<0.1%

Data are expressed as mean ± standard deviation of three replicates. Means in the same row followed by the same letter are not significantly different (Tukey–Kramer HSD test at $p < 0.05$). * Carbohydrate contents were calculated by subtracting the sum of proteins, total fat, moisture, and ash from 100.

3.2. Lycopene Content of DWP Samples

The results of lycopene determination in DWP samples are reported in Figures 2 and 3, with corresponding statistical significance reported in Table 3. The top points of each curve represent the lycopene content in freshly prepared samples. As the curves move downward, they show the lycopene content of samples after increasing storage periods.

The lycopene concentration in freshly prepared samples (days of storage = 0) ranged from 1.572 to 0.734 mg/g, which was consistent with previous studies [5]. Cultivars G and PN consistently showed the highest lycopene values both in freshly prepared samples and throughout various storage periods. This observation may be influenced by a combination of intrinsic factors, such as cultivar-specific traits, and extrinsic factors, such as cultivation practices. For example, previous research has highlighted the profound impact of light exposure [47], cultivation site temperature, and ripening stage [48] on the lycopene content in tomatoes. The cultivars G and PN are cultivated by local Italian consortia in regions selected for optimal pedoclimatic conditions, emphasizing quality over mass production. These cultivation practices likely contribute to the superior quality of the pomace, whereas watermelons of cultivars C and AM are primarily cultivated for mass consumption. Cultivars grown for mass consumption often prioritize traits such as yield and shelf-life over specific quality features.

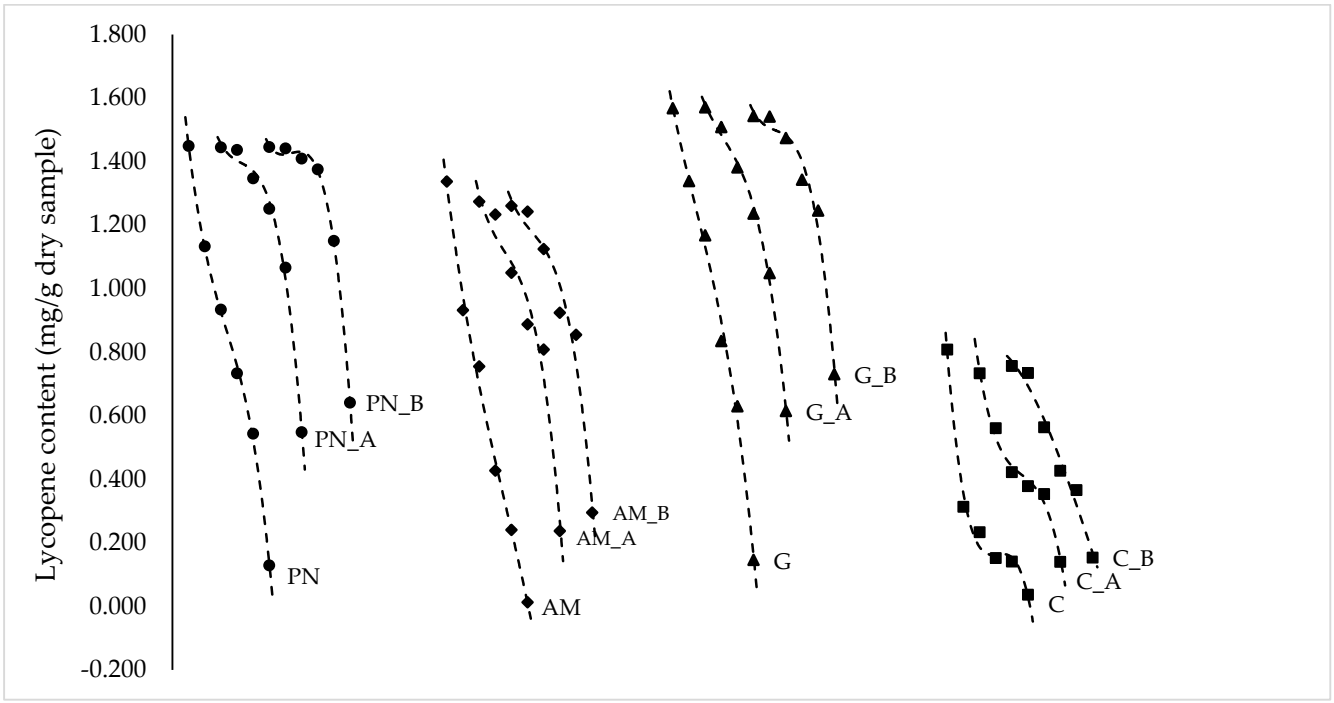

Figure 2. Lycopene content (mg/g dry sample) in DWP samples from different cultivars, vial-sealed. The different markers (circles, diamonds, triangles, and squares) represent the different cultivars (PN, AM, G, and C, respectively), with dashed lines illustrating the decline in lycopene content during storage.

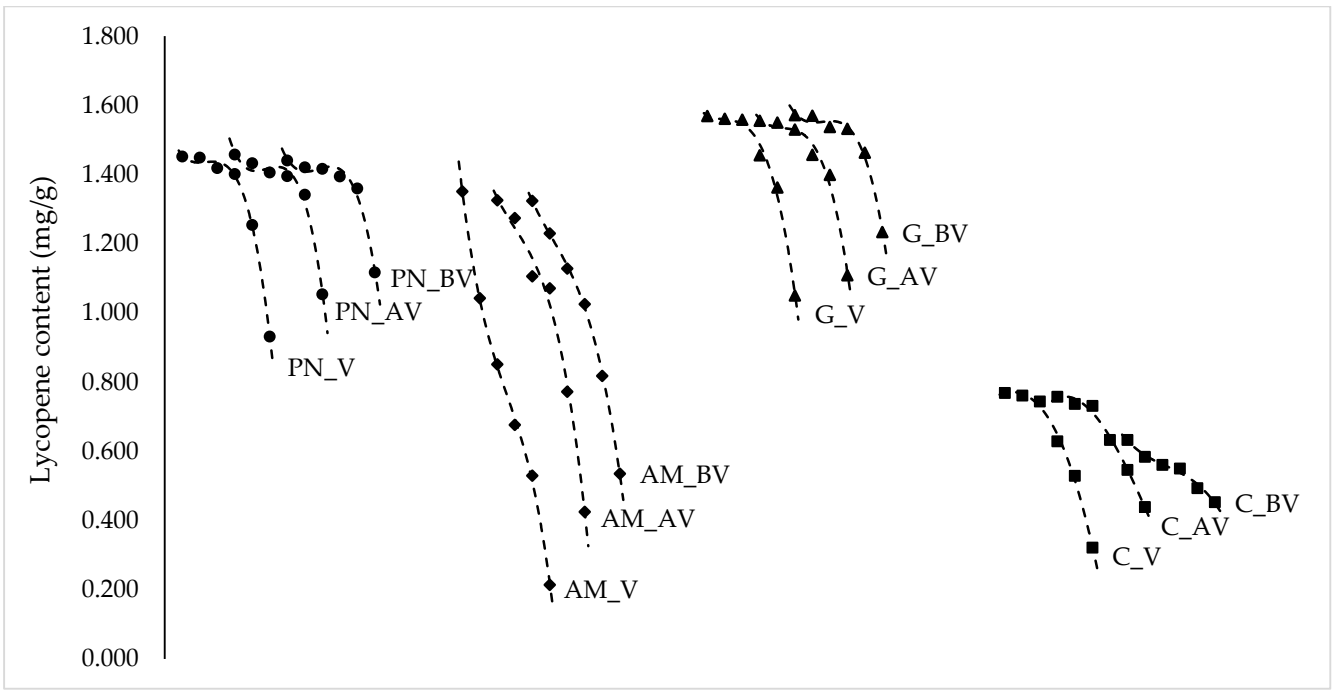

Figure 3. Lycopene content (mg/g dry sample) in DWP samples from different cultivars, vacuum-sealed. The different markers (circles, diamonds, triangles, and squares) represent the different cultivars (PN, AM, G, and C, respectively), with dashed lines illustrating the decline in lycopene content during storage.

Table 3. Lycopene content (mg/g) of the DWP samples.

Days of Storage	0	7	14	21	28	90
PN		1.135 ± 0.051 b	0.934 ± 0.030 c	0.734 ± 0.052 d	0.544 ± 0.041 e	0.129 ± 0.012 f
PN_A	1.445 ± 0.051 a	1.437 ± 0.054 a	1.347 ± 0.063 ab	1.252 ± 0.048 b	1.066 ± 0.070 c	0.549 ± 0.035 d
PN_B	1.446 ± 0.059 a	1.442 ± 0.061 a	1.409 ± 0.051 a	1.376 ± 0.075 a	1.151 ± 0.052 b	0.641 ± 0.034 c
AM	1.337 ± 0.050 a	0.932 ± 0.034 b	0.758 ± 0.071 c	0.435 ± 0.062 d	0.244 ± 0.057 e	0.013 ± 0.006 f
AM_A	1.274 ± 0.042 a	1.234 ± 0.059 a	1.050 ± 0.075 b	0.888 ± 0.067 c	0.809 ± 0.061 c	0.237 ± 0.014 d
AM_B	1.261 ± 0.047 a	1.243 ± 0.048 a	1.125 ± 0.021 b	0.924 ± 0.045 c	0.855 ± 0.044 c	0.295 ± 0.044 d
G	1.568 ± 0.042 a	1.339 ± 0.039 b	1.168 ± 0.056 c	0.835 ± 0.059 d	0.630 ± 0.063 e	0.147 ± 0.013 f
G_A	1.571 ± 0.060 a	1.509 ± 0.061 ab	1.382 ± 0.066 bc	1.236 ± 0.051 c	1.049 ± 0.054 d	0.615 ± 0.025 e
G_B	1.544 ± 0.047 a	1.542 ± 0.048 a	1.474 ± 0.083 ab	1.343 ± 0.064 bc	1.246 ± 0.054 c	0.731 ± 0.030 d
C	0.809 ± 0.069 a	0.314 ± 0.046 b	0.234 ± 0.060 bc	0.152 ± 0.042 cd	0.141 ± 0.051 cd	0.037 ± 0.0013 d
C_A	0.734 ± 0.050 a	0.561 ± 0.037 b	0.423 ± 0.077 c	0.379 ± 0.046 c	0.354 ± 0.049 c	0.140 ± 0.018 d
C_B	0.757 ± 0.052 a	0.735 ± 0.063 a	0.564 ± 0.047 b	0.427 ± 0.079 bc	0.366 ± 0.043 c	0.154 ± 0.008 d
PN_V	1.452 ± 0.055 a	1.449 ± 0.045 a	1.419 ± 0.058 a	1.402 ± 0.070 ab	1.254 ± 0.045 b	0.932 ± 0.046 c
PN_AV	1.458 ± 0.060 a	1.433 ± 0.041 a	1.406 ± 0.056 a	1.395 ± 0.040 a	1.342 ± 0.046 a	1.054 ± 0.040 b
PN_BV	1.441 ± 0.048 a	1.421 ± 0.067 a	1.417 ± 0.071 a	1.395 ± 0.051 a	1.360 ± 0.045 a	1.117 ± 0.030 b
AM_V	1.351 ± 0.045 a	1.042 ± 0.056 b	0.851 ± 0.039 c	0.677 ± 0.051 d	0.530 ± 0.052 e	0.214 ± 0.019 f
AM_AV	1.326 ± 0.058 a	1.274 ± 0.052 a	1.106 ± 0.034 b	1.071 ± 0.052 b	0.772 ± 0.042 c	0.425 ± 0.027 d
AM_BV	1.324 ± 0.052 a	1.230 ± 0.047 ab	1.128 ± 0.049 bc	1.026 ± 0.042 c	0.818 ± 0.055 d	0.535 ± 0.028 e
G_V	1.569 ± 0.042 a	1.562 ± 0.055 a	1.559 ± 0.046 a	1.456 ± 0.031 ab	1.363 ± 0.047 b	1.050 ± 0.051 c
G_AV	1.555 ± 0.060 a	1.550 ± 0.043 a	1.530 ± 0.037 a	1.457 ± 0.039 ab	1.399 ± 0.023 b	1.109 ± 0.019 c
G_BV	1.572 ± 0.048 a	1.570 ± 0.064 a	1.532 ± 0.062 a	1.516 ± 0.024 a	1.463 ± 0.047 a	1.234 ± 0.031 b
C_V	0.769 ± 0.042 a	0.761 ± 0.049 a	0.744 ± 0.054 ab	0.629 ± 0.050 bc	0.529 ± 0.051 c	0.322 ± 0.030 d
C_AV	0.758 ± 0.053 a	0.737 ± 0.055 a	0.731 ± 0.047 a	0.633 ± 0.059 ab	0.546 ± 0.046 bc	0.439 ± 0.052 c
C_BV	0.633 ± 0.057 a	0.584 ± 0.056 ab	0.561 ± 0.038 ac	0.550 ± 0.043 ac	0.494 ± 0.030 bc	0.453 ± 0.011 c

SD < 0.005. Data are expressed as mean ± standard deviation of three replicates. Differences between means indicated by the same letters are not statistically significant ($p < 0.05$) using a Tukey–Kramer HSD post-hoc test.

The lycopene content in the DWP samples exhibited variable rates of decline, depending on the cultivar and storage conditions (vial-sealed and vacuum-sealed). The loss of lycopene during storage was accompanied by a noticeable decline in the red color of the samples. This indicated the degradation of this carotenoid, as it is the primary pigment responsible for the vibrant red hue in watermelon pomace. Generally, vacuum-sealed samples showed a more gradual decrease in concentration, and higher lycopene content after 90 days for all cultivars studied. Specifically, vacuum-sealed PN and G samples showed significantly lesser decline in the initial 21 days of storage compared to their vial-sealed counterparts (ranging from 1.7% to 7.2% in vacuum-sealed PN and G samples versus 13.0% to 49.3% in vial-sealed PN and G samples). After 90 days, lycopene content ranged between 0.214 and 1.234 mg/g in vacuum-sealed samples, and from 0.013 to 0.731 mg/g in vial-sealed samples. These findings underscore the substantial effect of air exposure on DWP, highlighting that prolonged contact accelerates the loss of lycopene.

Pretreatment has demonstrated a notable stabilizing effect on lycopene, effectively mitigating its degradation across all analyzed samples. Specifically, pretreatment "B", which included a mixture of ascorbic acid and citric acid, emerged as the most effective, yielding significantly higher lycopene levels compared to pretreatment "A" ($p < 0.05$), which included only ascorbic acid. Ascorbic acid (vitamin C) is well-known for its antioxidant properties. By scavenging free radicals and inhibiting oxidative reactions, ascorbic acid helps maintain the structural integrity and nutritional quality of food products during storage [49]. Citric acid also contributes to the preservation of food products by acting as a pH regulator and chelator, and has anti-bacterial effects [50,51]. The combination of these two acids in pretreatment "B" likely synergizes to provide a more robust protective effect on lycopene content in DWP. This effect became more pronounced with increased storage time, highlighting a growing discrepancy between the lycopene concentrations in samples treated with solution A and those treated with solution B as aging progressed.

In a study conducted by Arocho et al. [5], comparable samples of DWP were stored at −20 °C, revealing minimal decreases in lycopene content over a 1-year period. While air exposure is certainly a significant factor in lycopene degradation, as demonstrated in the present study, storage temperature appears to exert a greater influence, as evidenced

by the substantial degradation observed in Figures 2 and 3. Future research could expand upon these findings by investigating the same cultivars under varied storage temperatures, thereby enhancing the current understanding of lycopene preservation strategies in DWP.

The incorporation of powdered dried fruits into food products has significant potential to enhance both nutritional and technological qualities [52–54]. These powders are rich in bioactive components, which can elevate antioxidant capacity and increase the levels of essential vitamins and minerals in food products [55,56]. Additionally, the high content of both soluble and insoluble fibers found in powdered dried fruits contributes to improve technological properties [57]. For instance, their fiber content can enhance the gelling, thickening, and emulsifying properties of food formulations, making them valuable additives for various food applications. Furthermore, the inclusion of carotenoid-rich powders such as DWP can impart a vibrant color to food products, which is particularly advantageous in enhancing the visual appeal of items such as confectioneries, beverages, and dairy products [46,52,54]. However, it is crucial to consider the thermal sensitivity of lycopene during processing to maximize its retention and efficacy. The aroma and flavor profiles were also significantly affected by the addition of powdered dried fruits. DWP, in particular, has a distinctive aromatic profile that can add a unique and appealing flavor to food products [58–60]. However, controlling the storage conditions of DWP is essential because of the rapid degradation of lycopene observed in this study.

4. Conclusions

This study identified significant factors influencing lycopene stability in DWP across different watermelon cultivars and storage conditions. The initial lycopene concentrations varied notably among cultivars, with G and PN consistently exhibiting the highest levels, reflecting both intrinsic genetic traits and careful cultivation practices. Throughout storage, lycopene degradation was evident, with vacuum-sealed samples generally showing slower decline rates than vial-sealed ones, underscoring the critical role of air exposure in accelerating lycopene loss.

Pretreatment with a combination of ascorbic acid and citric acid (pretreatment "B") emerged as being particularly effective in mitigating lycopene degradation, outperforming pretreatment "A" (ascorbic acid alone). This finding highlights the synergistic antioxidant and pH-regulating properties of these compounds in the preservation of lycopene integrity during storage.

Comparative insights from the literature underscore the influence of storage temperature on lycopene retention, suggesting potential avenues for future research to optimize the storage conditions of DWP. By further investigating these variables, future studies can advance strategies to enhance the shelf-life and nutritional quality of watermelon pomace-derived products, thereby benefiting both food preservation practices and dietary health.

Funding: This research received no external funding.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The author declares no conflicts of interest.

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