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The Influence of Ultraviolet-C Light Pretreatment on Blackcurrant (*Ribes nigrum*) Quality During Storage

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Abstract

Blackcurrant is a notable superfruit in Europe, and its vitamin C content surpasses the well-known blueberry superfruit. However, due to its short shelf life during storage, consumption is mainly accounted by frozen berries, extracts, and concentrates. This study applied an intensity of 1.2 W/m^2 UVC with different durations, including control (non-treated), UVC irradiation for 0.5 h (0.5 h treatment), UVC irradiation for 1 h (1 h treatment), and UVC pretreatment for 2 h (2 h treatment) to blackcurrant berries before storage. Fundamental physical (firmness and weight loss) and physicochemical characteristics (SSC, pH, and acids), microbial population changes, total phenolic content, antioxidant capacity, and specific phenolic compound changes were evaluated every five days over a twenty-day storage period. The results indicated that the longer the UVC pretreatment, the lower the water weight losses during storage. Meanwhile, the UVC pretreatment significantly affected the blackcurrant soluble solid content, resulting in higher soluble solid contents detected in the blackcurrants with the higher doses of UVC. For the mold population control, UVC effects were highly correlated with the pretreatment duration. However, UVC did not have a significant influence on the berry pH and acid contents, but the storage length slightly increased the pH and decreased the acids. At the same time, UVC pretreatment did not affect the berry firmness, polyphenols, ascorbic acid content, or antioxidant capacities, which were primarily influenced by the storage duration. The monophenolic compounds detected before and after storage indicated that more than one hour of UVC radiation influenced most of the phenolic contents largely before storage. The UVC pretreatment has also influenced some phenolic compounds. After storage, half an hour of UVC pretreatment increased cyanidin levels, and two hours of UVC pretreatment increased catechin and epicatechin levels. However, most of the compounds remained at similar amounts during storage in each treatment. Further research is needed to improve the UVC radiation time length or intensity or explore other technology combinations to optimize UVC pretreatments for blackcurrant storage.

Keywords: blackcurrant; ultraviolet-C (UVC); postharvest storage

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1. Introduction

Blackcurrant (*Ribes nigrum* L.) is widely grown in cool-climate areas, mostly in Europe, with more than 220,000 metric tons in global production [1]. Blackcurrant fruits are rich

in anthocyanins and ascorbic acids, which are beneficial for health. To preserve beneficial nutrients, volatile composition, and unique odor characteristics, storage conditions and processing methods must be considered [2].

Most of the research on blackcurrant postharvest processing has focused on berry processing. Frozen storage and cold storage enhance the extraction of anthocyanins in juice, possibly due to the easier extraction of anthocyanins from partly degraded berries [3]. The storage conditions also influenced the major anthocyanins in blackcurrants, depending on the berry development stages (early ripe, fully ripe, and overripe) [4]. Blackcurrant berry content, such as pectin, influences anthocyanin extraction and stability [5]. Processing methods, such as pasteurization, influence blackcurrant juice stability as well [6].

Until now, there has been limited research on the fresh storage of blackcurrants. One study indicated that a controlled atmosphere performed the best in maintaining blackcurrant quality compared to normal conditions (0–1 °C) and modified conditions with Xtend® films [7]. Controlled atmosphere storage also altered the volatile constituents of blackcurrants [8]. High hydrostatic pressure conditions were assessed to preserve blackcurrants the best [9].

Due to the similar sizes and colors to blackcurrants, blueberry postharvest storage methods can potentially be applied to blackcurrants. Heat treatment, such as 30–40 °C hot air, can eliminate microorganisms and decay on blackberry surfaces [10]. A 1–4 kJ/m^2 of UVC light can decrease the decay of blueberries and enhance their antioxidant levels [11]. On the other hand, higher doses (8 kJ/m^2) of UVC have increased the blueberry decay incidence [12]. UVB at 6 kJ/m^2 has reduced the blueberry weight loss and decay, and delayed the increase in soluble solid-to-titratable acidity ratios, but reduced the volatiles and phenolics in the berries [13]. Pulsed UV light, with intense broad-spectrum electromagnetic radiation (100–1100 nm) energy, had a positive effect on the decontamination of blueberry skins [14]. Oxidizers, such as chlorine dioxide (ClO_2) and ozone, have also shown potential as sanitizers for blueberries [15]. Edible coatings can generally maintain fruit freshness and increase the shelf life of blueberries. For example, a chitosan coating with salicylic acid and titanium dioxide nanoparticles was applied to harvested blueberries, indicating that all three combined maintained the nutrient composition of blackcurrants most effectively [16].

Light irradiation, an easy-to-operate technology, has been studied in postharvest treatment for over four decades; however, it has not been applied to blackcurrants [17]. The sources of UV can be mercury lamps, pulsed light, and light-emitting diodes (LEDs), and their quantum efficiency can be variable [18]. In the food industry, UV technology can be applied to surface sterilization, water disinfection, insect trapping, air treatment, and waste treatment [17]. Based on the UV wavelength regions, UV can be separated into UVA (315–400 nm), UVB (280–315 nm), and UVC (200–280 nm). Differentiated radiation has different effects on fruits and vegetables during storage. UVA studies have indicated its main effects on increasing antioxidants, flavonoids, and total polyphenols [19]. UVB has some functions in inductive effects on phenolics, total antioxidants, and primary compound accumulation in fruits and vegetables [20]. For fruit and vegetable storage, UVC has been reported to have two main functions: physiological effects, such as reducing postharvest microbial decay, and nutritional effects, including improving the bioactive compounds in fruits and vegetables [20,21]. Besides the similar influence of UVB, which affects the accumulation of anthocyanins and total phenolics, UVC has been reported to influence the activities of enzymes [22]. UVC, as one of the non-thermal technologies, has been used for food surface decontamination and postharvest decay reduction, which might be due to its functional mechanisms, affecting the stability, structure, and functions of nucleic acids or amino acids, which directly or indirectly inactivate the microorganisms, namely molds, bacteria, and yeast [23,24]. It has been reported that the dose of UVC should be adjusted

based on the types of microorganisms present on the surfaces of fruits and vegetables. The doses needed increase dramatically from bacteria and yeast, to mold [25].

Earlier, our study demonstrated that a large microbial population developed during 15 days of blackcurrant storage, and UVA had a negative influence on controlling weight loss during blackcurrant storage [26]. Therefore, in this study, we investigated the effects of pretreatment with UVC on blackcurrant postharvest storage to find a more effective method for maintaining blackcurrant fruit quality and nutrition during postharvest storage, particularly for long-distance transportation without optimum storage conditions. The evaluation of UVC pretreatment influences on blackcurrants includes the tests on fruit quality and bioactive compounds (Figure 1).

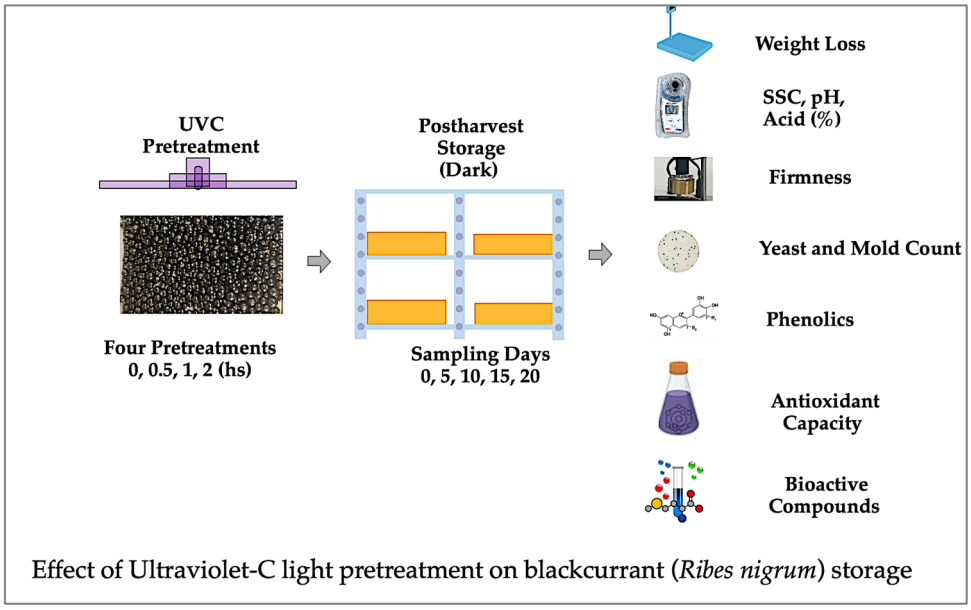

Figure 1. Graphic abstract of UVC pretreatment on blackcurrant storage.

2. Materials and Methods

2.1. Plant Materials and Light Treatment

Blackcurrant (*Ribes rubrum*) variety 'Nikola' was cultivated at the Western Agricultural Research Center of Montana State University. Fruits were hand-harvested into sanitized bins on 18 July 2024. Afterward, fruits were visually selected to remove damaged, deformed, or off-sized berries. Berry sizes ranged from 9.0 to 13.5 mm. Berries were evenly placed onto trays in a single layer and separated into four groups for different treatments.

Germicidal UVC linear lights were purchased from ELEDLIGHTS (Hatboro, PA, USA) and installed on storage shelves. Poly films (iPower, Duarte, CA, USA) were used to cover the shelves, reflecting light and preventing the lights from automatically powering off. Based on preliminary studies on shorter periods of UVC irradiation for blackcurrants and microbial population tests on 3M Petri films (Carolina Biology, Burlington, NC, USA), the results indicated that mold was the predominant microbial population on blackcurrants. Berries were subjected to four UVC pretreatments with a peak emission at 254 nm at an intensity of radiation (1.2 W/m^2) in a walk-in cooler at 0–4 °C and ≥90% humidity. The exposure time and treatments were as follows: (1) control (darkness): 0 h (0 h) UVC pretreatment; (2) 0.5 h (0.5 h) UVC pretreatment (2.16 kJ/m^2); (3) 1 h (1 h) UVC pretreatment (4.3 kJ/m^2); and (4) 2 h (2 h) UVC pretreatment (8.6 kJ/m^2).

The trays with berries in each treatment were covered with a thin layer of plastic wrap (Reynolds, College Station, TX, USA) and moved into darkness after exposure to different lengths of UVC light radiation. Five sampling time points included day 1, day

5, day 10, day 15, and day 20. Blackcurrants were collected from each treatment for the following tests. Forty berries from each pretreatment were randomly selected and placed into clamshells on day 0 to monitor weight loss during storage. At each sampling date, the clam shells of each treatment were weighed to record the weight loss.

2.2. Weight Loss

The clam shells were weighed at each sampling time to calculate the berry weight loss. The weight loss percentage (%) was calculated as weight loss (%) = $(1 - Ws/Wi) \times 100\%$, where Wi is the initial weight of the blackcurrants in each clam, and Ws is the weight of the blackcurrants at the sampling point during storage [26].

2.3. Firmness of Blackcurrants

For each treatment, fifty blackcurrants were randomly picked from the walk-in cooler on each sampling day. According to the FirmTech FT7 manuals and overall blackcurrant firmness assessment, the firmness of the blackcurrants was measured using a FirmTech FT7 (UP GmbH, Ibbenbüren, Germany). The firmness of each berry was expressed as gm/mm, indicating the force (grams) increases per unit of deformation (mm) on the fruit [27].

2.4. Phytochemical Properties of Blackcurrants

Blackcurrants were homogenized by an FSH-2A high-speed homogenizer (Generic, Beijing, China). According to the manuals of Atago meters and juice physicochemical characteristic measurement, the blackcurrant juice was measured for soluble solid content (°Brix) by Atago 3810 (PAL-1) digital pocket refractometer (Atago, Tokyo, Japan). The pH was measured with an Atago PAL-pH meter (Atago, Japan). For acids, one gram (~1 mL) of blackcurrant mixture was diluted 50 times using diH_2O, then measured by an Atago 7101 PAL-BX/ACID1 pocket citric acid meter (Atago, Japan). Acidity was expressed as % citric acid equivalent.

2.5. Microbial Population During Storage

According to the blueberry microbial population measurement and modifications, blackcurrant microbial populations were examined by placing 30 ± 0.1 g of blackcurrants from each pretreatment into sterile BagPage paddle blender bags with 170 mL of deionized water (Interscience, Saint-Nom-la-Bretèche, France), and homogenizing them using a Bagmixer 400 (Interscience, France) within 30 s. Serial dilutions (10^{-1}, 10^{-2}, and 10^{-3}) were prepared by subtracting the blended liquid from the filter bags [28]. Selective media, including 3^M Petrifilm for yeast and mold (Carolina Biology, Burlington, NC, USA), and 3M petrifilm for aerobic count plates for aerobic bacteria (Carolina, USA), were utilized in the microbial population growth study. On each selective plate, 1 mL of each serial dilution solution was used for spreading. For the yeast and mold study, incubation conditions were 25 °C for 3 days. For the aerobic population, incubation conditions were 37 °C for 3 days. The results were calculated as log CFU/g (colony forming unit per gram). The results were analyzed with two sample containers (technical replicates) with two replicate counts of each treatment (biological replicates).

2.6. Sample Extraction

The acidified ethanol extraction method was used to extract blackcurrants with some modifications [23]. Briefly, homogenized samples (1 g) were treated with ethanol at a 1:10 (w/w) ratio in 15 mL centrifuge tubes. The solvent was 2% citric acid acidified with 80% ethanol. Extraction conditions were 40 °C for 2 h in a water bath (Cole-Parmer WB-400, Vernon Hills, IL, USA). Afterward, tubes were centrifuged at $2800\times g$ for 15 min at room

temperature (20 °C). Supernatants were transferred into new tubes and stored at −20 °C until further assays.

2.7. Total Phenolics

The total phenolic content of blackcurrant extract was determined by the Folin–Cioalteu colorimetric method with the BQC KB03006 polyphenol quantification assay kit (BQC Redox Technologies, Asturias, Spain) [29]. The total phenolic content was expressed as μg gallic acid equivalents (GAEs) per mL of each sample.

2.8. Antioxidant Activity Assay

Two methods were used in this study to measure antioxidant activity: the 2,2-diphenyl-1-picrylhydrazyl (DPPH) assay and the ferric reducing antioxidant power (FRAP) assay. The antioxidant capacity of blackcurrants measured by DPPH assay was through the 2,2-Diphenyl-1-picrylhydrazyl DPPH Antioxidant Capacity kit (KF01007, BQC Redox Technologies, Asturias, Spain) [30]. The results are expressed as trolox equivalent antioxidant capacity (TEAC) mM/mg. In the other method, the FRAP assay kit (MAK369) was purchased from Sigma-Aldrich (St. Louis, MO, USA). The antioxidant capacity was assessed according to the manufacturer's protocols. The results are expressed as FRAP nM/mg [31].

2.9. Ascorbic Acid Assay

Ascorbic acid in each blackcurrant juice sample was measured by the colorimetric method with the Ascorbic Acid Assay Kit AB65346 (Abcam, Waltham, WA, USA) [32]. To prevent the rapid degradation of ascorbic acid in the samples, they were stored at 4 °C and tested within 48 h. The results are expressed as milligrams per 100 g of each sample.

2.10. Monophenolic Compound Measurements by LC-MS

An aliquot of 100 mg of the sample from the mixed berry samples was extracted for flavonoids and phenolic acids using 100% methanol. There was no problem with dissolving compounds for the mobile phase; therefore, no acidified solvent was used. An internal standard was spiked before extraction. The samples were dried down and then reconstituted in 100 μL of 30% methanol. They were injected twice: once after a tenfold dilution and once after a two-fold dilution at 1 μL [33].

2.11. Statistical Analysis

The statistical design used for data analysis was factorial analysis through the "doebioresearch" package in R Studio version 2024.12.1+563 [34]. The package ggplot2 generated the plots. The data obtained were analyzed using variance analysis to estimate the differences among the means (n = 2) by comparing the means of each treatment using the least significant difference (LSD) at a 5% probability level in R Studio.

3. Results and Discussion

3.1. Analysis of the Variance of the Treatment

An ANOVA was conducted to identify the significant factors and interactions affecting postharvest storage. The variance analysis (Table 1) indicated that the UVC pretreatments significantly influenced the weight loss of blackcurrants, their soluble solid content, and mold population. Storage time significantly influenced the majority of blackcurrant characteristics, including weight loss, pH, acidity, firmness, ascorbic acid content, and results from DPPH and FRAP assays, as well as mold population. The interactions between pretreatment and storage time resulted in significant changes in fundamental physicochemical properties (SSC, pH, and acids) and antioxidant capacities, as assessed through FRAP and DPPH assays.

Table 1. Analysis of variance (*p*-values) for the significance of pretreatment influence on blackcurrant characteristics during postharvest storage.

Factor	Pretreatment	Storage Time	Pretreatment × Storage Time
df	3	3 for weight loss percentage or 4 for others	6 or 8
Weight loss (%)	1.053×10^{-5} ***	$<2.2 \times 10^{-16}$ ***	ns
SSC (°Brix)	0.0001709 ***	ns	6.934×10^{-5} ***
pH	ns	6.863×10^{-7} ***	5.569×10^{-5} ***
Acid (%)	ns	9.039×10^{-8} ***	0.001989 **
Firmness	ns	$<2.2 \times 10^{-16}$ ***	ns
Polyphenol content	ns	0.058	ns
Ascorbic acid content	ns	0.004 **	ns
DPPH	ns	0.00032 ***	0.04463 *
FRAP	ns	2.712×10^{-7} ***	0.04384 *
Mold	5.97×10^{-7} ***	$<2.2 \times 10^{-16}$ ***	ns

Note: The characteristics analyzed in blackcurrants include weight loss, SSC, pH, acid, firmness, polyphenol, ascorbic acid, DPPH values, FRAP values, and mold populations. The significance codes are *** $p < 0.001$ (the effect is highly statistically significant); ** $p < 0.01$ (the effect is statistically significant at the 1% level); * $p < 0.05$ (the effect is statistically significant at the 5% level); and ns indicates the effect is not statistically significant at the 5% level. There were four pretreatments in this study: 0 h UVC, 0.5 h UVC, 1 h UVC, and 2 h UVC. Storage time points are days 0, 5, 10, 15, and 20. For weight loss, the df of storage time is 3, and the df of Pretreatment × Storage time is 6. For other characteristics, the df of storage time is 4, and the df of Pretreatment × Storage time is 8.

3.2. UVC Pretreatment Effects on Blackcurrant Postharvest Storage

The blackcurrant weight loss percentage continued to increase across postharvest storage, from 0% on day 0 (before storage) to approximately 2.0% weight loss on day 20 (Figure 2). It was noticeable that 2 h of UVC pretreatment reduced weight loss compared to other pretreatments, possibly because UVC has a positive effect on reducing weight loss with longer pretreatment, which may be attributed to a reduced respiratory rate or enzymatic activities. Further research is needed to address this issue and determine the underlying reasons. Besides influencing the fruit transpiration and respiration rate, UVC effects might be related to the blackcurrant fruit structure, especially the berry skin. Sunburn in warm or hot weather can alter skin structures, making berry transpiration and respiration more difficult during storage [35,36]. Further research at the cellular level could help determine the detailed modification under UVC radiation. In this study, other pretreatments did not appear to affect weight loss significantly compared to the control treatment. The LSD revealed that there were about 10% differences among the pretreatments.

Preharvest and postharvest UVC treatments were studied on fruit and vegetable varieties. Ten and twenty minutes of UVC (28.8 kJ m^{-2}) treatments on peaches positively controlled weight loss [37]. UVC treatments (0.32, 0.97, 2.56, 4.16, and 4.83 kJ m^{-2} at 254 nm) on tomatoes resulted in less weight loss compared with the control treatment (no UVC), whereas 0.97 kJ m^{-2} had fewer effects compared to other UVC treatments [38]. The publications indicated that UVC with specific doses could have a positive impact on fruit weight loss control, which corresponded to this study, where only 2 h of UVC had significant weight loss control. To more effectively control the blackcurrant weight loss during postharvest storage, other strategies can be combined, such as hydro-cooling and biopolymers (e.g., chitosan) [39,40].

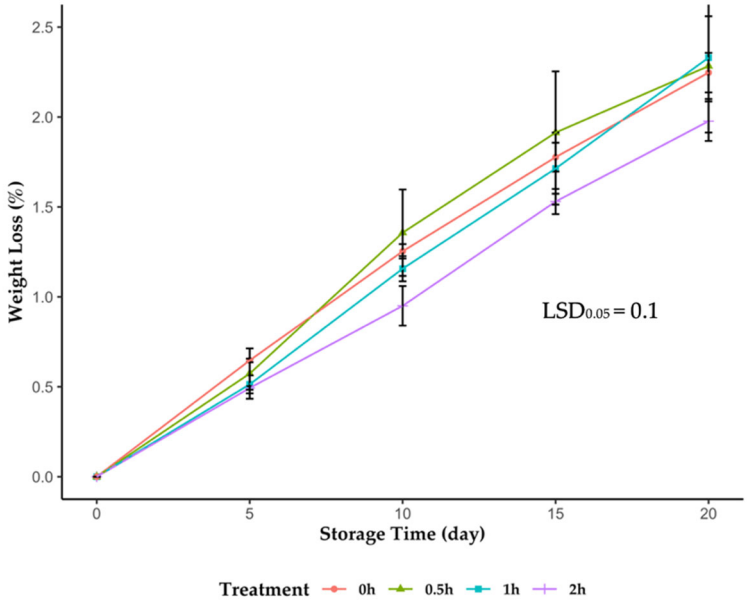

Figure 2. UVC pretreatment affects the weight loss of blackcurrants during storage. Each treatment contained three replicates. Bars indicate the mean ± standard deviations of the replicates. LSD (least significant differences) shows the means of the treatment differences.

3.3. Blackcurrant Physicochemical Changes During Storage

From the previous ANOVA analysis (Table 1), it has been concluded that pretreatments significantly influenced the SSC content of blackcurrants. In contrast, storage length had a significant impact on the pH and acid content during blackcurrant storage. In detail, the trend was listed in Table 2. The SSC results indicated that the 1 h and 2 h UVC pretreatments increased the SSC content by 0.27 to 0.30 °Brix on average, and both were significantly different ($p < 0.001$) from 0 h and 0.5 h UVC pretreated blackcurrants. In summary, UVC pretreatment accelerated SSC changes in blackcurrants. This may be correlated with UVC stress-induced resistance in blackcurrant berries, which has been observed in other fruits and vegetables [41]. Further research is needed to determine whether the fruit possesses a defense against UVC irradiation, such as oxidase activities and expression.

Table 2. The changes in blackcurrant physicochemical characteristics during storage.

Pretreatment (UVC)	SSC (°Brix)	*p*-Value	F-Value
0 h	14.31 ± 0.31 ^{b}	0.0001709 ***	11.37
0.5 h	14.42 ± 0.26 ^{b}		
1 h	14.61 ± 0.13 ^{a}		
2 h	14.58 ± 0.21 ^{a}		
Storage Duration (days)	**pH**	***p*-Value**	**F-Value**
0	3.27 ± 0.01 ^{c}	6.863×10^{-7} ***	21.85
5	3.27 ± 0.02 ^{c}		
10	2.28 ± 0.03 ^{c}		
15	3.29 ± 0.01 ^{b}		
20	3.31 ± 0.02 ^{a}		
Storage Duration (days)	**Acidity (%)**	***p*-Value**	**F-Value**
0	2.37 ± 0.06 ^{a}	9.04×10^{-8} ***	28.31
5	2.40 ± 0.09 ^{a}		
10	2.41 ± 0.05 ^{a}		
15	2.39 ± 0.06 ^{a}		
20	2.19 ± 0.08 ^{b}		

Means followed by the same letter within columns are not significantly different for each character of blackcurrants. Values are listed as the mean ± standard deviation of replicates. Acidity is detected as citric acid (%) with an Atago meter. The significance codes are *** $p < 0.001$ (the effect is highly statistically significant). The F-value indicates that the difference in the group means is substantially greater than the variability within each group.

pH differential changes in blackcurrants were significant among the storage sampling days, ranging from 3.27 to 3.31 on average. Although the changes were minimal, with a 0.04 pH change, the longer the storage time, the higher the pH level in the blackcurrants. Acid differences across storage were also detected significantly ($p < 0.0001$): the range of the changes was from 2.19% to 2.41% on average. In general, the acid content decreased over time, and the acids on day 20 were significantly different from those on other storage days.

Several publications mention that UVC pretreatment has an influence with or without causing physicochemical changes. UVC, at doses of 2 and 4 J/cm^2 for postharvest treatment, did not influence the sugar, pH, or titratable acidity in tomatoes and apples, but improved their antioxidant capacities [42]. On the other hand, UVC pretreatment on peaches reduced the total soluble solids during storage, which may be because UVC can enhance antioxidants and reduce oxidative enzyme activities [37,43]. In this study, pretreatment with UVC caused significant SSC changes among the samples during storage in blackcurrants; however, the effects on pH and acids were primarily due to the storage duration, rather than the pretreatment (Table 2). Therefore, in addition to the intensity of UVC pretreatment, the types of fruit also react differently to UVC pretreatment.

3.4. Blackcurrant Firmness Reduction During Storage

The ANOVA test (Table 1) showed that storage time is the only factor that significantly influences blackcurrant firmness. Over the storage period, the firmness of blackcurrants decreased from an average of 170 g/mm to 110 g/mm (Figure 3).

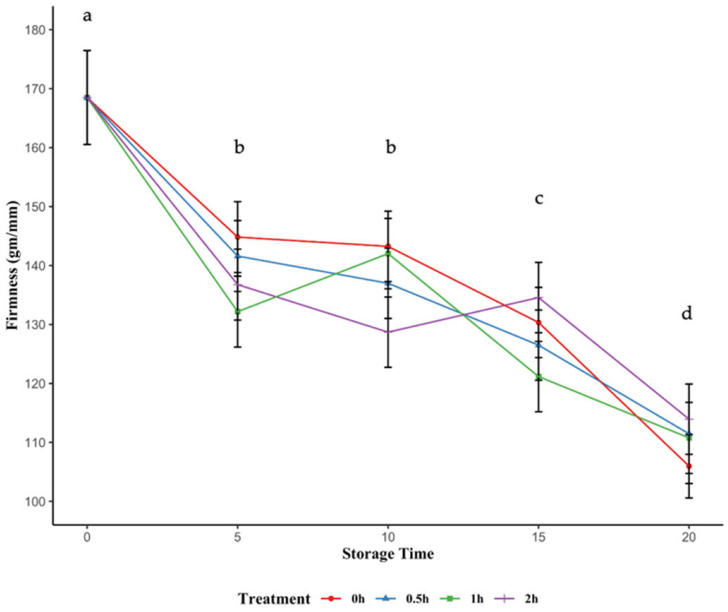

Figure 3. Blackcurrant berry firmness changes during storage. Each treatment contained three replicates. Bars indicate the mean ± standard deviations of the replicates. The letters indicate significant differences across storage.

UVC pretreatment has been reported to maintain fruit firmness in other postharvest storage systems. It has been mentioned that a higher dose (8 kg/m^2) of UVC had a better effect on maintaining tomato firmness than the lower dose of UVC (3 kg/m^2) [44]. One reason for maintaining firmness through UVC pretreatment might be related to inhibiting cell wall degradation enzyme activities, such as xylase and β-galactosidase. The multi-step UVC treatment (multiple times of UVC irradiations) on strawberries was the most effective method for maintaining berry firmness [45]. Therefore, it is worth trying the repetitive UVC treatment on blackcurrants in future investigations.

3.5. Yeast and Mold Population Changes During Blackcurrant Postharvest Storage

The results on yeast and mold populations of UVC pretreatments are shown in Figure 4. The results indicate that UVC pretreatments of varying lengths significantly differed from the control on most days (days 0 to 15) of postharvest storage. There were no significant differences on day 20, although UVC-pretreated blackcurrants had lower average populations (<24 Log CFU/g). Two hours of UVC-pretreated blackcurrants on day 0 effectively inhibited yeast and mold populations, with approximately 2 log CFU/g differences compared to the other pretreatments. Various lengths of UVC pretreatments showed effects on days 5 and 10 compared to the control (0 h); however, no significant differences were observed among the different lengths of UVC pretreatments.

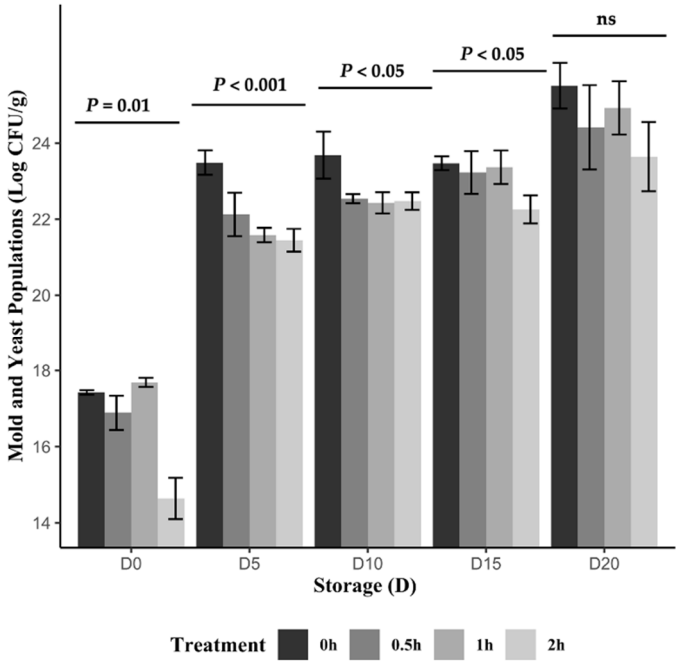

Figure 4. UVC pretreatment effects on blackcurrant mold and yeast population during storage. Each treatment contains three replicates. Bars indicate the mean ± standard deviations of the replicates. *p*-values indicate the differences among treatments on the sampling day; ns indicates not significant.

Compared to the mold and yeast population (average 17–18 log CFU/g) on day 0, the growth of yeast and mold was more dramatic on day 5 (average 22 log CFU/g), followed by less than 2 log CFU/g growth from day 10 to day 20. This was similar to the fungal development in barley ecosystems, although the fungal growth kinetics were not detailed before day 5 in this study [46]. In this blackcurrant storage, two hours of UVC pretreatment may not be sufficient to control mold growth in the long term, as evidenced by the lack of significant changes in yeast and mold populations on day 20. Therefore, repetitive UVC pretreatment or 360-degree radiation should be tested for blackcurrant postharvest storage.

3.6. Blackcurrant Total Phenolic, Antioxidant Capacity, and Ascorbic Acid Changes During Storage

Since there were no significant differences in total phenolics and antioxidant capacities caused by pretreatments (Table 1), the storage effects were analyzed for each characteristic, including the total phenolic content and antioxidant capacities assessed through the DPPH assay and FRAP assay.

On average, the total phenolics of blackcurrants ranged from 454.71 to 524.09 μg GAE/mL, and the statistical *p*-value was close to 0.05. From the changes in total phenolic contents across the storage (Table 3), the phenolics on day 20 were significantly lower than

the total phenolics on days 0, 5, and 10. This indicated that along with the storage, the total phenolic contents decreased.

Table 3. Blackcurrant total phenolic and antioxidant capacity changes during storage.

Storage Duration (Days)	Total Phenolics (μg GAE/mL)	DPPH (TEAC mM/mg)	FRAP (Fe^{2+} Equivalent nmol/mg)	Ascorbic Acids (mg/100 g)
0	520.33 ± 30.19^{a}	4.14 ± 0.08^{a}	321.87 ± 34.40^{a}	90.87 ± 13.54^{bc}
5	518.69 ± 52.33^{a}	4.07 ± 0.15^{a}	246.79 ± 47.55^{b}	82.13 ± 3.99^{c}
10	524.09 ± 87.43^{a}	4.10 ± 0.14^{a}	243.10 ± 39.70^{bc}	92.39 ± 9.64^{ab}
15	474.98 ± 37.81^{ab}	3.91 ± 0.10^{b}	187.40 ± 38.98^{ab}	98.81 ± 4.35^{a}
20	454.71 ± 61.64^{b}	3.97 ± 0.07^{b}	215.10 ± 25.78^{c}	94.95 ± 6.52^{ab}
F-value	2.74	8.88	24.64	5.46
p-Value	0.058	0.00032 ***	2.712×10^{-7} ***	0.004 **

Means followed by the same letter within columns are not significantly different for each character of blackcurrants. Values are the mean ± standard deviation of the replicates. *p*-value significance ($p < 0.01$ **, or $p < 0.001$ ***) indicates the statistically significant across the storage periods. The F-value indicates that the difference in the group means (sampling days) is substantially greater than the variability within each group (day).

Although there were no significant changes in antioxidant capacities under different pretreatments (Table 1), similar to the changes in phenolics, both DPPH and FRAP assays detected a decrease in antioxidant capacity during storage. DPPH decreased from 4.14 TEAC mM/mg on day 0 to 3.97 TEAC mM/mg on day 20. There were significant differences among the early storage days (days 0, 5, and 10) and the late storage days (days 15 and 20). The FRAP assay also detected a decreasing trend, from 321.97 to 215.10 Fe^{2+} equivalent nmol/mg, across the storage period. It also revealed statistical differences on each sampling day, indicating that the FRAP sensitivity was higher than that of the DPPH assay in this study. Many studies have also highlighted the differences between these two methods, which may be due to their detection of different targets [47]. In summary, the antioxidant content of blackcurrants decreased over time under UVC pretreatments.

Interestingly, for the specific antioxidant ascorbic acid, a slight increase was detected over the storage period, with changes of about 4 to 5 mg/100 g. Its concentration typically decreases during storage in other fruits due to oxidation and other degradation processes [48]. In certain circumstances, ascorbic acid can be converted back from its oxidized form, dehydroascorbic acid, potentially leading to an increase in the amount of ascorbic acid [49]. Whether the scenario is the same in this study, further chemical analysis of ascorbic acid in blackcurrants shall be conducted.

3.7. Antioxidant Phenolic Compounds in Blackcurrants

Since the antioxidant capacities showed a consistent reduction trend, we compared the specific phenolics of blackcurrant fruit extracts with Borges's methods [50]. The results (Figure 5) indicated differences between day 0 (d0) and day 20 (d20) under each pretreatment, and the distinct differences were observed in 1 h treated blackcurrants. Under 1 h pretreatment, the value of most compounds (d1–1 h) was higher than the values after storage (d20–1 h). Meanwhile, 2 h of UVC pretreatment before and after storage had lower values of each compound than other pretreated blackcurrants, since the color of the compounds was lighter in the heatmap. This indicated that extended UVC pretreatment (more than 1 h) negatively affected the preservation of specific phenolic compounds in blackcurrants, even though storage did not influence the total amounts as determined by colorimetric assays (Table 2).

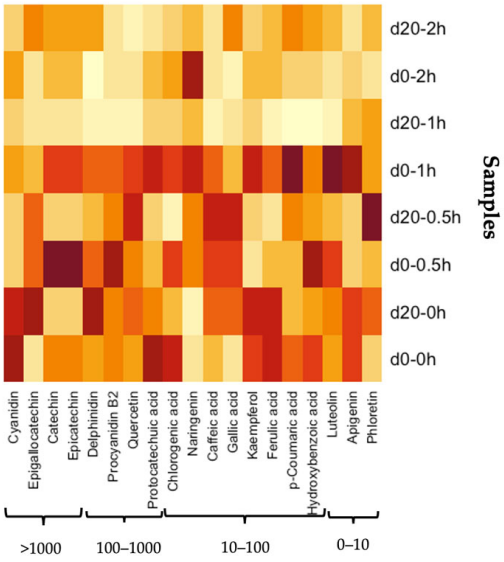

Figure 5. Heatmap of monophenolic compound changes after UVC pretreatment. The heatmap uses tested values from LC-MS. The d0 and d20 represent the first and twentieth days of storage, respectively. The 0 h, 0.5 h, 1 h, and 2 h indicate the duration of UVC pretreatment. The darker the color in the heatmap, the higher the value of each compound data point. Four categories of phenolic compounds based on quantity are listed here: more than 1000 ng/g, 100–1000 ng/g, 10–100 ng/g, and 0–10 ng/g.

There were no massive changes between the most antioxidant phenolic compounds before and after storage (Figure 6). Four large compounds (>1000 ng/g) were detected: cyanidin, epigallocatechin, catechin, and epicatechin. Cyanidin in blackcurrants without treatment (0 h) had the most considerable amounts, with 31,788.1 ng/g before storage and 29,692.4 ng/g after storage. Interestingly, UVC had a substantial influence on cyanidin quantities, as the amount of cyanidin in the treatments decreased from approximately 30,000 ng/g without UVC pretreatment (0 h) to 10,000 to 18,000 ng/g under 1 h and 2 h UVC pretreatments. Cyanidin and its glycosides belong to anthocyanins and are responsible for the bright colors of fruits and flowers [51]. It has been reported that this pigment can be degraded by UV light, which breaks the cyanidin molecule [52]. The amount of degradation was observed even with half an hour of UVC pretreatment in this study. Meanwhile, it has been noticeable that approximately 10.6% more cyanidin was detected in the 0.5 h UVC sample on day 20 compared to the 0.5 h pretreated blackcurrants before storage (d0–0.5 h). Some studies have indicated that different exposure durations and intensities of UVC can trigger varying mechanisms in fruits, which further impact fruit quality and shelf life [53]. Therefore, it is worth testing in the future whether the UVC length effect triggers a different mechanism in blackcurrants with a short exposure time.

The quantities of catechin and epicatechin in blackcurrants ranged from approximately 500 to 3000 ng/g. Compared to the amounts before storage, the levels of catechin and epicatechin decreased after storage in most treatments except for 2 h UVC pretreatments. Catechin decreased from more than 1500 ng/g under 0 h, 0.5 h, and 1 h pretreatments to less than half of the original amounts. A similar reduction was also observed in the changes in epicatechin during storage. Earlier studies on green tea indicated that continuous 68 mJ/cm^2 UVC irradiation induced a minor decrease in the concentration of the most abundant catechin in green tea [54]. On the other hand, UVC irradiation of 720 Jm/m^2 could increase catechin synthesis in banana fruits [55]. In chokecherries, 2.3 J/m^2 UVC irradiation increased the content of catechin and epicatechin [56]. The UVC differential effects may be complex, which could be attributed to the type of fruit, UVC irradiation intensity, and duration.

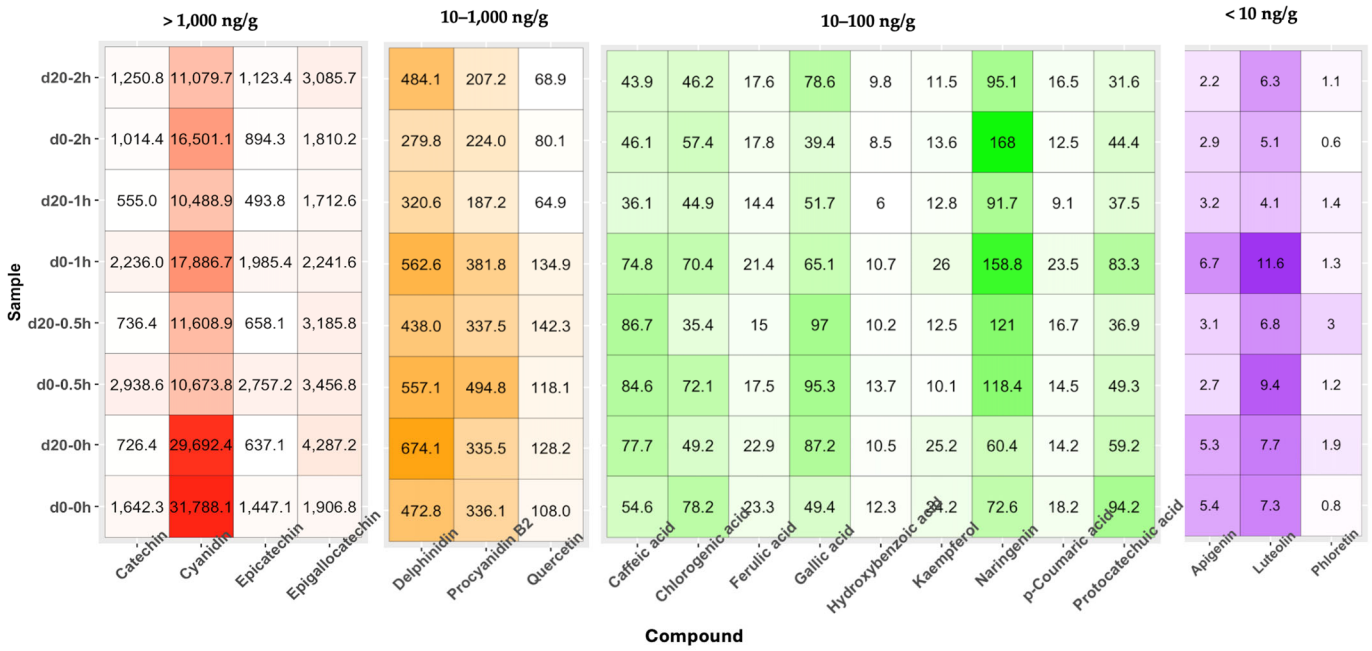

Figure 6. The phenolic profiles in UVC-pretreated blackcurrants during postharvest storage. The quantity of each compound detected by LC-MS is shown in the tile maps. There are four groups of phenolics based on the amounts, and they are more than 1000 ng/g (red tiles), 100–1000 ng/g (orange tiles), 10–100 ng/g (green tiles), and less than 10 ng/g (purple tiles) on average. The intensity of the color indicates the amount of each compound in each category.

Earlier research on the phenolic profile of blackcurrant extracts from fruits, leaves, and pomace only detected epigallocatechin in the leaves but not in the fruits and pomaces of blackcurrants [57]. In this study, we found that blackcurrants contained a certain amount of epigallocatechin, although there was not much difference in their quantities. Catechin, epicatechin, and epigallocatechin, as the major blackcurrant catechins in this study, might indicate the blackcurrant health benefit potential [58]. It has been reported that these polyphenolic compounds are highly associated with health promotion and antioxidant effects, including anti-obesity and anticancer functions [58,59].

Delphinidin is one of the most common and essential anthocyanidin molecules of flower pigments, and contributes to the antioxidant activity of blackcurrant fruits [60,61]. Procyanidin B2, another pigment commonly found in plant seeds, fruits, and leaves, exhibits various bioactivities to prevent a wide range of human diseases, such as diabetes mellitus [62]. There were moderate amounts (100–1000 ng/g) of delphinidin, and procyanidin B2 were also detected in the blackcurrants. Procyanidin B2 showed a decreased amount under UVC pretreatments, but only slightly in the control (0 h-UVC). As catechin and epicatechin exhibit a nonlinear relationship with UVC treatment, the delphinidin content was not related to the irradiation duration. Specifically, 2 h UVC enhanced its content, whereas 1 h and 0.5 h-UVC reduced its amounts. Little UVC irradiation (0–0.5 h) may enhance the quercetin amount by 20 ng/g, but not with 1 h and 2 h UVC pretreatments, where a decrease in the amount was detected.

The amounts of phenolic compounds between 10 and 100 ng/g included protocatechuic acid, chlorogenic acid, naringenin, caffeic acid, gallic acid, kaempferol, ferulic acid, p-coumaric acid, and hydroxybenzoic acid. All these compounds are highly linked to remarkable antioxidant effects, which could further contribute to health promotion [63–67]. Among them, only chlorogenic acid showed a consistent reduction in concentration during storage under each treatment, decreasing from 20 to 40 ng/g. Chlorogenic acid is commonly found in green coffee extracts and tea, and it plays several critical therapeutic roles,

including anti-inflammatory, antiviral, and anti-obesity effects [68]. Chlorogenic acid in tomato mediated the protective effect under UVC stress. However, the protective capacity was also determined by the total levels of phenolics and the specific composition of the phenolic profile [69].

For the low amounts (0–10 ng/g) of phenolic compounds, luteolin, apigenin, and phloretin were detected. The quantity of phloretin was slightly increased after storage. As one of the best-known and abundant dihydrochalcones, phloretin exhibits versatility with multiple biological functions, including anti-inflammatory, antibacterial, and anticancer activities [70,71]. Luteolin and apigenin have been used to treat various disorders, including hypertension, inflammatory disorders, and cancers [71,72].

In summary, pretreatment with UVC degraded some phenolic compounds, including cyanidin, catechin, epicatechin, and chlorogenic acids, while most of the compounds remained unchanged. Few compounds were even enhanced during storage, such as phloretin.

4. Conclusions

Different lengths of UVC pretreatment affected the soluble solid content of the blackcurrants. None of the UVC pretreatments affected weight loss, pH, or acids in blackcurrants during storage.

The UVC antimicrobial effects were significant during storage, particularly during the first 15 days. None of the UVC pretreatments had a considerable long-term influence, with notable differences observed on day 20.

Based on the secondary metabolisms and antioxidant capacity assay results, UVC pretreatments did not significantly influence total phenolics and antioxidant capacities. However, the antioxidant capacities decreased across storage, and specific antioxidant phenolic compounds underwent significant changes during storage. This indicates that the postharvest storage of blackcurrants had adverse effects on the quantities of specific phenolic compounds, such as catechin, epicatechin, and chlorogenic acid, in blackcurrants. Nevertheless, it was noticeable that certain compounds, such as catechin and epicatechin, might be enhanced with more extended UVC irradiation. Although UVC had positive effects on mold control, the degradation effects on specific anthocyanins cannot be neglected. Future research could focus on optimizing UVC pretreatment for blackcurrant postharvest storage. The strategies include, but are not limited to, optimizing UVC intensity or duration, 360-degree irradiation, and combining them with other postharvest therapies, such as coatings.

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