PAN
POLSKA AKADEMIA NAUK

JOURNAL OF WATER AND LAND DEVELOPMENT

e-ISSN 2083-4535

ITP-PIB

Polish Academy of Sciences (PAN) Institute of Technology and Life Sciences – National Research Institute (ITP – PIB)

JOURNAL OF WATER AND LAND DEVELOPMENT
DOI: 10.24425/jwld.2025.156045
2025, No. 67 (X–XII): 120–127

Effect of gaseous ozone and storage time on chemical and mechanical properties of *Vitis vinifera* L. fruits

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RECEIVED 12.06.2025 ACCEPTED 05.09.2025 AVAILABLE ONLINE 12.12.2025

Abstract: Grapes are an important source of essential micro- and macro-nutrients, vitamins, and bioactive compounds that support human health. Their chemical composition can vary depending on factors such as harvest timing and storage duration. In this study, the impact of ozone treatment at a concentration of 10 ppm applied for 15 and 30 minutes was evaluated in relation to selected chemical and mechanical properties of *Vitis vinifera* L. fruit. In the *Vitis vinifera* fruit of the studied varieties, the content of chemical compounds varied depending on the cultivar. Fruit storage had significant effect on the content of health-promoting substances, which decreased with prolonged storage time. Fruit subjected to the ozonation process, depending on the concentration applied, exhibited a 2.54% higher content of vitamin C and a 29.1% increase in phenolic compounds. The 'Barbera Bianca' cultivar was characterized by the greatest resistance to mechanical damage compared to the other varieties. After 22 days of storage, the fruit was characterized by greater hardness than in the other storage periods. Storing grapes at low temperatures for a longer period caused changes in mechanical properties, which reduced the value of the fruit. The use of gaseous ozone had a significant effect on selected chemical and mechanical properties of grapes. The use of post-harvest fruit ozonation may contribute to the advancement of fruit storage technologies for the majority of grape varieties.

Keywords: chemical composition, grapevine, mechanical properties, ozone fumigation, storage duration

INTRODUCTION

The grape (*Vitis*) is among the world major fruit crops, both in terms of cultivated area and economic value. Grapes are considered one of the most important and beneficial agricultural products, making viticulture – the cultivation of grapes – advantageous and popular forms of agriculture. There are over 10,000 different grape varieties worldwide. *Vitis vinifera* L. is one of the most widely cultivated grape and is well-known across from North and Central America to Europe and from Central to East Asia (Bouquet *et al.*, 2007; Parihar and Sharma, 2021).

Grapes are best known for their juicy berries, which serve various purposes beyond winemaking, including consumption as fresh fruit, dried fruit, and in juice production (Kersh, Hammad and Donia, 2023). Various phytochemical substances are present in the roots, stem, leaf, seeds, fruits, pomace, and skin (Yeola *et al.*, 2023; Căpruciu, 2025). Grapes contain a range of nutritious elements, including minerals, proteins, carbohydrates, fats, fibres, vitamin C, and sugars. They contain large amounts of phenolic compounds, phenolic acids (caftaric, caffeic, and gallic acids), flavanols anthocyanins (malvidin-3-O-glucoside, malvidin-3-O-(6-O-caffeoyl)-glucoside), flavonoids (e.g., quercetin-3-Orutinoside, kaempferol-3-O-glucoside), flavanols (Epicatechin, catechin), proanthocyanins (B2 and B3), and stilbenoids (E-viniferin, transresveratrol) are some of the most significant chemicals that have been identified (Sousa *et al.*, 2014; Aubert and Chalot, 2018; Fia *et al.*, 2018; Vilanova *et al.*, 2019). Numerous studies have indicated that the bioactive compounds present in grapes possess antioxidant, antidiabetic, anticancer, antibacterial, antifungal, and anti-inflammatory properties (Szajdek and Borowska, 2008; Iriti and Faoro, 2009).

The nutrients in the soil, its moisture content, and the way plants are grown have a major impact on the quantity of healthy substances found in the fruit (Brataševec, Sivilotti and Vodopivec, 2013; Cataldo *et al.*, 2020; Singh *et al.*, 2023). Phenolic compounds exhibit limited stability, as some undergo degradation during storage or processing. Factors such as pH, presence of metal ions, light exposure, temperature fluctuations, oxygen contact, and enzymatic activity can all influence the stability of phenolic compounds over time. These conditions may lead to the degradation or alteration of polyphenols, thereby diminishing their efficacy and potential health benefits (Bąkowska, Kucharska and Oszmiański, 2003). Post-harvest deterioration of grapes can be attributed to many factors that may occur before and after harvest. Physical factors, such as mechanical damage during harvesting or transportation, can lead to bruising and crushing of grapes, thereby accelerating their deterioration. Physiological factors relate to the fruit's natural metabolic processes, including enzymatic browning and respiration, which over time can alter texture, flavour, and appearance (Shiri *et al.*, 2013). Although grapes have short storage time (up to 7 days), this period can be extended through appropriate measures, such as careful harvesting and rapid cooling (Sabir and Sabir, 2013).

Ozone (O_3), commonly applied in its gaseous state, is known for its potent oxidizing properties. As a non-thermal method of food preservation, ozone is environmentally friendly and does not compromise fruit quality (Alexandre *et al.*, 2011; Ji, Pang and Li, 2014). Through gaseous ozone fumigation, bacteria can be effectively eliminated by targeting phospholipid molecules and proteins in the cell membrane without affecting the fruit's integrity. Ozonation yields beneficial effects such as reduced water loss during storage, increased antioxidant activity, and lower ethylene emission from treated fruit (Jaramillo-Sanchez *et al.*, 2019; Piechowiak, Skóra and Balawejder, 2020). Ozonation serves as an effective post-harvest preservation method that extends the shelf life of fruit while mitigating the loss of nutrients such as phenolic compounds during storage. Post-harvest ozonation of fruits acts as a stress factor that can activate the plant's defence mechanisms, leading to increased production of phenolic compounds and antioxidants. As a result, ozonation can improve the antioxidant properties of fruit during storage (Zardzewiały *et al.*, 2020; Gorzelany *et al.*, 2023). Mechanical damage, such as abrasion, bruising, or crushing, may occur during the manual harvesting, transportation, and processing of the grapes, occasionally rendering entire batches of raw material unsuitable for the market. The use of ozone may have a positive effect on water retention during storage and improve resistance to mechanical damage (Aslam, Alam and Saeed, 2020; Gorzelany *et al.*, 2022).

The aim of the study was to evaluate selected chemical and mechanical properties of four grape varieties (*Vitis vinifera* L.) during harvest and storage as well as the effect of ozonation on extending the storage time and the health-promoting value of fruit.

MATERIALS AND METHODS

MATERIALS

The study material consisted of grape fruits from the cultivars 'Alwood' (*Vitis vinifera* × *Vitis labrusca*, dark purple, commercial or dessert cultivar), 'Einset Seedless', 'Barbera Bianca' and 'Muscat Blanc'. The fruits were harvested manually from a farm located in Siedliska (49°45'31.119" N, 22°14'19.666" E, Podkarpackie Voivodeship, Poland) with 2000 g of each cultivar collected. The grapes were harvested at full ripeness, determined by the sugar content of the fruit. Following the ozonation process, the fruits were stored at a low temperature of 2°C for a period of 22 days.

SUGAR CONTENT IN BERRIES

In order to determine the harvest maturity of *Vitis vinifera* L., the glucose and fructose contents in the fruit were determined. Sugar content was measured using high-performance liquid chromatography (HPLC) with refractive index detection, following the procedure described by Gorzelany *et al.* (2023). The analysis was conducted using chromatographic equipment from SYKAM (Sykam GmbH, Eresing, Germany), which included a sample injector (S5250), a pump system (S1125), a column oven (S4120), and a refractive index detector (S3590). All measurements were performed three times.

TREATMENT OF FRUIT OZONE

Following harvest, the fruits was randomly divided into three portions, each weighing 500 g. The first portion served as the control and remained untreated. The other two portions were exposed to ozone treatment inside a plastic chamber at a concentration of 10 ppm for 5 and 15 min, respectively, with an ozone flow rate of 40 g $O_3 \cdot h^{-1}$. Ozone was produced with a KORONA A 40 Standard (Korona, Piotrków Trybunalski, Poland) and the concentration was measured using a 106 M UV Ozone Solution detector (Ozone Solution, Hull, MA, USA).

DETERMINATION OF pH AND ACIDITY

The pH value and total acidity (calculated as citric acid equivalent) of fresh *Vitis vinifera* fruits were assessed via potentiometric titration, using a 0.1 M sodium hydroxide (NaOH) solution to reach an endpoint of pH 8.1. The analysis was conducted with a TitroLine 5000 device (SI Analytics, Weilheim, Germany) in accordance with the PN-EN 12147:2000 standard (Polski Komitet Normalizacyjny, 2000). The acidity was reported as mg ascorbic acid per 100 g of fresh fruit. Each measurement was repeated three times.

DETERMINATION OF BIOACTIVE COMPOUNDS AND ANTIOXIDANT ACTIVITY IN FRUIT

Vitamin C (ascorbic acid) was determined according to PN-A-04019:1998 (Polski Komitet Normalizacyjny, 1998). The results were expressed as mg ascorbic acid per 100 g of fresh fruit. Total polyphenol content was determined using the Folin–Ciocalteu method (Piechowiak *et al.*, 2019). The results were expressed in mg of gallic acid per 100 g of fresh fruit. The analyses were performed in triplicate.

The free radical scavenging activity using DPPH (2,2-diphenyl-1-picrylhydrazyl radical) method was determined according to the methodology described in the study of Djordjević *et al.* (2010), and results were expressed as IC50 ($mg \cdot cm^{-3}$) of fresh fruit. The antioxidant activity, using the ABTS (2,2'-azino-bis-(3-ethylbenzothiazoline-6-sulfonic acid)) method, was determined according to the methodology described in study of Jakobek *et al.* (2007), the result was expressed in μM TE·g^{-1} of fresh fruit. The iron-reducing capacity method – FRAP (ferric reducing antioxidant power) was determined according to the methodology in Chiabrando and Giacalone (2015); the result was expressed in mM Fe^{2+}·(100 g)$^{-1}$ of fresh fruit. All analyses were performed in triplicate.

DETERMINATION OF THE MORPHOLOGICAL AND PHYSICAL CHARACTERISTICS OF BERRIES

Each experimental variant consisted of 15 individual fruits. For every fruit, diameter (d) and weight were measured with a precision of 0.01 mm and 0.001 g, respectively. Fruit density was calculated by dividing the fruit's mass by the volume of a sphere based on its measured diameter. Moisture content was assessed using the drying method specified in the PN-90/A-75101-03:1990 standard (Polski Komitet Normalizacyjny, 1990). The drying was carried out at 105°C using a laboratory balance (Radwag, Radom, Poland).

DETERMINATION OF THE MECHANICAL PROPERTIES OF FRUITS

The mechanical properties of the fruits were evaluated through a compression test conducted between two horizontal plates using the Brookfield CT3-1000 texture analyser (AMETEK Brookfield, Middleboro, MA, USA) along with TexturePro CT software. The initial tension force applied to the specimen was 0.05 N, with a compression speed of 0.2 mm·s^{-1}. Key parameters recorded after each test included the destructive force (F_D), absolute strain (λ), and destructive energy (E_D). Additionally, relative deformation (ϵ) was determined by calculating the ratio of absolute deformation (ΔL) to the fruit's diameter (d, mm) and expressed as a percentage. The apparent modulus of elasticity (E_C), representing the mechanical resistance of the material, was derived using a modified formula (Djordjević *et al*., 2010; Vakula *et al*., 2015).

$$E_C = \frac{E_D}{0.26 \cdot d^2 \ \cdot \lambda} \tag{1}$$

where: E_C = apparent modulus of elasticity; E_D = destructive energy (mJ); d = diameter of the fruit (mm); λ = fruit deformation in the load direction (mm).

STATISTICAL ANALYSIS

Statistical analysis was performed using the Statistica software, ver. 13.3 (TIBCO Software Inc., Tulsa, OK, USA). The evaluation included an analysis of variance (ANOVA), followed by the least significant difference (*LSD*) test to determine significant differences at the 0.05 significance level (α = 0.05).

RESULTS AND DISCUSSION

SUGAR CONTENTS OF ANALYSED FRUITS

In our experiment, the sugar content in *Vitis vinifera* L. fruit varies depending on the cultivar (Tab. 1). Glucose values range from 2.113 to 2.672 mg·(100 g)$^{-1}$, and fructose from 2.625 to 3.414 mg·(100 g)$^{-1}$. The sugar content results are comparable to the study of Mota *et al.* (2018), Bashir, Kaur and Arora (2018), where researchers determined sugar content in ripe fruits, the glucose value ranged 210.90–269.70 mg·g^{-1}, and the fructose 293.20–347.70 mg·g^{-1}. Based on the sugar content of individual varieties, it was determined that the fruits were fully ripe and could be subjected to chemical analysis.

Table 1. Sugar content in *Vitis vinifera* L. fruits during harvest

Cultivar	Alwood	'Barbera Bianca'	'Einset Seedless'	'Muskat Blanc'
Glucose (mg·(100 g)$^{-1}$)	2.672	2.485	2.305	2.113
Fructose (mg·(100 g)$^{-1}$)	3.414	3.085	2.846	2.625

Source: own study.

CHANGES IN pH AND ACIDITY IN RELATION TO STORAGE DATE AND OZONATION TIME

Table 2 show the effect of storage and ozonation times on changes in pH and acidity in grapes. The average pH values of the analysed *Vitis vinifera* varieties range from 3.49 to 3.77 (Tab. 2).

These results are comparable to those obtained by other authors. In the study of Fumagalli *et al.* (2019), the pH value in grapes ranged from 3.3 to 3.4. In study of Rolle *et al.* (2011), the pH value in grapes ranged from 2.89–3.33 depending on cultivar. The pH values obtained are comparable to those obtained in experiment Eshghi, Salehi and Karami (2014), the pH value of 35 cultivars of grape ranged from 3.2 to 4.2. In this study, light

Table 2. Changes in the pH of *Vitis vinifera* L. fruit depending on the cultivar, storage time, and ozone exposure time

Variable		pH	Titrable acidity (mg·(100 g)$^{-1}$)
Cultivar	'Alwood'	3.49a ±0.10	3.27b ±0.60
	'Barbera Bianca'	3.77c ±0.10	2.69a ±0.40
	'Einset Seedless'	3.65b ±0.20	3.29b ±0.90
	'Muscat Blanc'	3.77c ±0.20	2.82a ±0.60
Significant level		***	***
Storage time (day)	1	3.67b ±0.10	2.60a ±0.70
	8	3.72b ±0.20	3.43c ±0.20
	15	3.74b ±0.20	2.90ab ±0.50
	22	3.50a ±0.10	3.15bc ±0.60
Significant level		***	***
Ozone exposure time (min)	control	3.71a ±0.20	3.07a ±0.80
	5	3.62a ±0.20	3.02a ±0.80
	15	3.68a ±0.20	2.96a ±0.70
Significant level		ns	ns

Explanation: data are expressed as mean values (n = 3) ± *SD*; *SD* = standard deviation, *** = p < 0.001, ns = not significant; mean values with different letters are significantly different (p < 0.05).
Source: own study.

grapes of 'Barbera Bianca' and 'Muscat Blanc' varieties, had the same pH value of 3.77, which was significantly higher compared to the rest of the tested grape varieties, including dark varies of 'Alwood' and 'Einset Seedless'. Storing fruit for 4 weeks resulted in average drop of 5.6% in pH value, compared to fruit stored for a shorter period. In the study of Biesiada *et al.* (2011), long storage of pumpkins resulted in a drop of pH in some of varieties. There are no significant differences in the pH value depending on the ozone exposure time. A similar relationship to present study could be observed in the study of Kuźniar *et al.* (2022), where the fruits of red currant cultivars were characterized by different pH values depending on cultivar, storage time and ozone exposure time.

The average titratable acidity of *Vitis vinifera* varieties was ranging from 2.69 to 3.29 mg·(100 g)$^{-1}$ (Tab. 2). Results obtained in this study were comparable with study of Trendafilov and Almaliev (2016), titratable acidity was ranging from 3.80 to 7.57 mg·(100 g)$^{-1}$, depending on direction of growth, cultivar, and watering. After 4 weeks of storage of *Vitis vinifera* fruits, titratable acidity significantly increased by 34.4%. In study of Kuźniar *et al.* (2022), the acidity of red currant fruit increased depending on the length of storage and cultivar. There were no significant differences in the pH value depending on the ozone exposure time.

CONTENT OF BIOACTIVE COMPOUNDS IN BERRIES

Results obtained in this study were comparable with study of Boas *et al.* (2014), content of ascorbic acid in tested cultivars of grape was ranging from 32.43 to 130.00 mg·(100 g)$^{-1}$. In this study, significantly higher content of ascorbic acid (52.90 mg·(100 g)$^{-1}$) was found in the fruits of the 'Barbera Bianca' cultivar, 17.9% more compared to other varieties. Storage time and ozone exposure time did not significantly influence content of ascorbic acid in the analysed varieties. The use of ozone may result in an increase in the ascorbic acid content in fruit, thereby increasing its health-promoting value (Alexander *et al.*, 2012; Minas *et al.*, 2012; Ali *et al.*, 2014).

The average content of polyphenols in *Vitis vinifera* fruits was ranging from 44.70 to 128.90 mg·(100 g)$^{-1}$ (Tab. 3). Results obtained in this study were comparable with those obtained by Zeghad *et al.* (2019), total phenol content was dependent on cultivar, it was ranging from 75.41 to 147.51 mg·(100 g)$^{-1}$. The content of polyphenols was significantly different in *Vitis vinifera* cultivars, whereas 'Alwood' cultivar had on average 47.4% more polyphenols in comparison to other tested cultivars. After 4 weeks of storage average content of polyphenols was significantly lower. Fruits after 1 week of storage had on average 62.2% more total polyphenols. Exposure for gaseous ozone had significant impact on total polyphenols content. *Vitis vinifera* fruits exposed to ozonation had on average 27.2% higher total polyphenol content in comparison to un-treated fruits. The use of gaseous ozone had a positive effect on *Vitis vinifera* fruits, increasing the total content of phenolic compounds, thereby increasing the health-promoting value of the fruits. In the study of Fumagalli *et al.* (2019), the use of ozonation resulted in an increase in phenolic compounds in grapes.

The average DPPH and ABTS antioxidant activity in tested *Vitis vinifera* cultivars was: 37.85–43.89%, 2.72–3.46 mM TE·mg^{-1} respectively (Tab. 3). Results obtained in this study were comparable to the study of Boas *et al.* (2014), DPPH antioxidant activity of grape is 42–114%. In study of Yemis, Bakkalbasi and

Table 3. Content of ascorbic acid, total polyphenols and antioxidant activity of *Vitis vinifera* L. fruit depending on the cultivar, storage time, and ozone exposure time

Variable		Ascrobic acid (mg·(100 g)$^{-1}$)	Total polyphenols content (mg gallic acid·(100 g)$^{-1}$)	DPPH (% inhibition)	ABTS (mM TE·mg^{-1})
Cultivar	'Alwood'	40.71a ±0.04	128.90c ±0.50	40.63a ±0.60	3.46b ±0.70
	'Barbera Bianca'	52.90c ±0.05	77.60b ±0.50	37.85a ±0.60	2.71a ±0.20
	'Einset Seedless'	47.93b ±0.03	81.30b ±0.40	43.89b ±0.60	2.72a ±0.10
	'Muscat Blanc'	41.52a ±0.07	44.70a ±0.10	40.10a ±0.80	2.85a ±0.20
Significant level		***	***	***	***
Storage time (day)	1	46.01a ±0.04	119.02c ±0.60	43.3b ±0.70	2.84a ±0.20
	8	47.06a ±0.06	83.08b ±0.50	42.2b ±0.50	2.85a ±0.20
	15	45.12a ±0.07	86.12b ±0.50	41.5b ±0.50	2.88a ±0.20
	22	45.18a ±0.11	45.13a ±0.20	35.4a ±0.80	3.17b ±0.80
Significant level		ns	***	***	**
Ozone exposure time (min)	control	45.62a ±0.08	66.81a ±0.50	39.8a ±0.80	2.91a ±0.50
	5	44.59a ±0.08	89.10b ±0.50	39.4a ±0.80	2.94a ±0.50
	15	46.78a ±0.06	94.21b ±0.60	42.7a ±0.40	2.95a ±0.40
Significant level		ns	**	ns	ns

Explanations: DPPH = 2,2-diphenyl-1-picrylhydrazyl radical, ABTS = 2,2'-azino-bis-(3-ethylbenzothiazoline-6-sulfonic acid), ** = $p < 0.01$, *** = $p < 0.001$, ns = not significant; other information as in Tab. 2.
Source: own study.

Artik (2008), ABTS antioxidant activity *Vitis vinifera* ranged from 2.67 to 4.00 mM TE·mg^{-1}. In this research, a significant difference was observed in the DPPH antioxidant value of the tested varieties. Dark-coloured grapes had an average antioxidant value that was 7.8% higher compared to light-coloured fruits. A similar relationship can be observed in the case of the antioxidant value of ABTS. The average ABTS value in dark-coloured fruits was 10.1% compared to light-coloured fruits. After 4 weeks of storage, the DPPH and ABTS antioxidant activity was lower by 18.3% in comparison to 1 week storage. The inverse relationship can be observed in the case of ABTS antioxidant. After 4 weeks of storage, antioxidant level was higher by 11.2% when compared to one week storage. Ozone exposure did not significantly influenced DPPH and ABTS antioxidant activity. The results obtained in the experiment indicate a greater health-promoting value of dark-coloured fruits of 'Alwood' and 'Einset Seedless' cultivars, which were characterized by a greater antioxidant value and total content of phenolic compounds. Long storage of *Vitis vinifera* fruit led to a decrease in the antioxidant value of DPPH and the total content of phenolic compounds. In the study of Admane *et al.* (2018), the use of gaseous ozone increased the ABTS antioxidant value of grapes during cold storage. This indicates a different response depending on the tested variables and ozone concentration.

MECHANICAL PROPERTIES OF FRUITS

Table 4 show 'Barbera Bianca' cultivar also had the highest deformation of 7.04%, and the highest conventional modulus of elasticity of 59.65·10^{-3} MPa. The fruits of the 'Muscat Blanc' cultivar are the most vulnerable to damage. The destruction of these fruits occurred at a force and energy of 3.45 N and 11.29 mJ, respectively. The use of ozonation did not significantly affect the value of destructive force and energy. The deformation of the tested fruits decreased after the application of gaseous ozone. The conventional modulus of elasticity did not increase significantly as a result of the application of gaseous ozone. During 22 days of storage, the value of the destructive force of the tested fruits increased significantly. The deformation and energy decreased between 1 and 8 days of storage. The tested parameters increased and reached the highest values on the 22 day of storage. The value of the conventional modulus of elasticity increased until the 15 day of storage of the tested fruits. In the study of Zapałowska *et al.* (2021), the value of destructive force and energy level decreased during storage of both ozonated and non-ozonated sea buckthorn fruits. In the study of Horvitz and Cantalejo (2012), the hardness of non-ozonated peppers was lower after 14 days of storage compared to ozonated peppers. In the study of Gorzelany *et al.* (2017), regardless of the cultivar and its purpose, ozonated cucumbers showed better mechanical properties compared to the control samples.

MORPHOLOGICAL FEATURES AND MOISTURE CONTENT OF FRUITS

Detailed values of morphological features, density, and moisture of four grapevine varieties exposed to different ozonation and storage times are presented in Table 5.

The fruits of the studied cultivars differed in morphological features. The fruits of the 'Alwood' cultivar were the longest (20.9 mm), whereas the 'Barbera Bianca' cultivar fruits the shortest (16.7 mm). Fruits differed by diameter, with the 'Alwood' cultivar having the largest diameter (22.5 mm), while the 'Muscat Blanc' cultivar the smallest (14.2 mm). The weight also differed significantly between the studied fruits. The lowest weight of 1.96 mg was recorded for the 'Muscat Blanc' cultivar, and the highest 6.41 mg for the 'Alwood' cultivar. Another parameter which differed significantly between the fruits was their density. The lowest density (1.06·10^{-3} kg·m^{-3}) was noted for the 'Alwood' cultivar, and the highest (1.29·10^{-3} kg·m^{-3}) for the 'Muscat Blanc'

Table 4. Effect of grape cultivar, storage time, and ozone exposure time on the mechanical response of *Vitis vinifera* fruit

Variable		Destruction force (N)	Relative deformation (%)	Destruction energy (mJ)	Apparent modulus of elasticity (·10^{-3} MPa)
Cultivar	'Alwood'	3.89a ±1.03	4.80a ±1.32	13.87b ±4.07	26.70a ±8.02
	'Barbera Bianca'	8.55c ±2.93	7.04d ±0.94	30.44d ±9.68	59.65d ±17.94
	'Einset Seedless'	5.67b ±1.25	5.57c ±0.71	21.51c ±4.17	38.90c ±6.85
	'Muscat Blanc'	3.45a ±0.74	5.28b ±0.70	11.29a ±2.53	34.12b ±7.60
Significant level		***	***	***	***
Storage time (days)	1	5.09a ±2.16	5.54a ±1.33	18.95a ±9.03	37.64 ±13.03
	8	5.29ab ±2.91	5.48a ±1.35	18.84a ±10.45	40.20 ±18.19
	15	5.71bc ±2.71	5.67a ±1.13	20.15ab ±9.81	43.41 ±18.37
	22	6.14c ±2.78	6.24b ±1.21	21.79b ±8.04	39.47 ±16.98
Significant level		***	*	**	ns
Ozone exposure time (min)	0	5.79 ±2.95	5.93b ±1.31	20.67 ±10.31	39.54 ±17.78
	15	5.19 ±2.57	5.46a ±1.19	19.00 ±9.38	40.78 ±17.83
	30	5.58 ±2.44	5.71ab ±1.33	19.75 ±8.71	40.36 ±14.85
Significant level		ns	*	ns	ns
Mean		5.52 ±2.67	5.70 ±1.29	19.81 ±9.49	40.23 ±16.85

Explanations: data are expressed as mean values (n = 15) ± standard deviation, * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$, ns = not significant; mean values within columns with different letters are significantly different ($p < 0.05$).
Source: own study.

Table 5. Influence of grape cultivar, storage period, and gaseous ozone treatment on the morphology and moisture level of *Vitis vinifera* fruits

Variables		Length (mm)	Diameter (mm)	Weight (mg)	Density ($\cdot 10^{-3}$ kg$\cdot$m^{-3})	Moisture content (%)
Cultivar	'Alwood'	20.9d ±1.50	22.5d ±1.60	6.41d ±1.50	1.06a ±0.11	66.5a ±4.90
	'Barbera Bianca'	16.7b ±1.00	15.6b ±1.00	2.54b ±0.44	1.27c ±0.09	85.0c ±4.20
	'Einset Seedless'	19.6c ±1.00	19.0c ±1.10	4.23c ±0.59	1.18b ±0.07	76.2b ±6.40
	'Muscat Blanc'	15.6a ±0.80	14.2a ±0.70	1.96a ±0.29	1.29c ±0.08	88.9d ±1.10
Significant level		***	***	***	***	***
Storage period (days)	1	18.6b ±2.50	18.2a ±3.40	3.99a ±1.96	1.19a ±0.13	84.0d ±6.80
	8	18.1ab ±2.30	17.9a ±3.40	3.76a ±1.86	1.18a ±0.12	80.5c ±9.20
	15	17.9a ±2.30	17.7a ±3.50	3.65a ±1.80	1.20a ±0.13	77.8b ±9.10
	22	18.9b ±2.30	18.7a ±3.30	4.32a ±2.09	1.19a ±0.13	69.3a ±8.10
Significant level		**	ns	ns	ns	***
Ozone exposure time (min)	0	18.5a ±2.50	18.2a ±3.40	3.97a ±1.85	1.19a ±0.12	78.1a ±10.70
	15	18.3a ±2.70	18.0a ±3.80	3.99a ±2.31	1.20a ±0.14	78.1a ±10.30
	30	18.3a ±2.00	18.0a ±3.00	3.75a ±1.55	1.18a ±0.12	79.2a ±8.10
Significant level		ns	ns	ns	ns	ns
Mean		18.4 ±2.40	18.1 ±3.40	3.90 ±1.93	1.19 ±0.13	78.5 ±9.80

Explanations: data are expressed as mean values (n = 10) ± standard deviation; ** = $p < 0.01$, *** = $p < 0.001$, ns = not significant; mean values within columns with different letters are significantly different ($p < 0.05$).
Source: own study.

cultivar. The water content was significantly varied. The lowest water content was found in the 'Alwood' cultivar (66.5%), while the highest in the 'Muscat Blanc' cultivar (88.9%). Ozonation time did not significantly affect the water content in the fruits of the analysed varieties, while storage time significantly affected the water content. There was no significant effect of ozonation time and storage on the morphological features and density of the fruits. Storage time significantly affected length and moisture content. Storage time did not significantly affect diameter, weight, and density. The length and diameter of grapevine fruit depend on their water content. As water content in grapevine fruit decreased, the parameters studied decreased as well. At the moisture level of 71%, the average fruit length was 16.56 mm (Mezzatesta *et al.*, 2022). According to previous studies, the average water content in grapevine fruit was 81% (Khodaei and Samimi-Akhijahani, 2012).

CONCLUSIONS

The study demonstrated that the application of gaseous ozone had a selective and measurable effect on the physicochemical properties and health-promoting potential of *Vitis vinifera L.* fruits. Although ozone treatment did not significantly affect pH, ascorbic acid content, or antioxidant activity (DPPH, ABTS), it notably influenced total polyphenol content. Fruits exposed to ozonation showed, on average, a 27.2% increase in total polyphenols compared to untreated fruits, with values ranging from 66.81 to 94.21 mg$\cdot$(100 g)$^{-1}$ depending on the exposure time. In terms of mechanical properties, ozonation slightly reduced fruit deformation (from 5.93 to 5.46%) and did not significantly affect destructive force or energy, suggesting a potential improvement in fruit firmness and resistance to mechanical damage. The apparent modulus of elasticity also remained stable across all treatments, indicating that the structural integrity of fruit tissues was preserved. Regarding morphological traits, ozone treatment did not significantly influence fruit length, diameter, weight, density, or water content, confirming its safety in preserving external fruit characteristics. However, storage time had a significant impact on several parameters, including a reduction in water content (from 84.0 to 69.3%) and a decline in total polyphenols over 22 days. Overall, ozonation proved to be a promising method for enhancing the bioactive potential of grape fruits by increasing polyphenol content, with no detrimental effects on fruit morphology or basic quality traits.

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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