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ORIGINAL ARTICLE

The Effectiveness of Ozone Technology Application in Extending the Shelf Life of Berry Fruit

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Abstract
This study investigates the effectiveness of ozone technology in extending the shelf life of soft fruits, focussing on blueberries, raspberries and strawberries. We evaluate the effects of ozone application on reducing post-harvest fungal rots and extending storage time, considering variations in ozone concentration and exposure time. Fruit coming directly from the field is subjected to ozone treatment without surface sterilisation, allowing monitoring of naturally occurring yeasts and moulds. The results show consistent positive effects for all fruit species, with a significant reduction in fruit decay observed in the ozone-treated groups compared to the controls. For blueberries, raspberries, and strawberries, ozone exposure ranging from 0.7 to 4.3 mg/kg was effective in controlling decay, with the 20-minute ozone treatment showing the most favorable outcomes. The study observed that the longer ozone treatments resulted in reduced pathogen presence. This study highlights the growing importance of ozone technology in post-harvest management, offering a promising strategy for reducing food waste and improving food safety in the agricultural sector.

Keywords Blueberries · Raspberries · Strawberries · Diseases · Ozone · Post-harvest · Preservation

Research Highlights

1. Ozone technology extends the shelf life of soft fruits and offers practical solutions for post-harvest preservation.
2. Our study evaluates the optimal ozone concentrations and exposure times to minimise post-harvest fruit decay and maximise the benefits of preservation.

Introduction

In recent years, there has been a significant global increase in demand for berries among various crops, with particularly notable demand for strawberries, raspberries, blueberries, and cranberries (Brennan et al. 2014). This growth is partly due to recognized health benefits associated with the consumption of berries, as well as changes in agronomic practices that have expanded the availability and distribution of these crops (Brennan et al. 2014). As a result, berries are now accessible for a larger part of the year in many countries, thanks to the extension of the growing season through improved agronomic strategies and imports outside the main domestic growing season. The berry industry holds significant economic value globally, in the United States, and in Europe. Globally, the berries and grapes mar-

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ket was valued at approximately USD 233.69 billion in 2023, with projections indicating growth at a compound annual growth rate (CAGR) of 5.5%, reaching nearly USD 378.63 billion by 2032. Specifically focusing on berries, the global market was estimated at USD 38.42 billion in 2023 and is expected to grow to USD 67.03 billion by 2032, reflecting a CAGR of around 6.38% (Market Research Future 2023). In the United States, strawberries and blueberries are among the most economically significant fruits. In 2020, strawberries generated over $ 2 billion in annual farm gate sales, accounting for 13% of the total production value of fruits, ranking third among all fruits produced in the country. Blueberries contributed 5% of the total fruit production value during the same period (Yeh et al. 2023). The U.S. blueberry market alone was valued at USD 3.5 billion in 2024, with projections to reach USD 4.70 billion by 2029, growing at a CAGR of 5.30%. Additionally, the blueberry industry supports the U.S. economy by creating and sustaining over 44,535 full-time equivalent jobs annually and generating a total economic impact of $ 4.7 billion (USHBC 2024). In Europe, the berry industry has experienced growth over the past decade, establishing itself as one of the most valuable sectors in the fresh produce market. In 2015, the United Kingdom led European berry sales, achieving £ 1.1 billion during the summer season, with berry sales increasing by 132% over ten years. Similarly, red berry sales across Europe doubled in both volume and value during this period, driven by rising consumer demand for healthy and locally produced fruits (International Blueberry Organization 2016). Analysts forecast continued expansion in the European berry market, supported by investments in advanced technologies and local production efforts (East-Fruit 2023). Given the high value of berry crops, their production and marketing can significantly contribute to rural economies (Brennan et al. 2014; Di Vittori et al. 2018).

Berries are classified as some of the least durable fruits due to their delicate structure and thin skin, making them susceptible to damage during harvesting and transportation (Jatoi et al. 2017). Additionally, berries typically contain a high percentage of water, rendering them prone to quicker spoilage and the development of diseases. The quality and nutritional value of fruit decrease during storage due to the high sensitivity of fruit to environmental conditions (Bower 2007). Compared to other types of fruits, berries and small fruits have a very short shelf life after harvesting. Therefore, to ensure the highest level of quality and freshness of the fruit after harvesting, careful handling during the stages of harvesting, transportation, and packaging is necessary (Jatoi et al. 2017). To preserve the quality of fruit during storage, it is necessary to slow down respiration and ethylene production, which plays a significant role in fruit aging and ripening. Although respiration and ripening cannot be completely halted, suitable storage procedures can significantly slow them down (Bičak 2014). After harvesting and packaging, common practice involves rapidly cooling the fruit at the producer's site. For example, strawberries may be available for sale just a few days after being picked, while apples, with proper storage, can be preserved for up to six months (Bičak 2014; Moslavac 2021).

The main types of berries cultivated in Croatia include strawberries, raspberries and blueberries. Strawberries are particularly susceptible to infections caused by various phytopathogenic fungi, bacteria, and viruses (Pan et al. 2014). Among the main pathogens affecting strawberries are *Botrytis cinerea*, the causal agent of grey mould, *Rhizopus stolonifer, Colletotrichum* spp. and other fungi, affecting fruits in a specific manner (Feliziani and Romanazzi 2016). The main diseases affecting blueberry fruits postharvest are *Botrytis cinerea*, causing grey mould, and *Alternaria* spp. causing fruit rot. Additionally, cases have been recorded where blueberries are attacked by the fungus *Penicillium chrysogenum* (Umagiliyage et al. 2017), *Fusarium oxysporum*, but also contaminated by bacteria such as *Escherichia coli, Listeria monocytogenes*, and *Salmonella typhimurium* (Liato et al. 2017). In raspberries, as with most berry fruits, one of the significant diseases is grey mould (*Botrytis cinerea*). Grey mould in storage can occur as a result of fruit infection post-harvest, during the storage period (Mitcham and Mitchell 2002).

It is evident that *B. cinerea* is the most important cause of disease of berries especially after harvesting until the moment of putting on the market. *Botrytis cinerea* is a typical necrotroph that first destroys plant cells and then colonizes dead tissue. It is characterized by the production of pectolytic and other enzymes that effectively break down host tissue during colonization. Additionally, *Botrytis cinerea* easily spreads from infected to adjacent healthy fruits. The optimal temperature for the growth of this fungus is 20 °C, with a maximum of 30 °C and a minimum of –2 °C, making *B. cinerea* a significant post-harvest pathogen even in modern storage conditions (Mitcham and Mitchell 2002; Droby and Lichter 2007).

Preserving the quality of products and extending their shelf life are key elements in fruit production. Given the limited options and challenges in pest control, it becomes imperative to implement new strategies and measures (Xu 1999). Recently, ozone has been applied in agriculture with potential uses such as reducing odours in poultry farming, eliminating odours from pig manure, and reducing pathogens in the storage of grapes, potatoes, and onions (Işikber and Öztekin 2009). Previous studies suggest the effectiveness of ozone against fungal infections while simultaneously extending the shelf life through surface disinfection of food (Işikber and Öztekin 2009; Lemic et al. 2024). The efficacy of ozone application depends on various factors, including the microbial population, exposure time to ozone, concentration, type of treated product, and relative humidity (Brodowska et al. 2018). Since ozone can be easily generated on-site using only electrical energy and air, it offers several safety advantages compared to chemical pesticides. First, there is no need for storage of toxic chemicals, and there is no risk of residual pesticides from chemical mixing or disposal, in addition to no packaging waste being produced (Law and Kiss 1991). Second, due to its short half-life, ozone reverts to naturally occurring oxygen, leaving no residue on the product. Third, if necessary, ozone can be neutralized by thermally activated carbon as well as by catalytic reduction of emissions (Law and Kiss 1991). In June 2001, the application of ozone was approved by the United States Food and Drug Administration (US FDA) as an "antimicrobial agent for the treatment, storage, and processing of food in gaseous and aqueous phases". It was also endorsed by the United States Department of Agriculture (USDA) for the processing of organic food (Pureox Gaseous), gaining recognition in the food industry. Ozone, defined as a highly reactive and potent oxidizing agent, was classified as Generally Recognized as Safe (GRAS) by the United States Environmental Protection Agency (US EPA) in 1982 (Pureox Gaseous). Efforts are being made to find more acceptable methods of fruit storage that consider the physiological and biochemical characteristics of individual fruit species to preserve better quality (Moslavac 2021). Several treatments, such as controlled temperature and atmosphere, heat treatment, ozone treatment, have been shown to be effective in maintaining fruit quality during storage (Panou et al. 2021).

The aim of our research is to evaluate the efficacy of ozone technology in extending the shelf life of berry fruits, with a focus on blueberries, raspberries, and strawberries.

Materials and Methods

The research was conducted from May to September 2023 at the Entomological Laboratory of the University in Zagreb Faculty of Agriculture. The controlled temperature in the growing chambers was 10 °C, and the humidity was 90% throughout the study period.

Freshly harvested strawberries (15th May), blueberries (19th June), and raspberries (20th August) from "Ekoberry" company (Velika Ludina, Croatia) were used for the study. The fruits were not treated or cooled before the experiment. The fruits were transported to the Laboratory in temperature-controlled containers to maintain their freshness and minimize environmental exposure during transit. To prevent mechanical damage, the fruits were placed in padded trays and carefully packed to avoid contact between individual fruits.

Ozonation

In the experimental procedure, the iOzone+ model MF 108 generator was utilized for ozonation. This device employs an electric charge to transform oxygen molecules (O_2) from the air into ozone (O_3). The concentration of ozone at the output was 400 mg/h. The ozone output could not be changed, and the time of exposure to ozone also defined the amount of ozone used as the test variable. Considering the test parameters, we started the study to determine the ozone production per hour and then determine the ozone concentration in mg/kg in the storage chamber. The treatments in the experiment were as follows: 10 min: 67 mg O_3 (0.7 ppm); 20 min: 133 mg O_3 (1.4 ppm); 30 min: 200 mg O_3 (2.2 ppm); 60 min: 400 mg O_3 (4.3 ppm); control (without O_3).

The ozone treatment was performed in a specially designed plastic chamber with a volume of 10,965 cm^3. An opening was made at the chamber's bottom, through which an ozone tube was inserted to introduce ozone into the experimental chamber.

Berry Fruits in the Experiment

Before the experiment all fruits were carefully sorted to remove damaged or overripe fruit. In the experiment with strawberries, 200 fruits of 'Joly' variety were used. For the experiment, strawberries were arranged in 20 plastic containers, each container containing 10 fruits, a total of 40 fruits per treatment. In the experiment, a total of 520 raspberries of 'Enrosadira' variety were used. Raspberry fruits were arranged in 20 plastic containers, each container (replication) containing 26 fruits. A total of 2000 g (2 kg) of fresh blueberries of 'Duke' variety were used for the experiment. Also, the blueberry fruits were divided into 20 plastic bowls (replication), where each one contained 100 g of blueberries. Each treatment was set up in four replicates.

The containers in which the fruits were placed did not have a lid so that the ozone could circulate freely between the fruits. After the end of the ozonation process, the ozonated variants were stored in a separate chamber from the control to prevent contamination by potential spores and other pests.

Readings and Analysis

The measurements were carried out two times for strawberries and raspberries (5 and 10 days after treatment) and three times for blueberries (20, 25, and 30 days after the experiment). Each individual fruit was analysed and the presence of infection with diseases was determined. Readings were carried out by visually inspecting the fruits without unnecessary movement. When handling was required, such as to ensure clear visibility of all fruits in the container, it was done gently and with sanitized gloves to prevent contamination or mechanical damage.

Strawberries and raspberries were first classified according to the degree of damage of 8%, 28%, 46%, 77%, 82 and 100% according to Filippi et al. (2021). In the case of blueberries, the number of infected and healthy fruits was determined in each reading period.

After the last reading, the samples were microscopically analysed for the presence of moulds and yeasts on fruits. Identification of moulds was carried out by examination of their mycelium, conidia and other relevant morphological structures, following descriptions of Ellis and Waller (1974), Smith and Black (1990), Leslie and Summerell (2006) and Simmons (2007). The incidence of particular moulds and yeasts was determined for each replicate, treatment and fruit species.

The percentage of infected fruit (disease incidence: %) per treatment to determine the effect of ozone on disease development at different exposure times was subjected to an analysis of variance ANOVA (ARM 2023.6 GDM software), with the mean distance estimated using the Duncan Multiple Range Test (MRT). The MRT was employed to identify statistically significant differences between treatment means, allowing for a clear comparison of how different ozone exposure times influenced disease incidence.

Table 1 Infected blueberry fruits (% ± SE) after ozone treatments

	Damage fruits (%)			
Treatment	*Duration of Ozonation (min)*	*Reading 1*	*Reading 2*	*Reading 3*
Control	No ozone	16.7 ± 4.1 a	33.7 ± 6.8 a	80.3 ± 8.5 a
Ozone	10	12.6 ± 3.8 ab	19.0 ± 5.2 b	27.8 ± 6.3 bc
	20	9.3 ± 1.0 b	13.2 ± 1.4 b	21.4 ± 4.2 c
	30	9.9 ± 1.1 b	18.7 ± 5.3 b	24.5 ± 6.3 c
	60	9.7 ± 2.5 b	26.6 ± 8.3 ab	39.7 ± 8.2 b
LSD P = 0.05		5.8	13.6	12.7
Standard Deviation		4.6	10.8	10.1
CV		39.9	48.7	26.1
Treatment F		1.7	2.1	23.1
Tratment Prob (F)		0.199	0.133	0.0001

Treatments sharing the same letter (e.g., "a", "b") are not significantly different at $P = 0.05$

LSD Least Significant Difference, *CV* Coefficient of Variation

Treatment F and Prob(F) represent the F-value and associated probability from ANOVA

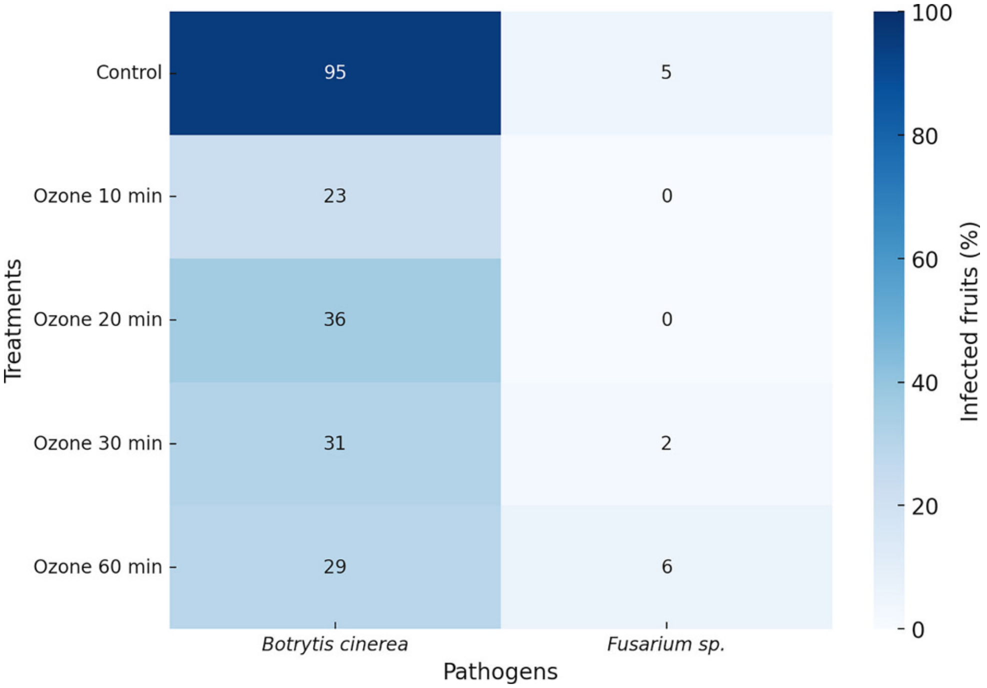

Fig. 1 The presence of pathogens on blueberry fruits at the end of experiment

Results

Blueberries

Table 1 shown the percentage of fruit decay observed in blueberries throughout the study period. At the first measurement (20 days after ozone application), the control group exhibited the highest fruit decay (17%), while the 10-minute ozone treatment showed a slightly lower but comparable level of decay (12%). The 20-, 30-, and 60-minute ozone treatments demonstrated lower decay percentages, ranging between 9.3 and 9.9%, with no significant differences among these treatments.

At the second measurement (25 days after ozonation), fruit decay levels increased, with the control again showing the highest decay percentage (34%). Among the ozone treatments, the 60-minute exposure showed the next highest decay level (27%), while the 20-minute treatment had the lowest decay (13%). The 10- and 30-minute treatments exhibited intermediate decay levels, which were statistically similar to the 20-minute treatment.

By the third measurement (30 days after ozonation), decay levels had further increased. The control group exhibited the most severe fruit decay, exceeding 80%, while the 20- and 30-minute ozone treatments showed significantly lower decay levels of 21 and 25%, respectively. In contrast, the 60-minute ozone treatment displayed a higher decay level (40%) than the shorter treatments, suggesting that prolonged ozone exposure may have negatively impacted fruit preservation.

Table 2 Infected raspberry fruits (% ± SE) after ozone treatments

	Damage fruits (%)		
Treatment	*Duration of Ozonation (min)*	*Reading 1*	*Reading 2*
Control	No ozone	67.2 ± 1.9 a	100.0 ± 0.0 ns
Ozone	10	55.0 ± 2.1 bc	98.9 ± 0.6 ns
	20	53.1 ± 0.9 c	98.4 ± 0.9 ns
	30	57.9 ± 2.5 bc	98.1 ± 0.8 ns
	60	62.1 ± 2.5 ab	99.1 ± 0.5 ns
LSD P = 0.05		7.1	1.8
Standard Deviation		4.6	1.1
CV		7.8	1.2
Treatment F		5.9	1.5
Tratment Prob (F)		0.007	0.250

Treatments sharing the same letter (e.g., “a”, “b”) are not significantly different at $P = 0.05$
LSD Least Significant Difference, *CV* Coefficient of Variation
Treatment F and Prob(F) represent the F-value and associated probability from ANOVA

Figure 1 highlighted the detection of the fungus *Botrytis cinerea* across all treatments. The control group showed the highest incidence of *B. cinerea* infections (95%), along with a small presence of *Fusarium* sp. (5%). Among the ozone-treated groups, *B. cinerea* infections ranged from 23 to 36%. Notably, the 30- and 60-minute ozone treatments exhibited a reduced incidence of *Fusarium* sp., ranging from 1 to 6%.

Raspberries

Table 2 summarized the percentage of decay observed in raspberries throughout the study period. At the first measurement (5 days after ozone application), the control group exhibited the highest decay level (67%), which was not significantly different from the 60-minute ozone treatment (62% decay). The other ozone treatments (10, 20, and 30 min) showed lower decay percentages, ranging from 55 to 57.9%, with no significant differences among them. Notably, significant differences were observed between the control and the 20-minute treatment (53%) and between the 60-minute treatment and the 20-minute treatment.

At the second measurement (10 days after ozonation), the control group showed complete decay (100%), while the ozone-treated groups had slightly lower decay levels, ranging from 98.1 to 99.1%, with no significant differences among the treatments.

Figure 2 illustrated the presence of pathogens in the treatments. The fungus *Botrytis cinerea* was detected in 100% of the fruit across all treatments. The pathogenic fungus *Fusarium* sp. was found in the control and in the 10-, 20-, and 30-minute treatments but was absent in the 60-minute treatment. Among the treatments, the 20-minute ozone exposure had the highest incidence of *Fusarium* sp. (31%), while the other treatments ranged between 8 and 27%. Similarly, the fungus *Rhizopus* sp. was detected in all treatments, with the 20-minute treatment showing the highest incidence (69%).

Yeasts were present in all treatments, with the control group showing yeast infections in 38% of the fruit. In the ozone-treated groups, yeast incidence ranged from 8 to 15%. Additionally, a lower percentage of fruit (8 to 19%) was infected with the fungus *Alternaria* sp. in the control group and in the 30- and 60-minute ozone treatments.

Strawberries

Table 3 summarized the percentage of decay observed in strawberries throughout the study. At the first measurement (5 days after ozone application), the control group exhibited the highest decay level (68%), which was not significantly different from the 60-minute ozone treatment (65%

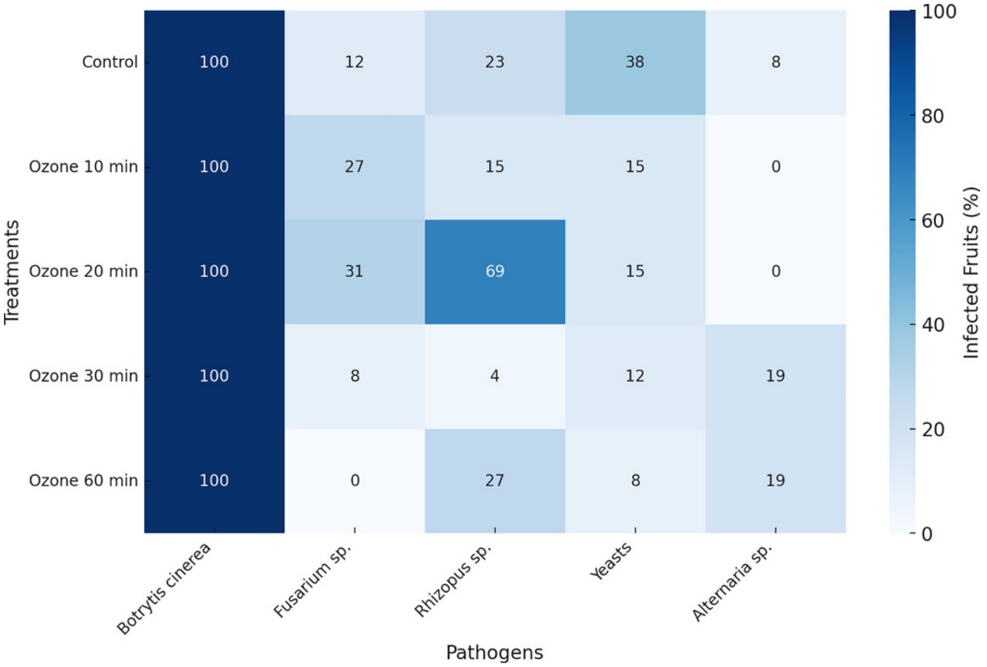

Fig. 2 The presence of pathogens on raspberries fruits at the end of experiment

Table 3 Infected strawberry fruits (% ± SE) after ozone treatments

	Damage fruits (%)		
Treatment	*Duration of Ozonation (min)*	*Reading 1*	*Reading 2*
Control	No ozone	67.5 ± 2,5 a	85.8 ± 0.4 a
Ozone	10	43.3 ± 2,8 b	71.6 ± 3.6 b
	20	49.6 ± 4.1 b	73.7 ± 2.2 ab
	30	48.3 ± 4.4 b	75.0 ± 6.3 ab
	60	65.0 ± 5.0 a	81.7 ± 5.4 ab
LSD P = 0.05		9.7	11.6
Standard Deviation		7.7	9.2
CV		14.1	11.8
Treatment F		7.7	1.6
Tratment Prob (F)		0.0025	0.223

Treatments sharing the same letter (e.g., "a", "b") are not significantly different at $P = 0.05$

LSD Least Significant Difference, *CV* Coefficient of Variation

Treatment F and Prob(F) represent the F-value and associated probability from ANOVA

decay). The other treatments (10, 20, and 30 min) showed significantly less decay, ranging from 43.3 to 49.6%, although there were no significant differences among these treatments.

At the second measurement (10 days after ozonation), the control group again showed the highest decay level (86%). The 20-, 30-, and 60-minute treatments exhibited slightly lower decay percentages, ranging from 73.7 to 81.7%, but these differences were not significant compared to the control. The 10-minute ozone treatment showed the lowest decay level (71.6%) and was significantly different from the control, although no significant differences were observed between the 10-minute treatment and the other ozone treatments.

Figure 3 illustrated the presence of pathogens across the treatments. In the 10-, 20-, and 30-minute ozone treatments, *B. cinerea* was detected in 100% of the fruit. In the control and the 60-minute treatment, *B. cinerea* was detected in 88% of the fruit. Additionally, the fungus *Colletotrichum* sp. was detected in the 60-minute ozone treatment.

Discussion

The aim of this study was to evaluate the effectiveness of ozone technology in extending the shelf life of different soft fruit species, a topic of increasing interest in the context of EU legislation, particularly the European Green Deal and the Farm to Fork Strategy. These initiatives emphasize sustainable agricultural practices, reducing food waste, and minimizing chemical use in food production (European Commission 2022). By demonstrating ozone's effectiveness as a non-chemical alternative for post-harvest preservation, our research supports the development of science-based guidelines and risk assessments by European institutions, such as the European Food Safety Authority (EFSA) (European Food Safety Authority 2021).

The results indicate that ozone treatment positively impacts all three types of berries studied, reducing post-har-

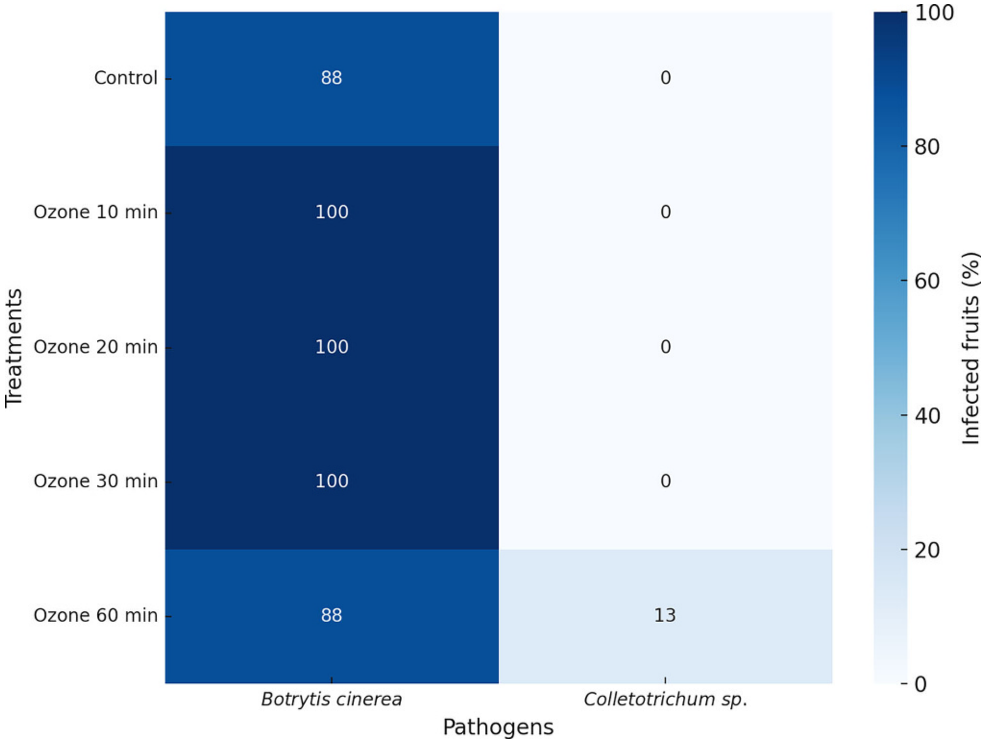

Fig. 3 The presence of pathogens on strawberry fruit at the end of experiment

vest rot and extending the storage period. Ozone concentrations ranged from 0.7 to 4.3 mg/kg, with consistently positive effects across fruit species. In blueberries, the control group consistently exhibited the highest decay rates (17–80%), whereas the 20-minute ozone treatment achieved the lowest decay levels. In raspberries, the 20-minute ozone treatment similarly was the most effective in reducing decay (67–100%) compared to the control. For strawberries, the control group showed the highest decay (68–86%), while the 10-minute ozone treatment yielded consistent results with decay ranging from 43 to 71%. These findings highlight the positive influence of ozone across all fruit species. Due to their firmer skin and protective wax layer, blueberries exhibited a naturally longer shelf life compared to raspberries and strawberries. In blueberries, differences between ozone treatments and the control were minimal at first, but differences became apparent after 20 days. The presence of yeasts and moulds, which naturally occur on the fruit, contributed to post-harvest decay. The ozone treatments successfully reduced fungal infection rates, including for common pathogens like *B. cinerea* and *Alternaria* spp., with particularly effective results for ozone treatments of 20 min or longer.

Our results are consistent with previous studies, such as those by Concha-Meyer et al. (2015) and Beuchat and Brackett (1990), which observed lower fungal populations at higher ozone concentrations. In strawberries, a 10-minute ozone treatment at 0.7 mg/kg achieved the best results, underscoring the delicate balance between ozone concentration and fruit quality. Studies by Aday et al. (2014), Chen et al. (2019) and Panou et al. (2021) confirm our findings and emphasise the importance of lower ozone concentrations for maintaining fruit firmness and overall quality. Moreover, ozone's ability to suppress enzyme activity, preventing fruit texture degradation, was also demonstrated in cyclic ozonation processes (Piechowiak et al. 2022). For raspberries, the optimal treatment of 20 min at 1.4 mg/kg resulted in the least damage, a result aligned with Onopiuk et al. (2017) who observed microbial inactivation and slowed respiration under ozone treatment.

The considerable variation in initial yeast and mould inoculum can greatly affect fruit quality throughout the year, as these pathogens are influenced by weather patterns, harvest conditions, and fruit moisture content. Berry fruits, which lack a natural protective wax layer due to unfavorable weather conditions or suboptimal harvesting methods, are particularly susceptible to yeast and mould proliferation. During storage, soft fruits are particularly vulnerable to phytopathogenic fungi, especially *B. cinerea*, the causative agent of grey mould, which occurs in all three types of berries examined. In addition, *Alternaria* spp., *Fusarium* spp., and *Rhizopus* spp. were detected in our fruit samples. The presence of yeasts during fruit storage is another quality concern that warrants careful monitoring and management. Several studies have investigated the use of ozone as an effective treatment for controlling postharvest pathogens in different type of fruits. In a study by Palou et al. (2003), ozone treatments were shown to significantly reduce the incidence of pathogens in citrus fruits. Ozone concentrations of 0.3 ppm were effective in slowing down mould development, though it did not fully prevent infection. Similarly, Smilanick et al. (1999) demonstrated that ozone could effectively kill up to 100% of *B. cinerea* spores in citrus when applied for 1–3 min at 1.5 ppm, highlighting ozone's potential as a quick and effective pathogen control method. Lemic et al. (2024) investigates the use of ozone as an alternative method for controlling post-harvest decay in mandarins, specifically targeting *Penicillium italicum* (blue mold). They tested various ozone treatments, including gaseous ozone and ozonated water, with concentrations ranging from 2 to 20 ppm and exposure times from 10 to 60 min. The results revealed that ozone treatments significantly reduced mould growth, with gaseous ozone achieving efficacy rates up to 97.5% and ozonated water preserving fruit between 95 and 97%.

Skog and Chu (2001) investigated the potential of ozone at a concentration of 0.04 mL/L for extending the storage life of broccoli and seedless cucumbers stored at 3 °C. They found minimal effects on mushrooms stored at 4 °C and cucumbers at 10 °C. The use of ozone at this concentration significantly reduced ethylene levels in vegetable storage rooms, from 1.5–2 mL/L (produced by apples) to undetectable levels. At higher concentrations of 0.4 mL/L, ozone was also effective in removing ethylene from apple and pear storage rooms, with no observed differences in fruit quality between ozonized and non-ozonized apples and pears.

Ozone also offers a significant advantage in reducing pesticide residues on fruits. Research by Metzger et al. (2007) showed that ozone exposure helped degrade pesticides like imazalil, malathion, and chlorpyrifos, highlighting ozone's potential as a pesticide substitute. Furthermore, Karaca and Velioglu (2007) found that ozone treatments can reduce pesticide and toxin residues along with fungal and bacterial contamination, supporting ozone's role in integrated pest management.

While ozone does not completely eliminate all pathogens, it significantly reduces their incidence, offering a sustainable and non-chemical alternative to traditional fungicides. This is especially important in the context of the European Green Deal and the Farm to Fork Strategy, which emphasize reducing the use of chemical treatments and minimizing food waste (European Commission 2022). The integration of ozone into post-harvest handling protocols could therefore contribute to the development of more sustainable and effective fruit preservation strategies.

Conclusions

This study demonstrates the effectiveness of ozone technology in extending the shelf life of soft fruits. By systematically evaluating the application of ozone to blueberries, raspberries and strawberries, we consistently observed positive effects in reducing post-harvest rots and extending shelf life. The results underline the importance of carefully balancing ozone concentration and exposure time to minimise fruit damage while maximising the benefits of preservation. This research contributes to the further development of post-harvest technologies aimed at improving food safety and reducing food waste in the agricultural industry.

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Author Contribution DL: Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Writing—original draft, Writing—review & editing, Supervision. BZ: Data curation, Methodology, Investigation, Writing—original draft. AN: Conceptualization, Methodology, Data curation. DI: Methodology, Investigation, Writing—original draft. MAG: Formal analysis, Writing—original draft, Writing—review & editing. HVG: Conceptualization, Methodology, Writing—original draft, Project administration, Resources

Availability of data and material Data are available upon reasonable request.

Declarations

Conflict of interest D. Lemic, B. Zorić, A. Novak, D. Ivić, M.A. Galešić and H. Viric Gasparic declare that they have no competing interests.

Ethical standards For this article no studies with human participants or animals were performed by any of the authors. All studies mentioned were in accordance with the ethical standards indicated in each case.

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