

Freshness vs. Hygiene: Evaluating the Limits of Ozone Air Treatment in Home Refrigerators

Astrid Klingshirn, Lilla Brugger, Benjamin Eilts, Dominique Bour-sillon und Verena Holzbaur

Abstract

This study investigates the effectiveness of ozone-based air purification systems in domestic refrigerators, focusing on their ability to preserve vegetable freshness and reduce microbial load. In realistic test scenarios with a mixed vegetable load, only continuous high-dose ozone treatments achieve measurable antimicrobial effects—but also cause noticeable sensory degradation, especially in sensitive products. Low-dose or intermittent settings preserve visual and textural quality but show no relevant microbial reduction. Ozone thus has limited value for directly extending freshness. Its more promising role lies in supporting air and surface hygiene, complementing consumer cleaning routines.

Keywords: Household technology, refrigerator, sensory analysis, hygiene, vegetable storage

Frische vs. Hygiene: Analyse der Grenzen von Ozon-Luftbehandlung in Haushaltskühlgeräten

Kurzfassung

Diese Studie untersucht die Wirksamkeit ozonbasierter Luftreinigungssysteme in Haushaltskühlgeräten hinsichtlich Frischeerhalt und Keimreduktion bei Gemüse. In praxisnahen Tests mit Mischbeladung erzielen nur kontinuierliche Hochdosis-Anwendungen messbare antimikrobielle Effekte – jedoch mit deutlichen sensorischen Beeinträchtigungen, insbesondere bei empfindlichen Produkten. Niedrig dosierte oder intermittierende Einstellungen erhalten Aussehen und Textur, zeigen aber keine relevante Keimreduktion. Der direkte Nutzen zur Frischeverlängerung ist begrenzt. Vielversprechender erscheint der Einsatz zur Unterstützung der Luft- und Oberflächenhygiene im Kühlschrank als Ergänzung zur Verbraucherreinigung.

Schlagwörter: Haushaltstechnik, Kühlgerät, Sensorik, Hygiene, Gemüselagerung

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Introduction: Ozone application in the food sector - Mechanism of action and areas of application

Ensuring food quality and safety during home storage is a critical challenge, as domestic practices often exhibit deficiencies in temperature control, packaging, and hygiene (James et al. 2008, Wucher et al. 2020, Klingshirn & Eilts 2022). In response, technological enhancements such as antimicrobial coatings and air purification systems are increasingly integrated into modern refrigerators (Epelle et al. 2023, Møretrø & Langsrud 2011). One such emerging technology is ozone-based air treatment.

Ozone (O_3) is a strong oxidizing agent with a pronounced antimicrobial effect against bacteria, yeasts, moulds, and spores. It works by oxidizing cell components of microorganisms - such as cell membranes, cell walls and the cytoplasm - thereby destroying their structure and function. Two central mechanisms of action are the oxidation of amino acids and sulfhydryl groups in proteins, which leads to denaturation, and the oxidation of unsaturated fatty acids in cell membranes, which leads to the formation of reactive oxygen species and membrane damage. These processes lead to the inactivation or killing of microorganisms. In addition, ozone can oxidize ethene - a ripening gas - and thus accelerate the ripening and spoilage process in fruit and vegetables (Dubey et al. 2022b).

Ozone is particularly suitable for the treatment of fresh fruit and vegetables (e.g. berries, salads, tomatoes), fish and seafood, meat, and poultry as well as for mould prevention in cereals, nuts, and dried fruit. It is also used in packaged foods to disinfect the packaging surface.

In the food environment, ozone is used either for **one-off treatment** or for **continuous application**:

- In **single-use applications**, ozone is used specifically for the pre-treatment of foodstuffs. Typical areas of application are the decontamination of fresh fruit and vegetables, meat, or fish before packaging. The treatment is conducted either by fumigation or by contact with ozonized water, e.g. as rinse or spray water.

- In food storage, ozone can be **used continuously** in low concentrations to improve air quality and inhibit the growth of microorganisms on surfaces and in the ambient air. This method is used in particular in cold stores, ripening chambers and storage rooms for fruit, vegetables, or meat products.
- In the field of **refrigerated storage**, ozone is used in **gaseous form** (for air and surfaces) or in **aqueous form** (e.g. as spray or rinse water, Dubey et al. 2022a).

The antimicrobial effect of ozone in storage is influenced by a large number of physical and chemical parameters. These factors act both in isolation and in interaction with each other and determine the extent to which ozone can be used to inactivate microbial contamination and for quality assurance:

- **Ozone concentration and exposure time:** The effectiveness increases with the concentration and exposure time of the ozone. Even low concentrations (0.05-0.1 ppm) show a microbial reduction in continuous use without causing sensory impairment of the food. Higher concentrations (> 0.5 ppm) can increase the effectiveness but are associated with risks such as texture changes or phytotoxic effects (Sukarminah et al. 2017).
- **Temperature and humidity:** Ozone stability decreases with rising temperature; a 10 K increase halves its half-life. Relative humidity also plays a critical role: while high humidity (>70%) accelerates ozone decay due to increased reactivity with water molecules, optimal stability is observed at 50–60% relative humidity. Very high humidity ($\geq 90\%$) enhances ozone's antimicrobial efficacy by increasing cell wall permeability and ozone reactivity. In contrast, dry air reduces the inactivation rate (Gómez-López et al., 2009). At 0 °C and 50–70% relative humidity, ozone's half-life is approximately 60 min, dropping to 30 min at 10 °C under the same conditions (Khadre et al., 2001, Mohapatra et al., 2015). On moist surfaces, such as food, the half-life ranges from 20–40 min at 0–4 °C and decreases to 10–20 min at 8–10 °C (Kim et al. 2003).
- **Surface structure and food type:** Smooth-surfaced materials (e.g. stainless steel or plastic) allow an even distribution of ozone and a better contact effect than porous or rough-textured surfaces of fresh plant products such as lettuce or berries. Likewise, each food matrix reacts differently: water-rich, non-sensitive products (e.g. grapes) benefit more from ozone treatment than fatty or sensitive products (Artés-Hernández 2004).
- **Organic load and degradation behaviour:** Ozone does not react selectively but oxidizes all organic substances. A high organic load in the storage air (volatile organic compounds) accelerates ozone degradation and reduces its effectiveness (Bayerisches Landesamt für Umwelt 2021).

As ozone is classified as a biocidal substance under EU Regulation (EU) No 528/2012, its use in food-related applications must comply with strict safety and exposure limits. Due to its strong oxidative properties, elevated ozone concentrations can pose health risks such as respiratory irritation, mucosal damage, and oxidative stress (Brodowska et al. 2018, Bundesumweltamt 2021). Therefore, ozone-generating devices must ensure that residual ozone levels remain below the permissible exposure limits defined by occupational and consumer safety guidelines (e.g. 0.1 ppm for continuous exposure).

Ozone generation technologies and their use in refrigerators

Ozone can be generated in different technical ways, with three processes being particularly relevant for use in refrigeration and storage technology.

Corona discharge is the most common technology for ozone generation. In this process, dry air or pure oxygen is passed through a strong electric field between two electrodes with a dielectric in between. The electrons released split oxygen molecules (O_2) into individual oxygen atoms, which then recombine to form ozone molecules (O_3). This process is characterized by high energy efficiency and continuous operation, making it particularly suitable for larger applications in cooling and storage systems (von Gunten 2003, Langlais et al. 1991).

An alternative method is based on the irradiation of air with short-wave **ultraviolet radiation** at 185 nm. The UV rays split oxygen molecules, creating ozone. Due to the comparatively low ozone yield, this method is mainly suitable for smaller applications, such as compact cooling systems or air purifiers (Sharma & Mishra 2019).

Electrochemical ozone production is achieved through the electrolysis of water. In an electrochemical reactor, water is oxidized at an anodic electrode, producing ozone. This process is particularly well established in water treatment, but can also be used for closed cooling systems, especially in humid environments (Kim et al. 2003).

In refrigerators, UV-based systems and corona discharge technologies are mainly used to generate ozone - these systems are then marketed by manufacturers as "Fresh Air", "Active Oxygen" or "Plasma Cluster" technologies (Yuan et al. 2021).

Typical application configurations for ozone in refrigerated storage for microbial control and freshness preservation

Ozone is often used for microbial control in storage systems in the form of continuous fumigation at low concentrations (100-500 ppb). This application over several h to days under refrigerated conditions (2-5 °C) and high relative humidity ($\geq 90\%$) shows reductions in microbial contamination on food surfaces of 1-2 log levels (Akbas & Ozdemir 2006b, Bigi et al. 2021).

E. coli and *B. cereus* in particular were reduced on fruit peel and in chilled air. In a refrigerator model experiment, continuous fumigation with 50 ppb over 60 min at 3 °C led to a 1.8 log CFU/m³ reduction in the total bacterial count in the air (Bigi et al. 2021).

In addition to its antimicrobial properties, ozone also interacts with ethene - a key plant hormone involved in the ripening of fruits and vegetables. By oxidizing ethene, ozone reduces its concentration in the storage environment, thereby slowing down ripening processes and extending the shelf life of produce. This ethene-scavenging effect is particularly beneficial for ethene-sensitive commodities such as berries, bananas, and brassicas (Dubey et al. 2022b, Forney et al. 2003). However, the application of ozone must be carefully controlled: excessive concentrations or prolonged exposure can lead to oxidative stress in plant tissues, potentially damaging cell membranes and increasing susceptibility to spoilage and mould development. For instance, a study by Pérez et al. (1999) demonstrated that a three-day treatment of strawberries with 350 ppb ozone at 2 °C resulted in a 15% reduction in mould growth compared to the untreated control.

In contrast, single applications at higher concentrations are used to reduce mould growth. *Botrytis cinerea* on grapes can be significantly reduced by a single ozone treatment with 2,500 ppm (Gabler et al. 2010). Table 1 summarizes the determined effect of gaseous ozone on microorganisms and food based on several studies (Table 1).

Table 1: Effect of gaseous ozone on microorganisms and foodstuffs

Ozone Concentration	Application Duration & Conditions	Effect / Result	Target Organism / Matrix	Reference
50 ppb	30–60 min, 3 °C, 90% r. H.	0.88–1.81 log reduction of airborne bacterial count (CFU/m ³)	Airborne germs in refrigerator environment	Bigi et al. 2021
50 ppb	6 months, 0.5 °C, >95% r. H.	Inhibition of lesion growth by <i>B. cinerea</i> but not by <i>S. sclerotiorum</i>	Inoculated carrots	Hildebrand et al. 2008
300 ppb	4 weeks, 5 °C, 90% r. H.	Inhibition of aerial mycelium formation but no significant reduction in rot except for <i>M. fructicola</i>	Inoculated peaches	Palou et al. 2002
1000 ppb	2 weeks, 10 °C	Delay of spoilage by <i>P. digitatum</i> and <i>P. italicum</i> for one week	Citrus fruits	Palou et al. 2001
5000 ppb	60 min	0.32 log reduction in yeasts and moulds (CFU/g)	Food surfaces	Habibi Najafi & Haddad Khodaparast 2009

Sensory effects as a limiting factor

The use of ozone requires a differentiated assessment regarding its effects on the sensory quality of the treated food. The oxidative properties of ozone not only affect microorganisms but can - depending on the concentration and duration of exposure - also damage sensitive food components such as flavourings, color pigments, fatty acids, and textural proteins (Miller et al. 2013).

In continuous applications with low concentrations (< 300 ppb), sensory impairments are reported to be minimal. Studies have shown, that fresh products such as lettuce, berries or tomatoes did not exhibit any significant negative changes when exposed continuously over several days, provided that the temperature and humidity were kept within the optimum range (Brodowska et al. 2018). At higher concentrations from approx. 350-400 ppb, there are losses in the aroma profile, particularly due to the reduction of volatile ester compounds (Pérez et al. 1999). Color changes or loss of firmness can also occur in sensitive products.

Sensory effects are much more pronounced in single-use applications with high concentrations ($> 1,000$ ppb to several ppm), particularly in industrial sterilization. In these cases, discoloration, bitterness, rancidity, and loss of texture have been documented - especially in high-fat products (e.g. nuts), fruit peel or dried foods (Akbas & Ozdemir 2006a, McKenzie et al. 1998).

As a tolerance limit at which the first sensory changes such as loss of aroma and changes in texture become apparent, continuous use at 350 to 400 ppb over several days can be derived.

The above derivations are based on idealized conditions, industrial storage rooms or controlled laboratory simulations with a focus on one product category. The actual use of ozone in household refrigerators has hardly been systematically investigated to date. In particular, there is a lack of practical studies on ozone systems marketed for refrigerators that are accessible to end consumers and are operated in the context of typical household use - such as the simultaneous storage of perishable fresh products.

The aim of this study is therefore to evaluate the effectiveness of ozone systems available on the market under standard household conditions in terms of their influence on freshness retention and antimicrobial effect with a focus on vegetables. For this purpose, a comparative test approach with and without the use of ozone in a closed storage system under cold storage conditions was chosen. The influence of ozone application on a practical mixed load of vegetables and inoculated test plates is analysed. The course of the sensory quality (color, odor, texture), the loss of fresh mass and the color changes as well as the microbial reduction are examined.

Materials and methods

Experimental setup storage trials are conducted using airtight plastic boxes (volume: 16 L) simulating a domestic refrigerator environment. Two comparison groups are used in all test series: a reference box without ozonization and test box(es) with an active ozone generator.

To simulate a practical storage environment with a basic moisture load, a standardized evaporation system is used in all test series. This consists of a test tray equipped with six test sheets of nonwoven fabric in accordance with DIN 63169 (DIN 2020), which ensures a saturated atmosphere (100 % rH). The boxes are stored in a refrigerator with a preset temperature of 7.5 °C to simulate typical household conditions on the one hand and to accelerate microbial spoilage on the other.

Mobile data loggers (EasyLog USB), which are attached to the inside of the lids, are used to continuously measure temperature and humidity: The average temperature measured is 7.3 °C. The relative humidity inside the box is constantly in the saturated range at 98-100 % rH.

The **ozone concentration** inside the boxes is monitored for unloaded and loaded boxes in pre-trials, using an Aeroqual Series 500 ozone measuring device. For this purpose, the device's sampling tubes are inserted through sealed boreholes in the lids of the storage boxes. These openings are tightly covered with adhesive tape to ensure an airtight seal.

Ozonization modes

Two different devices with corona discharge technology are used to generate ozone. Both devices are based on the generation of ozone from atmospheric oxygen by means of electrical high-voltage discharge, but they differ in terms of their installation type, application, and target group:

Device 1: A built-in module typically installed in the air duct of household refrigerators is integrated into the test box. The device is mounted through a sealed opening in the lid of the test chamber, simulating a fixed-use scenario.

Device 2: A battery-operated, stand-alone ozone module for flexible household use. This device is placed at the bottom of the storage box and programmed in two modes:

- **LOW:** Initial 20 min continuous release, then 40 seconds every hour.
- **HIGH:** Initial 30 min release, then 60 seconds every hour.

Table 2 shows the ozonization variants tested, and ozone concentrations determined in each case under no-load and loaded conditions.

Table 2: Maximum ozone concentrations (in ppm) in unloaded and loaded storage boxes for different ozonization modes

Abbreviation	Ozonization mode	Maximum ozone concentration (unloaded)	Maximum ozone concentration (with load)
OG 1 - C	Ozone generator 1 – continuous operation	29.5 ppm	4.9 ppm
OG 1 – 3/7	Ozone generator 1 – 3 runs of 4 h over 7 days	17.0 ppm	3.2 ppm
OG 1 – 1/7	Ozone generator 1 – 1 run of 4 h over 7 days	17.0 ppm	3.2 ppm
OG 2 – CL	Ozone generator 2 – continuous operation, setting "low"	7.1 ppm	4.2 ppm (after initiation) / 0.56 ppm (during interval phase)
OG 2 – CH	Ozone generator 2 – continuous operation, setting "high"	14.4 ppm	6.0 ppm (after initiation) / 0.65 ppm (during interval phase)

Storage trials

To investigate the effect of ozone on freshness and the potential to reduce microbial contamination, the storage boxes are each filled with four diverse types of vegetables: radishes, broccoli, carrots, and spinach. The vegetables are pre-sorted for uniformity and placed in open PE trays to avoid cross-contact and ensure air circulation.

To standardize the stored goods, broccoli is cut into florets of the same size (2.5 - 3.5 cm diameter), radishes are stored without the green leaves. The vegetables are stored in open PE plastic trays to avoid direct contact between the products and to ensure sufficient air circulation within the boxes (Fig. 1).

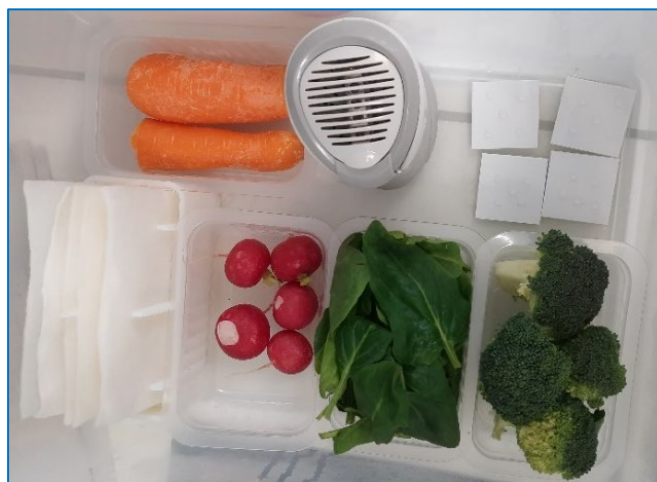


Figure 1: Exemplary storage setup with four vegetable types, inoculated test plates, moisture test tray and ozonization

The **storage period is seven days**, with interim tests being conducted after two and three or four days and on day seven. The tests include the analysis of **fresh weight loss, sensory quality, color changes** during storage and the **antimicrobial activity**.

To determine the **fresh weight loss (FWL)**, the samples are weighed at the beginning and on the defined intermediate analysis days. The fresh weight loss is calculated as a percentage (equation 1):

$$FWL \text{ (Fresh Weight Loss, \%)} = \frac{\text{initial mass (g)} - \text{final mass (g)}}{\text{initial mass (g)}} \cdot 100 \quad (\text{equation 1})$$

In addition, the daily percentage fresh weight loss is calculated to compare differences between the test conditions.

To evaluate quality retention during storage and to determine overall shelf life, a **descriptive sensory profile analysis** is performed in accordance with DIN EN ISO 13299. The assessment focuses on three key attributes: color, texture, and overall impression. Each attribute is rated using a six-point scale based on visual evaluation (1 = very good (fresh, unchanged) to 6 = unfit for consumption (sensory spoilage)). Evaluations are performed by trained sensory panellists. To reflect the relative importance of each attribute to overall quality, weighting factors are applied accordingly (Table 3).

Table 3: Evaluation system for sensory analysis with weighting

Quality attribute	Weighting factor	Relevancy
Color	0,4	First visible quality aspect: signals freshness, ripeness, and quality at first glance
Texture	0,3	influences consumer perception of freshness affects mouthfeel, eating satisfaction, and acceptance
Overall impression	0,3	integrated sensory experience, summarizing how appearance, texture, flavour, and aroma combine to influence product acceptance

The individual ratings are combined into a freshness quality index (FQI) according to the specified weighting (equation 2):

$$FQI \text{ (Freshness Quality Index)} =$$

$$\sum (\text{quality attribute score} \cdot \text{weighting factor}) \quad (\text{equation 2})$$

A low value indicates high freshness. Products with $FQI \leq 2$ are considered to be sensory flawless. Values > 3 show a significant loss of quality, from $FQI \geq 3.6$ the products are no longer considered fit for consumption.

Color evaluation is performed using Labcolor measurements. A color pin measuring device (Color Pin 2, NCS Color AB, Stockholm, Sweden) is used to record the L^* , a^* , and b^* values of a defined sample surface on day zero and at each subsequent analysis point. The color difference is calculated using the ΔE value according to the following formula (equation 3):

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (\text{equation 3})$$

The ΔE value (Delta E) in the CIELAB color space measures perceived color differences: the larger the ΔE value, the more noticeable the difference. Color differences above 6 are perceptually large and generally unacceptable in rigorous color evaluations (Sharma et al, 2005, Table 4). Although color is included as a weighted attribute in the sensory evaluation, its explicit measurement via ΔE values provides an essential complementary perspective. Sensory scoring, especially over short storage periods, may not fully capture early-stage visual degradation—particularly in products where discoloration precedes textural or aromatic changes. By quantifying color shifts objectively, ΔE analysis enables the identification of subtle oxidative damage that may remain below the sensory detection threshold. This approach not only enhances the resolution of quality assessment but also establishes ΔE as a sensitive analytical parameter for future studies targeting oxidative stress in fresh produce.

Table 4: Interpretation of ΔE values in terms of visual color differences and evaluation thresholds

ΔE Value	Visual Perception	Interpretation for Evaluation
$\Delta E \leq 1$	Not perceptible	No visible Color difference
$\Delta E \approx 2.3$	Just noticeable difference	Minimal color deviation under standard conditions
$1 < \Delta E \leq 2$	Noticeable only upon close inspection	Generally acceptable in most applications
$2 < \Delta E \leq 6$	Noticeable at a glance	Visible but often still tolerable deviation
$\Delta E > 6$	Clearly and easily visible; colors appear distinctly different	Critical threshold for significant color difference

To evaluate the **antimicrobial efficacy** of the ozone treatments, a standardized model surface contamination test is performed according to VDE SPEC 90016 (VDE 2020). A defined quantity of *Enterococcus faecium* (DSM 2146) is applied to a sterile reference surface (5x5 cm polypropylene test plates, four per test run), which is then exposed to the ozone treatment along with the vegetable storage load (Fig. 1). The reduction in viable cell count is subsequently determined to assess the antimicrobial activity of the ozone treatment after 24 and 48h, to capture the early-stage antimicrobial effects of ozone treatment.

The surface contamination is conducted by spot application of the microbial suspension. Each plate receives five drops of 10 µL of a standardized microbial suspension (concentration: approx. 10^8 CFU/mL), resulting in a total microbial load of approximately 5×10^6 CFU per plate. After application, the suspension is allowed to dry at room temperature for 30 min to simulate realistic adhesion to the surface. The contaminated plates remain in the boxes, where ozone treatment is applied at varying concentrations and intervals. After 24 and 48h, the plates are removed and placed upside down in sterile containers containing 10 ml of Ringer Solution with 0,1 % of sodium thiosulfate as a neutralizing buffer. The microbial count is then determined by serial dilution and spiral plating on TSA agar. Following incubation at 35 °C for 48 h, CFU are counted. The reduction in microbial count from the ozone-treated test boxes (test) is calculated as log values in comparison to the reference plates (reference), which are stored in boxes without ozonization (equation 4).

$$\log_{reduction} = \log_{10}(CFU_{reference}) - \log_{10}(CFU_{test}) \quad (\text{equation 4})$$

Results

Fresh Weight Loss under Different Ozonization Modes

The daily FWL is used as an indicator of storage stability in vegetables under ozone-enriched conditions. Table 5 presents the arithmetic means across measurement series for each vegetable type and ozonization mode. Spinach shows the highest sensitivity, with OG 1 – 3/7 resulting in a mean FWL of 3.16 %/day, compared to 0.61 %/day in the reference. Broccoli also exhibits increased FWL under ozone exposure, particularly in OG 1 – 3/7 and OG 2 – CH. Carrots and radishes show moderate to low sensitivity, with only slight deviations from reference values. Radish displays moderate sensitivity. The reference value is 0.17 %/day, while OG 1 – 3/7, OG 2 – CL and OG 2 – CH show the most pronounced increases.

Table 5: Mean daily FWL (%/day) in different ozonization modes compared to reference values

Ozonization mode	Spinach FWL %/day	Broccoli FWL %/day	Carrots FWL %/day	Radish FWL %/day
Reference	0.61	0.31	0.18	0.17
OG 1 - C	0.79	0.42	0.23	0.21
OG 1 – 3/7	3.16	1.03	0.48	0.46
OG 1 – 1/7	0.97	0.51	0.18	0.26
OG 2 – CL	1.22	0.76	0.59	0.41
OG 2 – CH	1.98	1.00	0.37	0.40

Impact of ozonization on sensory quality evolution in storage and shelf life

Figure 2 illustrates the evolution of the Freshness Quality Index (FQI) over the seven-day storage period. Reference samples retain the highest freshness across all vegetable types. Among ozone-treated samples, OG 1 – 1/7 maintains acceptable sensory quality in spinach, while other configurations lead to earlier deterioration. Broccoli, carrots, and radishes show greater resilience, with most treatments remaining below the rejection threshold ($FQI \geq 3.6$) until day 7.

In the case of spinach (Figure 2 – A), the ozone treatment OG 1 – 1/7 and the reference samples maintain sensory quality below the rejection threshold throughout the seven-day storage period. All other ozone configurations exceed the threshold between day two and day three, indicating early sensory deterioration.

For broccoli (Figure 2 – B), all ozone treatments except OG 1 – C remain below the rejection threshold during the entire storage period. The estimated shelf life for broccoli under these conditions ranges from 15 to 31 days, based on linear regression of the Freshness Quality Index.

Carrots (Figure 2 – C) retain high sensory quality across all tested ozone configurations. None of the treatments exceed the rejection threshold within the seven-day period. Shelf life estimates for carrots vary between 29 and over 90 days, indicating strong resilience to ozone exposure.

In the case of radish (Figure 2 – D), the OG 1 – C treatment exceeds the rejection threshold, doing so between day three and day four. All other ozone configurations maintain acceptable sensory quality throughout the storage period.

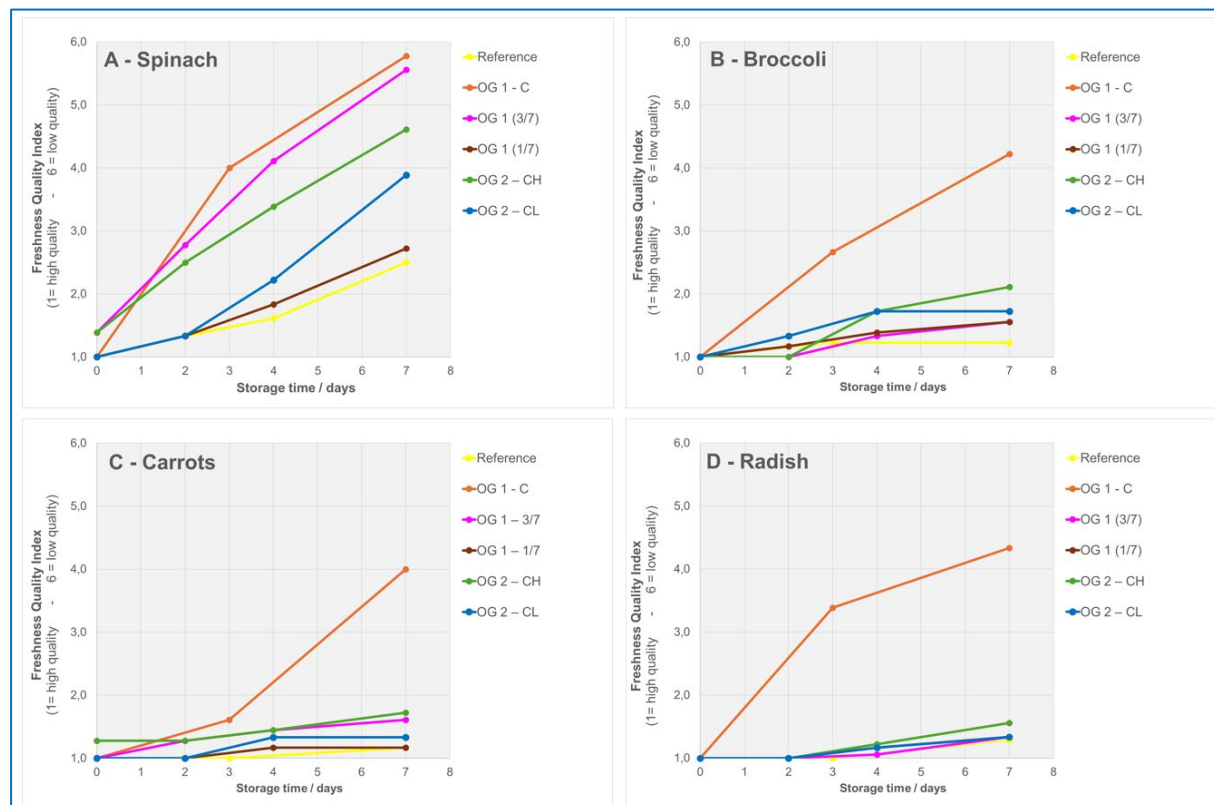


Figure 2: Freshness Quality Index evolution in storage under different ozonization configurations compared to reference value

Vegetable color stability under ozone treatment conditions

Figure 3 shows the ΔE values for each vegetable type under different ozonization modes. ΔE quantifies the perceptible color difference compared to reference samples. The threshold value of $\Delta E = 6.0$ is used to indicate significant visual change.

In the case of spinach (Figure 3 – A), most ozone treatments result in ΔE values above the threshold of 6.0, indicating clearly visible discoloration. The reference sample shows a gradual lightening over the storage period, with a final ΔE value of 3.2, confirming minimal visual change.

For broccoli (Figure 3 – B), moderate color changes are observed across treatments. Interestingly, the ozone configurations OG 1 – 1/7 and OG 2 – CH yield lower ΔE values than the reference sample, suggesting a more stable color profile under these conditions.

In carrots (Figure 3 – C), only the continuous ozone exposure mode OG 1 – C exceeds the ΔE threshold, reaching a maximum value of 23.2. All other treatments remain below $\Delta E = 6.0$, indicating acceptable color stability.

Radish (Figure 3 – D) shows the most pronounced color change under ozone exposure. The OG 1 – C treatment results in a ΔE value of 30.6, reflecting extreme discoloration. All other ozone configurations remain below $\Delta E = 10$, with the reference sample showing the least visual deviation.

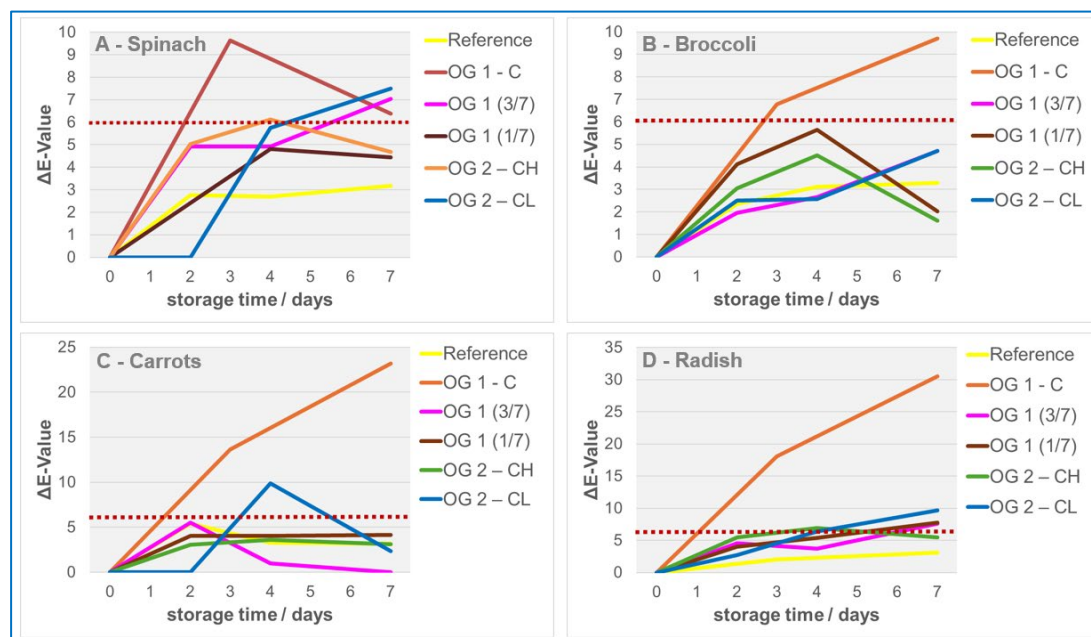


Figure 3: ΔE -value evolution in storage under different ozonization configurations compared to reference value

Maximum storage time under different ozonization configurations compared to untreated controls

Table 6 summarizes the maximum storage times based on sensory quality thresholds and linear regression analysis. Reference samples consistently show the longest shelf life. OG 1 – 1/7 (single short-term peak exposure) performs best among ozone treatments, with predicted shelf lives close to the reference in most vegetables. Continuous high-dose treatments (OG 1 – C) result in the shortest shelf lives.

Table 6: Maximum storage times (in days) for the reference and per ozonisation modes according to freshness quality index and regression analysis

Ozonization mode	Maximum storage time (days)			
	Spinach	Broccoli	Carrots	Radish
Reference	>7 (12)	>7 (85)	>7 (105)	>7 (64)
OG 1 - C	2	5,5	6	3
OG 1 – 3/7	3	>7 (30)	>7 (29)	>7 (55)
OG 1 – 1/7	>7 (10)	>7 (31)	>7 (93)	>7 (51)
OG 2 – CL	6	>7 (23)	>7 (46)	>7 (51)
OG 2 – CH	4	>7 (15)	>7 (35)	>7 (31)

Antimicrobial effect of ozone treatments on inoculated plastic carriers

To evaluate antimicrobial efficacy, plastic carriers inoculated with a standardized *E. faecium* suspension are stored in parallel with vegetables under different ozonization modes. Colony-forming units (CFU) are counted at 0, 24, and 48 h. The initial microbial load averages 3.6×10^6 CFU. After 24 h, all samples show similar CFU levels ($1.94\text{--}5.43 \times 10^6$), indicating no relevant reduction. After 48 h, only the OG 1 – C mode shows a substantial log reduction (5.83 log). OG 2 – CL achieves a limited but measurable reduction (0.64 log), while other treatments show minimal or no effects. Reference samples vary between -0.03 and 0.54 log, indicating biological variability.

Table 7: Antimicrobial effectiveness of ozonization modes after 2 days (log reduction)

Ozonization mode	OG 1 – C	OG 1 – 3/7	OG 1 – 1/7	OG 2 – CL	OG 2 – CH
Reference	0.54	0.19	-0.03	0.54	0.01
Treated samples	5.83	0.19	0.02	0.64	0.01

Discussion

Product-specific sensitivity to ozone exposure

The results demonstrate clear differences in ozone sensitivity among vegetable types. Spinach shows the highest susceptibility, with rapid degradation in both weight and sensory quality under most ozone configurations. This aligns with previous findings that leafy greens exhibit elevated respiration and transpiration rates under oxidative stress (Skog & Chu 2001). Broccoli also shows increased fresh weight loss, likely due to enhanced ethene production triggered by ozone exposure, as reported for brassica vegetables (Forney et al. 2003). In contrast, carrots and radishes display greater resilience, which may be attributed to their compact structure and protective skin layers that limit gas exchange (Selma et al. 2008; Graham et al. 1997).

Balancing freshness preservation and ozone intensity

The sensory analysis confirms that high-dose or continuous ozone treatments accelerate quality loss, particularly in sensitive produce. Only the short-term exposure mode OG 1 – 1/7 maintains sensory integrity comparable to the reference. This suggests that limited ozone application may mitigate oxidative damage while still offering hygiene benefits. The regression-based shelf life estimates further support this, showing that OG 1 – 1/7 achieves near-reference performance in spinach, carrots, and radishes. These findings are consistent with prior studies indicating that excessive ozone exposure can damage cellular structures and reduce shelf life (Tiwari et al. 2010; Brodowska et al. 2018).

Relevance of objective color measurement

Although color is included as a weighted attribute in the sensory evaluation, the explicit measurement of ΔE values provides a critical and complementary analytical dimension. Sensory scoring, particularly over short storage periods such as seven days, may not fully capture early-stage visual degradation—especially in products where discoloration precedes changes in texture or aroma.

In this context, ΔE analysis proves to be a more sensitive indicator of oxidative stress and visual quality loss. For instance, in spinach and radish samples, significant ΔE values are observed even when sensory scores remain within acceptable limits. This suggests that objective color measurement can detect subtle but meaningful changes that may not yet be perceptible to trained panellists. Such early detection is particularly relevant for ethene-sensitive or oxidation-prone vegetables, where visual cues are among the first indicators of declining freshness.

By quantifying color shifts in a reproducible and standardized manner, ΔE analysis enhances the resolution of quality assessment and supports a more nuanced understanding of ozone-induced changes. This approach not only strengthens the methodological robustness of freshness evaluation but also establishes ΔE as a valuable analytical parameter for future studies targeting oxidative degradation in fresh produce (McGuire 1992; Sharma et al. 2005).

Antimicrobial efficacy and its limitations

Only sustained high-dose ozone exposure (OG 1 – C) achieves significant microbial reduction, with a 5.83 log decrease in *Enterococcus faecium* CFU counts after 48 h. Low-dose or intermittent treatments show minimal effects, confirming that ozone's antimicrobial efficacy is strongly dose-dependent. Interestingly, OG 2 – CL performs better than OG 2 – CH, possibly due to differences in ozone stability or microbial stress responses (Khadre et al. 2001; Kim et al. 1999). These findings underscore the challenge of achieving hygiene benefits without compromising product quality. They support the positioning of ozone systems as hygiene-support tools rather than freshness-extending technologies.

Regulatory and consumer safety considerations

The use of ozone in domestic refrigerators must be critically assessed in light of regulatory frameworks and consumer safety. Ozone is classified as a biocidal substance under EU Regulation No 528/2012 and is subject to strict exposure limits. Although ozone is not continuously released into ambient air, opening the refrigerator during or shortly after application may lead to brief exposure to elevated concentrations.

In enclosed environments, such exposure—even if intermittent—can pose health risks if recommended thresholds are exceeded (Bundesumweltamt 2021, Brodowska et al. 2018). Therefore, any potential hygiene benefits must be weighed against the risks of consumer exposure, especially in devices lacking adequate ozone degradation or ventilation mechanisms.

Conclusion: Potentials and limits of household ozonization in vegetable storage

This study demonstrates that ozone-based air purification systems in domestic refrigerators provide only limited benefits for preserving the freshness of vegetables. High and continuous ozone exposure can effectively reduce microbial loads; it also causes accelerated degradation in sensory quality—especially in delicate leafy greens such as spinach and radishes.

While high-dose ozone treatments can achieve measurable antimicrobial effects, their use in household refrigerators must be critically assessed in light of regulatory and toxicological concerns. Ozone is a powerful oxidant and classified as a biocide, subject to strict legal frameworks such as the EU Biocidal Products Regulation (EU BPR, Regulation No 528/2012). Although ozone is not continuously released into the ambient air, opening the refrigerator during or shortly after ozone application may lead to brief exposure to elevated concentrations. In enclosed environments, such exposure—even if intermittent—can pose health risks if recommended thresholds are exceeded. Consequently, any potential hygiene benefits must be weighed against the risks of consumer exposure, especially in devices lacking adequate ozone degradation or ventilation mechanisms. This underscores the need for transparent risk communication and regulatory compliance in the marketing of ozone-based freshness technologies.

Low-dose or intermittent ozone applications maintain visual and textural integrity but lack antimicrobial effectiveness.

These findings underscore the need for a differentiated application of ozone in household refrigeration. Rather than being positioned as a freshness-extending solution for perishable produce, ozone systems may offer greater value as a hygiene support mechanism—reducing airborne contaminants and contributing to surface sanitation. Future design and marketing of such technologies should emphasize hygiene enhancement rather than shelf-life extension.

Ultimately, the results highlight the importance of balancing antimicrobial efficacy and food quality in domestic food storage. Targeted use of ozone may be appropriate in specific hygiene-focused contexts, but for general freshness preservation, conventional cooling remains the more reliable strategy.

References

- Akbas M, Ozdemir M (2006a): Effect of different ozone treatments on aflatoxin degradation and physicochemical properties of pistachios. *Journal of the Science of Food and Agriculture*, 86(13): 2099–2104.
- Akbas M, Ozdemir M (2006b): Effectiveness of ozone for inactivation of *Escherichia coli* and *Bacillus cereus* in pistachios. *Int. J. Food Sci. Technol.*, 41(5): 513–519.
- Artés-Hernández F, Artés F, Tomás-Barberán F (2004): Quality and safety of fresh-cut vegetables treated with ozonated water. *Food Science and Technology International*, 10(6), 321–329. doi 10.1177/1082013204048772
- Bayerisches Landesamt für Umwelt (2021): Infoblatt Ozon. Augsburg. Online verfügbar unter: <https://www.lfu.bayern.de> [Zugriff: 30.05.2025].
- Bigi F, Haghighi H, Quartieri A, de Leo R, Pulvirenti A (2021): Impact of low-dose gaseous ozone treatment in a cold chamber. *Journal of Food Safety*, 41(3), e12892.
- Brodowska A, Nowak A, Śmigielski K (2018): Ozone in the food industry: Principles, mechanisms, and applications. *Critical Reviews in Food Science and Nutrition*, 58(13): 2176–2201.
- Bundesumweltamt (2021). Ozon in der Luft. Online verfügbar unter: <https://www.umweltbundesamt.de/>, zuletzt abgerufen am 31.07.2025.
- Concha-Meyer, Anibal, Eifert, Joseph D., Williams, Robert C., Marcy, Joseph E., Welbaum, Gregory E. (2015): Shelf-Life Determination of Fresh Blueberries (*Vaccinium corymbosum*) Stored under Controlled Atmosphere and Ozone. In: *International Journal of food science* 2015, S. 164143. doi 10.1155/2015/164143.
- DIN Deutsches Institut für Normung (Hrsg., 2020): Elektrische Haushalts- und ähnliche Kühl- und Gefriergeräte – Lebensmittelkonservierung (IEC 63169:2020), Deutsche Fassung EN IEC 63169:2020. DIN EN IEC 63169 VDE 0705-3169:2021-07. Berlin: Beuth Verlag.
- Dubey A, Singh R, Kumar A (2022a): Ozone as a sustainable antimicrobial agent in food processing: Mechanisms and applications. *Journal of Food Safety and Hygiene*, 12(3): 45–58.
- Dubey P, Singh A, Yousuf O (2022b): Ozonization: An evolving disinfectant technology for the food industry. *Food and Bioprocess Technology*, 15, 2102–2113. doi 10.1007/s11947-022-02876-3.
- Epelle E, Macfarlane A, Cusack M, Burns A, Okolie J, Mackay W, Rateb M, Yaseen M (2023): Ozone application in different industries: A review of recent developments. *Chemical Engineering Journal* 454 (2).
- EU Regulation (EU) No 528/2012: Concerning the making available on the market and use of biocidal products. <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32012R0528>, zuletzt abgerufen am 31.07.2025.
- Forney C, Song J, Fan L (2003): Atmospheric effects on broccoli quality during controlled atmosphere storage. *Postharvest Biol Technol* 27(2): 241–250.
- Gabler F, Smilanick J, Mansour M, Karaca H (2010): Fumigation with high concentrations of ozone gas on table grapes. *Postharvest Biol. Technol.*, 55(2): 85–90.

- Gómez-López V, Ragaert P, Debevere J, Devlieghere F (2009): A review on the use of ozone in the treatment of food products. *Food Microbiology*, 26(6), 561–570. doi 10.1016/j.fm.2009.07.006.
- Graham H, Pariza M, Sinclair J (1997): Effect of ozone on postharvest storage and quality of radishes. *J Food Qual* 20(3): 197–210.
- Habibi Najafi, Mohammad B, Haddad Khodaparast M (2009): Efficacy of ozone to reduce microbial populations in date fruits. In: *Food Control* 20 (1): 27–30. doi 10.1016/j.foodcont.2008.01.010.
- Hildebrand P, Forney C, Song J, Fan L, McRae K (2008): Effect of a continuous low ozone exposure (50nLL–1) on decay and quality of stored carrots. In: *Postharvest Biology and Technology* 49 (3): 397–402. doi 10.1016/j.postharvbio.2008.03.012.
- James S, Evans J, James C (2008): A review of the performance of domestic refrigerators. *Journal of Food Engineering* 87(1), doi 10.1016/j.jfoodeng.2007.03.032.
- Khadre M, Yousef A, Kim JG (2001): Microbiological aspects of ozone applications in food: A review. *Journal of Food Science*, 66(9), 1242–1252. doi 10.1111/j.1365-2621.2001.tb15196.x.
- Kim J, Yousef A, Dave S (1999): Application of ozone for enhancing the microbiological safety and quality of foods: a review. *Journal of Food Protection*, 62(9): 1071–1087. doi 10.4315/0362-028X-62.9.1071
- Kim J, Yousef A, Dave, S. (2003): Application of ozone for enhancing the microbiological safety and quality of foods: a review. *Journal of Food Protection*, 66(9): 1474–1485.
- Kim J, Yousef A, Khadre M (2003): Ozone and its current and future application in the food industry. *Advances in Food and Nutrition Research*, 45: 168–218. doi 10.1016/S1043-4526(03)45005-5.
- Klingshirn A, Eilts B et al. (2022): Hygieneaspekte bei der Kühlung von Lebensmitteln: Verbraucherrealität und Verbraucheranforderungen. *Hauswirtschaft und Wissenschaft* (70) 2022. doi 10.23782/HUW_16_2022.
- Langlais B, Reckhow D, Brink D (1991): *Ozone in Water Treatment: Application and Engineering*. Chelsea, MI: Lewis Publishers.
- López-Rubira V, Allende A, Artes F, Tomas-Barberan F (2005): Influence of several oxygen concentrations on quality, polyphenol content and antioxidant capacity of fresh-cut radish. *Journal of Agricultural and Food Chemistry*, 53(25): 9180–9185.
- McGuire R (1992): Reporting of objective color measurements. *HortScience*, 27(12): 1254–1255.
- McKenzie K, Kotsonis F, Smith M (1998): Degradation of aflatoxins by ozone treatment in maize. *Food Additives & Contaminants*, 15(6): 783–790.
- Miller F, Ramos A, Brandão T, Silva C (2013): Effect of gaseous ozone on physicochemical and sensorial attributes of fresh-cut red bell peppers. *Food Control*, 34(2): 617–622.
- Mohapatra D, Mishra S, Giri S (2015): Ozone application in food preservation: A review. *Trends in Food Science & Technology*, 46(2), 102–110. doi 10.1016/j.tifs.2015.08.004.
- Møretrø T, Langsrud S (2011): Effects of Materials Containing Antimicrobial Compounds on Food Hygiene. *Journal of Food Protection* 74 (7), 1200–1211.

- Palou L, Crisosto C, Smilanick J, Adaskaveg J, Zoffoli J (2002): Effects of continuous 0.3 ppm ozone exposure on decay development and physiological responses of peaches and table grapes in cold storage. In: *Postharvest Biology and Technology* 24 (1): 39–48. doi 10.1016/s0925-5214(01)00118-1.
- Pérez A, Sanz C, Ríos J, Olías R, Olías J (1999): Effects of ozone treatment on strawberry quality. *J. Agric. Food Chem.*, 47(4): 1652–1656.
- Selma M, Allende A, López-Gálvez F, Conesa M, Gil M (2008): Disinfection potential of ozone, ultraviolet-C and their combination in wash water for processing of fresh-cut lettuce. *Postharvest Biol Technol* 50(2–3): 199–206.
- Selma M, Ibáñez A, Cantwell M, Suslow T (2008): Reduction by gaseous ozone of *Escherichia coli* O157:H7 on minimally processed lettuce. *Food Microbiology*, 25(4): 558–565. doi 10.1016/j.fm.2008.01.002.
- Sharma G, Wencheng W, Edul N (2005): The CIEDE2000 Color-Difference Formula: Implementation Notes, Supplementary Test Data, and Mathematical Observations. *Color Research & Application* 30, Nr. 1 (2005): 21–30, doi 10.1002/col.20070.
- Sharma R, Mishra R (2019): *Postharvest microbial ecology of produce: implications for shelf life and food safety*. Boca Raton: CRC Press.
- Skog L, Chu C (2001): Effect of ozone on qualities of fruits and vegetables in cold storage. *Can J Plant Sci* 81(4): 773–778.
- Sukarminah E, Nuraida L, Fardiaz D, Dewanti-Hariyadi R (2017): Ozonization technology and its effects on the characteristics and shelf-life of some fresh foods. *KnE Life Sciences*, 2(6), 262–273. doi 10.18502/kls.v2i6.1067.
- Tiwari B, Muthukumarappan K, O'Donnell C, Cullen P (2010): Ozone in fruit and vegetable processing. *Food Engineering Reviews*, 2(2): 83–94. doi 10.1007/s12393-010-9011-9
- VDE Verband der Elektrotechnik Elektronik Informationstechnik e. V. (Hrsg. 2020.): VDE SPEC 90016: Prüfverfahren zur Bestimmung der Wirksamkeit luftreinigender Technologien im Haushaltskühlgerät. Version 1.0. Frankfurt am Main: VDE Verlag.
- von Gunten U (2003): Ozonization of drinking water: Part I. Oxidation kinetics and product formation. *Water Research*, 37(7): 1443–1467.
- Wucher H, Klingshirn A, Brugger L, Stamminger R, Geppert J, Kölzer B, Engstler A, Härten J. *Tackling Food Waste* (2020): Impact of German Consumer Behaviour on Food in Chilled Storage. *Foods*. 9(10). doi10.3390/foods9101462.
- Yuan W, Zhang X, Wang J, Yang Y (2021): Effects of low-concentration ozone treatment on the quality and microbial safety of stored fresh produce. *Food Control*, 123.

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