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S Abirami
Department of Dairy Microbiology, Dairy Science College, Hebbal, Bengaluru, Karnataka, India

Ramachandra B
Department of Dairy Microbiology, Dairy Science College, Hebbal, Bengaluru, Karnataka, India

Malashree L
Department of Dairy Microbiology, Dairy Science College, Hebbal, Bengaluru, Karnataka, India

Manjunatha H
Department of dairy microbiology, Dairy Science College, Kalaburagi, Karnataka, India

Rajanna M
Department of dairy chemistry, Dairy Science College, Hebbal, Bengaluru, Karnataka, India

Rajunaik B
Department of dairy engineering, Dairy Science College, Hebbal, Bengaluru, Karnataka, India

Anushree YK
Department of Dairy Microbiology, Dairy Science College, Hebbal, Bengaluru, Karnataka, India

Corresponding Author:
S Abirami
Department of Dairy Microbiology, Dairy Science College, Hebbal, Bengaluru, Karnataka, India

Role of ozone in modern food preservation: A review

S Abirami, Ramachandra B, Malashree L, Manjunatha H, Rajanna M, Rajunaik B and Anushree YK

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Abstract
Food preservation has been practiced for centuries to prevent spoilage and ensure food availability. Initially people relied on traditional preservation methods and eventually modern methods evolved over time. These technologies lead to high energy consumption, chemical residue concerns and increasing consumer demand for minimally processed foods. To meet these requirements of fresh, safe minimally processed food, several emerging technologies have arisen, among that ozone technology is one such emerging food preservation method. It is highly unstable, ecofriendly and highly reactive gas generated commercially either by corona discharge or ultraviolet (photochemical) radiation. It is an emerging non thermal food preservation technique used in aqueous or gaseous form to inactivate microorganism approved by United States Food and Drug Administration (USFDA) in the year 2001 as Generally Recognized as Safe (GRAS). Ozone exhibits broad spectrum of inactivation of microorganism by direct and indirect oxidation. Ozone has been used in food processing sector like extension of shelf life in fresh produce, cereals and grain silo fumigation, meat surface decontamination, destructing food borne pathogens. In future ozone can be used as hurdle technology which holds vast application in food sector.

Keywords: Preservation, non-thermal, Ozone, eco-friendly, broad spectrum

1. Introduction
Ozone is a triatomic molecule of oxygen. The word ozone is derived from the Greek word ‘ozein’ meaning ‘to smell’ because ozone has a characteristic pungent odour. Its major significance lies in its strong oxidizing power, broad spectrum antimicrobial activity, ecofriendly green technology as it decomposes back into molecular oxygen and extensively used in food industry particularly for sanitizing dairy supply chain.

2. Ozone
2.1 Properties of ozone

Table 1: Physical properties: (Botondi *et al.,* 2023) [5]

Property	Description
Molecular Composition	Three oxygen atoms.
Molecular Weight	48 g mol^{-1} (at 1 atm of pressure).
Geometry	Trigonal planar (bond angle: 116.8°; bond length: 1.278 Å).
State at Room Temp	Gaseous.
Appearance	Bluish in colour if generated from dry air.
Odor	Pungent; often described as a "fresh and clean" smell.
Boiling Point	−111.9 °C (becomes a dark blue liquid below this).
Melting Point	−192.7 °C.
Solubility	Soluble in aqueous solutions; solubility increases as water temperature decreases

Table 2: Chemical property: (Botondi *et al.,* 2023) [5]

Property	Description
Oxidation Potential	−2.07 V (higher than chlorine at −1.36 V and hydrogen peroxide at −1.78 V).
Stability	Highly unstable with a very short half-life; degrades much faster in water than in air.
Residues	Leaves no chemical residues; naturally degrades back into molecular oxygen.
Reactivity	Acts as a strong pro-oxidant; decomposes in water into Reactive Oxygen Species (ROS) like hydroxyl radicals.
Material Compatibility	Compatible with plastics like PVC and PTFE; corrosive to natural rubber and carbon steel

Table 3: Natural and Regulatory Properties (Botondi *et al.,* 2023) [5]

Property	Description
Natural Occurrence	Concentrated in the ozonosphere (stratosphere) approximately 25 km above sea level.
Atmospheric Concentration	Approximately 0.04 ppm.
FDA Status	Classified as GRAS (Generally Recognized As Safe) for use in food production since 2001.
Olfactory Threshold	Humans can detect it at very low concentrations (0.02-0.04 ppm).
Safety Limits (OSHA)	Concentration limit of 0.1 ppm for an 8-hour exposure in the workplace

2.2 Discovery and history of ozone: (Li *et al.,* 2026) [20]

The history of ozone begins in 1785 when Dutch physicist Martinus Van Marum observed a peculiar odor during experiments with electrical discharges. However, he did not identify the source of this smell.

The gas was officially identified and named in 1840 by German chemist Christian Friedrich Schönbein. He named it "ozone" derived from the Greek word *ozein* (ὄζειν), which means "to smell," reflecting the distinctive sharp odor that is characteristic of ozone.

In 1857, Werner von Siemens invented the first practical ozone generator, known as the Siemens tube, which made it possible to produce ozone consistently for scientific and industrial applications.

Marius Paul Otto, a French scientist in the late 19th century, pioneered ozone use in water treatment, demonstrating its effectiveness as a powerful disinfectant. This marked the transition of ozone from a laboratory curiosity to practical industrial use in sanitation.

Before World War I, Europe had 49 ozone installations, with France leading in adoption. After World War II, ozone regained popularity, and installations surpassed 2,000 by 1985.

In 1990, the EPA approved ozone for drinking water treatment in the United States. A major milestone for food applications came in 2001 when the U.S. FDA approved ozone as a GRAS (Generally Recognized As Safe) substance for food contact applications.

Today, ozone is widely used in food preservation as a natural disinfectant with strong oxidizing power. Ozone treatment is considered a promising green technology for food preservation.

2.3 Ozone production method

Ozone production method mainly involves two methods: Ozone production by corona discharge and UV light ozone generator (Joshi *et al.,* 2025) [18].

Corona discharge ozone generator

A corona discharge generator typically consists of two electrodes: one high-tension electrode and one low-tension (ground) electrode, which are separated by a ceramic dielectric medium. This arrangement creates a narrow discharge gap. A high voltage alternating current is applied across the discharge gap. In the presence of oxygen, this current excites oxygen electrons. Electrons with sufficient kinetic energy (6-7 eV) collide with diatomic oxygen (O_2) molecules, causing them to split into individual, highly reactive oxygen free radicals. These free radicals quickly react and bond with other diatomic oxygen molecules to form the triatomic ozone molecule (O_3) (Joshi *et al.,* 2025) [18].

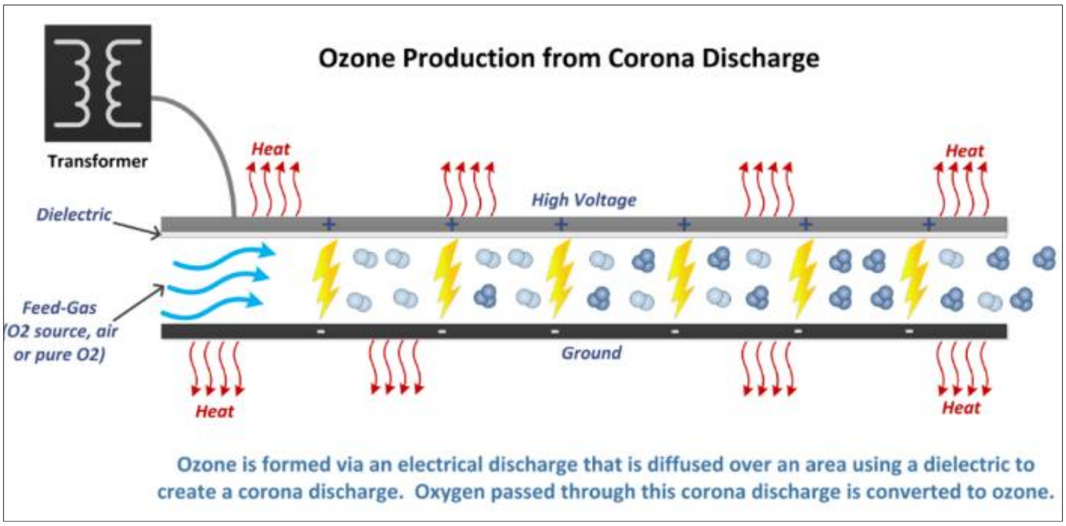

Fig 1: Corona discharge method

Feed Gas Requirements

The efficiency and safety of the CD method depend heavily on the quality of the "feed gas" (the gas entering the generator):

- **Air Preparation:** CD generators require prepared air, such as dry air or concentrated oxygen.
- **Moisture Control:** It is critical that the feed gas is dry, as moisture can react to form corrosive nitric acid, which can damage the generator.
- **Yield Efficiency:** When using ambient air, the generator typically produces 1-5% ozone by weight. However, using high-purity oxygen can boost this output up to 14%, increasing production by 2-3 times for the same energy cost

Ozone production by UV light (Joshi *et al.,* 2025) [18]

The ultraviolet (UV) photochemical method is one of the two primary commercial techniques used to generate ozone. This method mimics the natural process of ozone formation

in the atmosphere by using high-energy light to transform oxygen molecules.
O_2 molecules (either from air or oxygen) are exposed to UV light. The UV light must be tuned to specific wavelengths to be effective. Sources indicate that wavelengths between 140-190 nm are used, with 185 nm and 188 nm specifically highlighted as being used for production. The energy from the UV light splits the diatomic O_2 molecules into individual oxygen atoms. These free radicals then combine with other intact O_2 molecules to form triatomic ozone (O_3). Unlike the corona discharge method, UV generators do not require air preparation (such as drying or concentrating oxygen) to function. While cost-effective, UV technology generally generates less ozone than other methods and is consequently used for more limited applications in food processing and sanitation.

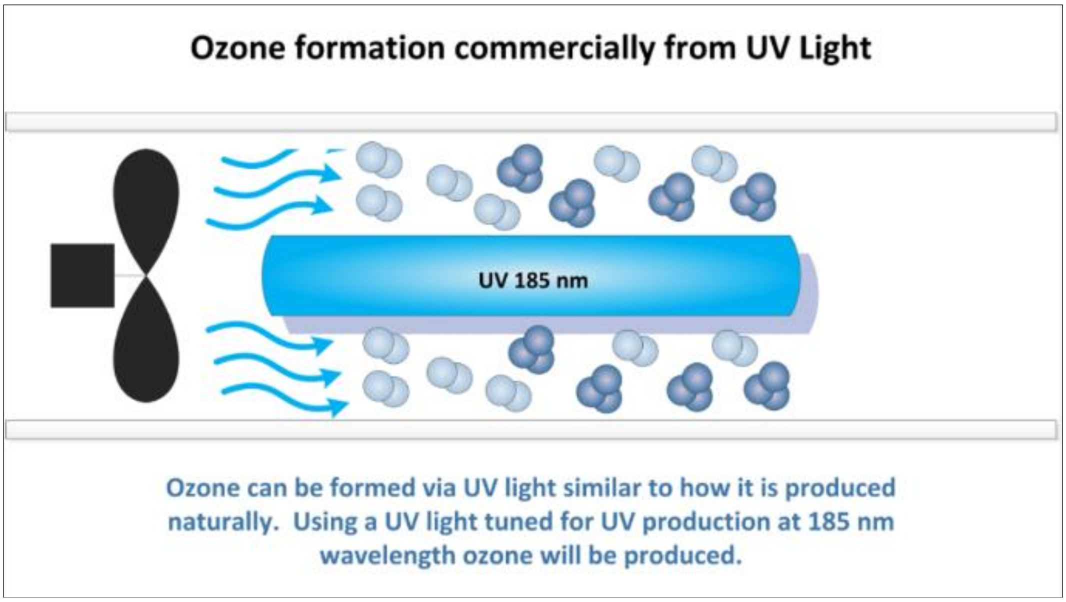

Fig 2: UV method

2.4 Components of ozone system: (Joshi *et al.,* 2025) [18]
A typical ozone system used in food processing and water treatment consists of several integrated components designed to generate, apply, and safely manage ozone gas. According to the sources, the primary components include:

1. Oxygen Concentrator
The process begins by preparing the feed gas. While ambient air contains only about 21% oxygen, an oxygen concentrator supplies oxygen-enriched air (containing more than 90% O_2). These machines use pressure swing adsorption (PSA) technology to filter out dust, remove nitrogen, and dry the air to a dew point of -4°C. Using high-purity oxygen is preferred because it can boost ozone production by 2 to 3 times for the same energy cost.

2. Ozone Generator
This is the core of the system where oxygen is converted into ozone (O_3). There are two primary commercial types:

- **Corona Discharge (CD):** These require prepared, dry air or oxygen. They are more efficient, producing 1-5% ozone by weight from air and up to 14% from high-purity oxygen.
- **Ultraviolet (UV):** These use specific wavelengths (typically 185 nm or 188 nm) to split oxygen molecules. Unlike CD generators, they do not require air preparation but generally produce lower concentrations of ozone.

Cooling System: Because ozone is unstable and heat-sensitive, generators must include air or water cooling systems to prevent the ozone from reverting back into oxygen.

3. Flow Meters
The system uses different meters to regulate the process:

- Mass flow meters measure the total oxygen flow from the concentrator to the generator.
- Ozone flow meters gauge the concentration of ozone by analyzing a small gas stream (typically less than 2 LPM).

4. Treatment Chamber
This is the airtight vessel where ozone is introduced to the product (such as food or water). Ozone can be applied as a gas or dissolved into water for aqueous applications (e.g., ozone dipping or washing). The chamber's size and design are tailored to the specific product being treated to ensure effective exposure while preventing gas leakage.

5. Ozone Analyser
This device monitors the concentration of ozone—measured as a percentage by weight or in grams per cubic meter ($g/m3$)—at both the inlet and outlet of the treatment chamber. It also collects data on exposure time, which is critical for analysing the effectiveness of the treatment

6. Ozone Destructor
Because ozone is toxic even at low concentrations, any excess gas must be eliminated before it is released into the environment. The ozone destructor converts leftover ozone back into safe oxygen, facilitating a safe working environment and ensuring that only non-hazardous by-products are produced.

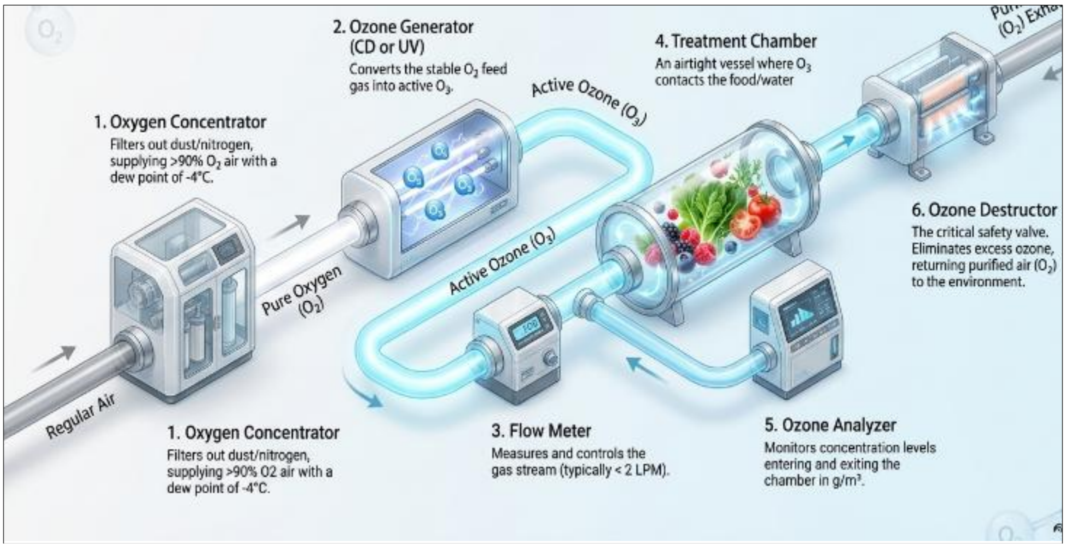

Fig 3: Components in ozone system

2.5 Forms of ozone application (Epella *et al.*, 2022) [14]

Ozone is used to decontaminate surfaces, prevent infection transmission, and ensure the reusability of materials through both gaseous and aqueous applications. The choice between these two forms depends on the specific food product and the desired level of cleaning versus disinfection.

Gaseous Ozone: Produced via ultraviolet (UV) radiation or electrical discharge within a closed chamber. In a food industrial setting, it is often preferred for high-speed decontamination because higher concentrations can be reached rapidly.

Aqueous Ozone: Created by dissolving ozone gas into water or through electrolysis. Its stability is significantly improved by the presence of nanobubbles, which stay in the water longer due to their low buoyancy and resistance to collapsing.

Table 4: Comparision between gaseous and aqueous ozone

Feature	Gaseous Ozonation	Aqueous Ozonation
Moisture Management	Keeps the food or packaging dry, eliminating the need for a secondary drying process.	The product becomes wet, which may require energy-intensive drying for certain food types.
Cleaning vs. Disinfection	Only disinfects or sterilises; a separate cleaning step is required beforehand to remove organic debris.	Allows for simultaneous cleaning and disinfection, making it highly efficient for washing produce or equipment.
Penetration Power	Offers superior penetration into hard-to-reach areas, cracks, or porous surfaces.	Penetration can be limited by liquid surface tension, potentially leaving "hidden" microbes untreated.
Safety and Health	Gaseous ozone is detrimental to human lungs if inhaled and requires strict containment or rapid extraction systems.	There is a significantly reduced impact on human health when the ozone is dissolved in water.
Target Pathogens	Generally more effective against fungi like *A. fumigatus* and bacteria like *E. coli* and *P. aeruginosa*.	Particularly effective against *S. aureus* and better for weakening biofilms and organic matter (like manure) on surfaces.

Industrial Advantages

For dry food products or packaging where moisture could lead to spoilage, gaseous ozone is the superior choice due to its high penetration and lack of wetting. However, for fresh produce or raw food processing environments where organic contaminants are present, aqueous ozone is preferred because it can clean and disinfect in one step while offering a much safer environment for workers. Furthermore, aqueous ozone at 4 ppm can retain its biocidal properties for up to 2 hours, making it a viable alternative for surface sanitation (Epella *et al.,* 2022) [13].

2.6 Mechanism of microbial action of ozone

Ozone acts as a powerful antimicrobial agent by progressively oxidizing essential cellular components, primarily targeting the surface of bacterial cells.

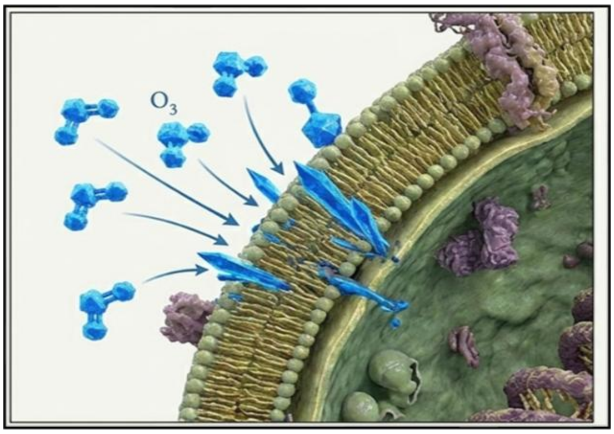

Fig 4: Direct oxidation

Direct and Indirect Pathways

Direct Oxidation: Molecular ozone is utilized for the direct oxidation of target cells. Depending on the electron density of the contaminants, ozone can act as either an electrophilic or nucleophilic agent (Joshi *et al.,* 2025) [18].

Indirect Inactivation (Free Radical Pathway): As ozone decomposes, it generates free radicals which play the "lead role" in inactivation. These radicals are highly reactive and scavenge the microbial cell to cause damage (Joshi *et al.,* 2025) [18].

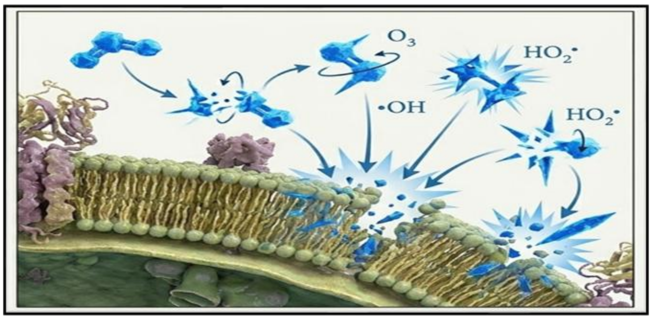

Fig 5: Indirect oxidation

1. Inactivation of gram negative bacteria (Lipid Peroxidation)

This is a critical step that leads to the physical breakdown of the cell. Ozone targets the double bonds of polyunsaturated fatty acids in the cell envelope. This "ozone attack" leads to lipid peroxidation, creating acid peroxides and causing the degradation of unsaturated lipids. This weakens the cell envelope until it suffers cell disruption and cell lysis, leading to the leakage of vital cellular contents in gram negative bacteria like *E. coli*, *Enterobacter sp.,* (Hamid *et al.,* 2024) [16]. Gram-positive bacteria are often slightly more resistant to low ozone concentrations than Gram-negative bacteria. This is because Gram-negative bacteria have an outer membrane rich in lipopolysaccharides and lipoproteins that are highly susceptible to rapid lipid peroxidation and instant cell lysis (Giménez *et al*., 2024; Mohamed & Rasco, 2021) [15, 21].

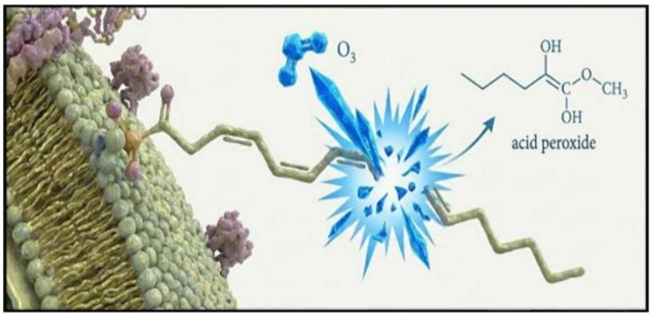

Fig 6: Ozone attacks lipid layer of bacterial cell

2. Inactivation of Gram-Positive Bacteria

Gram-positive bacteria (such as *Listeria monocytogenes*, *Staphylococcus aureus*, and *Bacillus cereus*) possess a thick, highly cross-linked peptidoglycan cell wall (Mohamed & Rasco, 2021) [21]. Ozone targets the cell surface by oxidizing amino acids, peptides, and sulfhydryl groups of proteins embedded within the peptidoglycan layers (Giménez *et al*., 2024) [15]. As ozone disrupts these surface proteins and oxidizes unsaturated fatty acids in the underlying cytoplasmic membrane, the membrane loses its structural integrity (Mohamed & Rasco, 2021) [21]. This alters cell permeability, resulting in the leakage of intracellular contents and eventual cell rupture (lysis) (Mohamed & Rasco, 2021) [21]. Once inside, ozone further deactivates essential metabolic enzymes and destroys nucleic acids, inhibiting the bacteria's ability to replicate or repair itself (Mohamed & Rasco, 2021) [21].

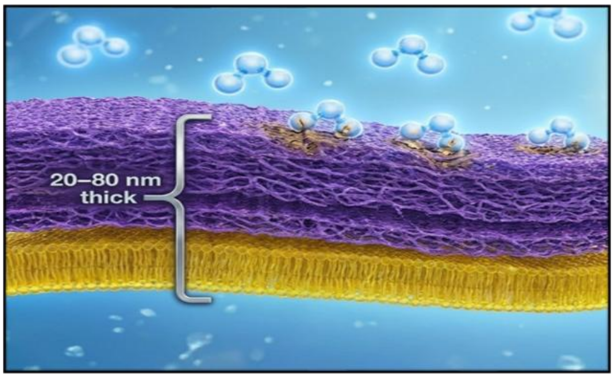

Fig 7: Ozone attacks gram positive cell wall

3. Inactivation of Spores (Bacterial and Fungal)

Microbial spores (such as *Bacillus* spores or *Aspergillus niger* mold spores) are notoriously resistant to conventional chemical and thermal sanitizers due to their complex, multi-layered protective outer coats. However, ozone can actively destroy them (Mohamed & Rasco, 2021) [21]. The principal mechanism against spores is the progressive oxidation of their thick outer protective layers (the spore coat and cortex) (Mohamed & Rasco, 2021) [21]. Ozone breaches this physical barrier by altering the structural proteins and specialized amino acids that maintain coat rigidity. Once the outer protective shield is compromised, ozone penetrates the core of the spore. It oxidizes essential core proteins, inactivates metabolic enzymes necessary for germination, and damages the genetic material (Mohamed & Rasco, 2021) [21]. This permanently inhibits cellular reactivation mechanisms, preventing the spore from germinating back into an active vegetative cell (Mohamed & Rasco, 2021) [21].

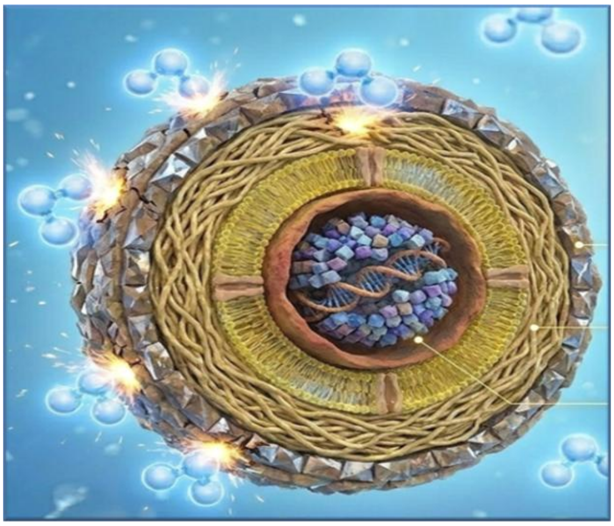

Fig 8: Ozone attacks spores

4. Inactivation of Yeast and Mold (Fungi)

Fungi have a rigid cell wall composed of chitin, glucans, and glycoproteins. Ozone is highly effective at reducing fungal spoilage and even degrading harmful mycotoxins (Giménez *et al*., 2024) [15]. Ozone primarily targets the polyunsaturated fatty acids, glycoproteins, and glycolipids within the fungal cell membrane (Mohamed & Rasco, 2021) [21]. It attacks the carbon-carbon double bonds of these lipids, disrupting the membrane matrix. Vegetative yeast cells (such as *Candida albicans*) are generally more sensitive to ozone treatment than molds (Mohamed & Rasco, 2021) [21]. Mold conidia and defensive structures require significantly higher ozone concentrations and extended exposure times to achieve complete inactivation (Çetinkaya *et al*., 2022) [8].

5.Oxidation of Proteins, Enzymes, and Peptides

Ozone attacks the structural and functional proteins of a microorganism. Ozone oxidizes sulfhydryl groups and amino acids within enzymes, peptides, and proteins. This oxidation breaks down these complex molecules into shorter peptides, which disrupts the biological functions necessary for the cell's survival. In viruses, ozone alters the polypeptide chains in viral protein coats, effectively neutralizing the virus's ability to infect host cells. (Joshi *et al.,* 2025) [18]

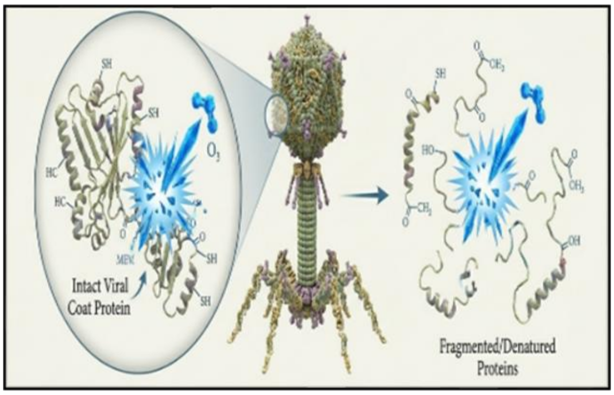

Fig 9: Viral protein destruction

6. Damage to Nucleic Acids (DNA and RNA)

Ozone can permanently damage the genetic material of a microorganism, preventing it from reproducing. Ozone attacks nucleic acids, with thymine being significantly more sensitive to ozone than cytosine or uracil. The ozone damages the DNA and RNA, causing permanent genetic faults that result in inactivation (Joshi *et al.,* 2025) [18].

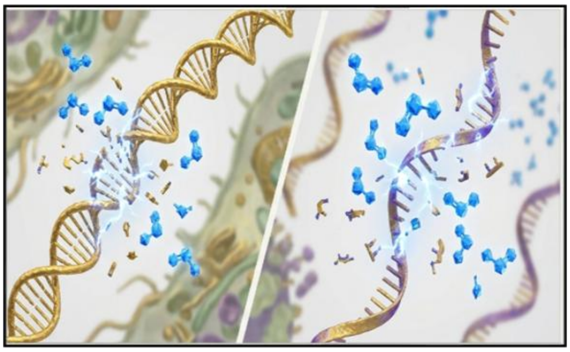

Fig 10: Nucleic acid strands unwinding

These mechanisms allow ozone to effectively target a wide spectrum of microorganisms, including bacteria, fungi, and viruses, making it a potent tool for food preservation and equipment sanitisation.

2.7 Factors affecting ozone efficiency

The efficiency of ozone technology in food preservation is determined by a complex interaction between intrinsic factors related to the food and microorganisms and extrinsic factors related to the treatment environment and process parameters.

1. Intrinsic Factors

These factors are inherent to the biological and physical makeup of the food product and the target contaminants (Xue *et al.,* 2023) [35].

- **Microbial Characteristics:** The type of microorganism, its initial population size (microbial load), and its physiological state significantly impact efficacy. For instance, gaseous ozone is more effective against *Listeria monocytogenes* than *E. coli* or *Salmonella*. High initial pathogen loads generally decrease the percentage of inactivation for the same dose.
- **Food Surface Properties:** Products with smooth surfaces, such as apples or tomatoes, require lower ozone volumes for effective decontamination. Conversely, complex, rough, or porous surfaces (like meat) provide crevices that protect microorganisms, requiring higher concentrations for complete inactivation.
- **Water Activity (*aw*):** The moisture level of the food itself is a major driver of efficiency. In grain storage, increasing the *aw* of wheat from 0.80 to 0.90 significantly enhanced the fungicidal effect of gaseous ozone, likely by facilitating the movement of ozone into the microbial cells.
- **Nutrient Composition (Organic Matter):** The presence of organic matter, such as fats or proteins, reduces ozone's efficiency because ozone reacts with these components instead of the target microorganisms. For example, higher fat content in milk powders has been shown to reduce the antibacterial effect of ozone treatment.

2. Extrinsic Factors

These factors involve the technical settings of the ozone application and the environmental conditions during treatment (Xue *et al.,* 2023) [35].

- **Ozone Concentration and Contact Time:** Efficacy generally increases with higher concentrations and longer exposure times. However, these effects often reach a plateau where further increases do not yield more inactivation, potentially due to the protective structure of the food.
- **Temperature:** Temperature affects both the stability and solubility of ozone. Ozone is more stable and soluble at lower temperatures; in aqueous systems, the highest saturation concentrations are achieved in cold, acidic water (e.g., 8 °C).
- **Relative Humidity (RH):** For gaseous applications, RH is critical. The optimal humidity for ozone gas is 90% to 95%. High RH enhances the inactivation effect, likely because moisture helps ozone penetrate microbial cell walls.
- **pH of the Environment:** In aqueous applications, the pH of the water dictates ozone's stability. Ozone remains more stable under acidic conditions; higher pH levels cause it to dissociate more rapidly, reducing its contact time with the food.
- **Application Method:** The way ozone is delivered—such as bubbling, spraying, rinsing, or dipping affects

results. Bubbling ozone gas directly into water during the washing process is often more effective than simply dipping food in pre-ozonated water.

- **Flow Rate and Pressure:** The velocity at which ozone gas or ozonated water moves through the treatment chamber influences how well it contacts the food surface and maintains a consistent concentration

2.8 Application of ozone in food industry

Table 5: Application of ozone

Product	Ozone concentration and exposure time	Observation	Reference
Raw and branded milk	Concentration: 2 g/L Time: 0,5,10 and 15 min	Complete removal (100% inactivation) at the end of 15 mins.	Sheelamary and Muthukumar, 2011 [30]
Milk (Skimmed and Whole)	28 mg/L for 5 to 15 min	1 log reduction (*P. aeruginosa*)	Munhôs *et al*., 2019
Raw milk	Concentration: 400 mg/h Time: 0,5,10,15,20,25 and 30 min	The ozone treatment for 20 min at 400 mg/h was found to be significantly improve the microbial quality of milk.	Younis *et al*., (2019) [36]
Skim milk powder	2.8 and 5.3 mg/L (gaseous) for 120 min	2.71 to 3.28 log reduction (*Cronobacter*)	Torlak *et al.,* (2013) [34]
Milk and whey concentrate	3.5 g/h (gaseous) for 60 min	Ozone treatment reached 18.9% and 9.9% degradation of the aflatoxin M1 in milk concentrate and whey concentrate, respectively	Sert and Mercan, (2021) [28]
Mozzarella cheese	Cooling water with 2 mg/L (aqueous) at 15 °C	3.58 log (Total Plate Count) and 6.09 log (*Pseudomonas*) reduction	Segat *et al*., (2014) [27]
Minas Frescal cheese (washing)	2 mg/L (aqueous) for 1-2 min	2 log reduction	Cavalcante *et al*., (2013) [7]
Italian Cheese	4 ppm (gaseous) for 8 min	*L. monocytogenes* counts were brought down from 10^3 CFU/g to 10 CFU/g	Morandi *et al*., (2009) [22]
Soft cheese	2-6 mg/m^3 for 30 days	The results showed that gas ozone treatments had a significant fungistatic effect on cheese surface molds for pilot and industrial scale	Tabla and Roa, (2022) [31]
Butter	3.5 g/h (gaseous) for 15-60 min	2.01 log reduction in *Staphylococci*; inactivation of *Salmonella* and coliforms	Sert *et al*., (2020) [29]
Yogurt and cups	2.5-3 ppm (gaseous stream) for 10-60 s	0.6 log CFU/g reduction in mold; delayed spoilage by 15 days	Alexopoulos *et al*., (2017) [2]
Cheese brine	0.20, 0.40 and 2.0 mg/L Time: 30 and 60 min	0.40 mg/L of ozone for a prolonged period of 240 min were able to reduce the Total microbial count >2 log CFU/ml and yeast > 1 log CFU/ml	Marilena Marino *et al.,* (2015)
Beef (carcasses and surfaces)	(aqueous) 12 ppm spray for 12h	1.46 log reduction (*E. coli*)	Kalchayanand *et al.,* (2019) [19]
Beef	154×10^{-6} kg m^{-3} Exposure time - 3 h & 24 h Temperature - 0°C & 4°C.	0.6 to 1 log cycle reduction in *E. coli*	Cárdenas *et al.,* (2011) [6]
Raw chicken	33 mg/min (gaseous) for 9 min	Effective inactivation of *L. monocytogenes*	Muthukumar and Muthuchamy (2013) [25]
Chicken and duck meat	10×10^{-6} kg/m^3/h for 4 days (gaseous)	Reduction in growth of coliform, aerobic and anaerobic bacteria in both chicken and duck breast.	Muhlisin *et al.,* (2016) [23]
Chicken breasts	2000 ppm for 30 min	Gaseous ozone reduced the counts of *Salmonellae* by 97% *and Pseudomonads* by 95%, but indigenous coliforms were unaffected	Al-Haddad *et al.,* (2005) [3]
Pork	Gaseous 100-1000 ppm for 10 min	Effective reduction of microbial growth with increasing ozone concentration.	Jaksch *et al.,* (2004) [17]
Apple	An aqueous ozone concentration: 24 to 25 mg/L, agitated for 1, 3, or 5 min using a magnetic stirrer at 2, 22, 45 °C	3.7 log reduction of *E. coli* after 3 mins	Achen and Yousef, (2001) [1]

2.9 Case Studies

Case Study 1: Ozonation of Raw Cow's Milk (Tampubolon *et al.*, 2025) [33]

This study evaluated the effectiveness of ozone in improving the microbial quality and shelf life of fresh cow's milk collected from 70 dairy farms in West Java, Indonesia. Milk samples were treated with ozone generated at 600 mg/h for 15 minutes, and microbial quality was assessed using the Total Plate Count (TPC) method.

Ozonation achieved an overall 94.5% microbial reduction, with 97.19% reduction of *Escherichia coli* and 95.97% reduction of *Staphylococcus aureus*. The proportion of milk samples meeting the Indonesian National Standard (SNI 3141.1:2011) increased from 20% before treatment to 36% after treatment, while microbial variation among samples also decreased. Younger cows showed greater bacterial reduction than older cows.

In addition to microbial control, ozonation extended the shelf life of raw milk from approximately 6 hours to over 19 hours at room temperature. No significant changes were observed in milk colour, taste, or consistency, although a slight temporary ozone odour was detected. The study concluded that ozone is an effective non-thermal and eco-friendly technology for improving raw milk safety while maintaining its nutritional and sensory quality.

Case Study 2: Ozone Treatment of Gorgonzola Cheese (Panebianco *et al.*, 2022) [26]

This study investigated the effect of low-dose gaseous ozone (2 and 4 ppm for 10 minutes) on *Listeria monocytogenes* inoculated onto Gorgonzola cheese rinds during 63 days of refrigerated storage. The researchers also examined changes in the cheese's natural microbial community using culturomic analysis and MALDI-TOF MS.

Contrary to expectations, ozone treatment did not effectively control *L. monocytogenes*. At the end of storage, ozone-treated samples contained approximately 1 log CFU/g higher Listeria counts than untreated controls. This occurred because ozone reduced populations of beneficial lactic acid bacteria (LAB), particularly mesophilic lactobacilli, which normally suppress pathogen growth through microbial competition (Jameson effect).

Despite this, ozone had little effect on the overall resident microbiota, with dominant genera such as *Candida*, *Carnobacterium*, *Staphylococcus*, *Penicillium*, and *Saccharomyces* remaining relatively stable. The study concluded that low-dose ozone may be counterproductive in complex fermented foods, where preserving beneficial microorganisms is essential for natural pathogen inhibition.

Case Study 3: Environmental Control of *Listeria* in a Cheese Processing Facility (Eglezos & Dykes, 2018) [12]

This study evaluated the use of gaseous ozone as a supplementary sanitation method in a cheese processing plant in Queensland, Australia, where persistent environmental *Listeria* contamination remained despite conventional cleaning practices. Ozone was generated on-site and applied automatically in production rooms after working hours, with routine daily treatments and extended weekend exposure at ≥2 ppm.

Over a 12-month period, analysis of 360 environmental samples showed that *Listeria* contamination decreased significantly from 15.0% before ozonation to 1.67% after ozonation ($P< 0.001$). Complete elimination of *Listeria* was achieved in boot wash and shredding areas, while contamination in the slicing room decreased from 20% to 3.33%. Noticeable reductions became evident after approximately six months of continuous treatment.

Importantly, prolonged ozone use caused no observable damage to processing equipment, stainless steel surfaces, flooring, or wall panels. The study concluded that gaseous ozone is an effective residue-free terminal sanitation method that complements conventional cleaning by reaching inaccessible areas and significantly reducing environmental *Listeria* contamination.

2.10 Advantages and disadvantages of ozone

Pros of ozone technology (Chuwa *et al.*, 2020) [10]

- It only requires oxygen or air for its production.
- It is faster and better at killing microbes than chlorine.
- It is a non-thermal way to control pathogens and microbes in food processing.
- It is a non-chemical alternative for treating water and sanitizing food contact surfaces.
- It saves money because water does not have to be heated.
- It is compatible with organic food processing.
- It can be generated onsite, so no storage is required.
- It is eco-friendly, leaves no residues in food or water.
- It can be applied in an aqueous or gaseous state.
- Strong antimicrobial activity
- Effective even at low concentrations
- Broad-spectrum activity

Cons of ozone technology (Chuwa *et al.*, 2020) [10]

- It could damage rubber and other polymers used for gaskets and o-rings.
- Its active life in water is less than 30 minutes, so it cannot be stored or moved.
- Like chlorine ozone is not selective.
- It will oxidize all organic material present.
- Ozone is instable and must produce before usage and can't be stored
- Toxicity at high concentration
- Initial Equipment cost is more
- Corrosion issues persists
- Limited penetration in some foods.

2.11 General consideration in ozone

Safety considerations for using ozone are primarily focused on its high reactivity with organic matter, including the human body, and the potential for both acute and chronic toxicity. While ozone is classified as Generally Recognized as Safe (GRAS) for food use, its application requires strict adherence to environmental and operational guidelines.

Human Health Impacts

Exposure to ozone gas can significantly affect the human respiratory tract. The severity of the health impact depends on the concentration of the gas and the duration of exposure. Health effects are categorized into three zones: acceptable, hazardous, and critical (Dubey *et al.,* 2022) [11].

- **Acute Toxicity Symptoms:** Exposure can cause burning sensations in the eyes and throat, headaches, coughing, and dizziness.
- **Chronic Toxicity Symptoms:** Long-term exposure may lead to memory loss, bronchitis, and muscular excitability.

Workplace Safety Limits

To ensure worker safety in the food industry, regulatory bodies have established specific exposure limits:

OSHA Limit: The Occupational Safety and Health Administration (OSHA) has set an endorsed limit of 0.1 ppm (parts per million) for an 8-hour exposure period in the workplace (Li *et al.,* 2026) [20].

1. **Fumigation Practices:** It is advised that the fumigation of crops in storage rooms be performed at night or when workers are absent to minimize contact.
2. **Lab Precautions:** Potassium iodine solutions are used to absorb excess liberated ozone gas to prevent it from entering the air (Dubey *et al.,* 2022) [11].

Operational and Environmental Factors

The physical environment can influence the risks associated with ozone:

1. **Temperature and Pressure:** High pressure and warm water can increase the chances of ozone toxicity.
2. **Ventilation:** Areas where ozone is applied should be covered in a way that allows air to be liberated easily.
3. **Instability:** Because ozone is unstable and decays rapidly into oxygen, it cannot be collected or stored; it must be generated continuously at the time of use. This instability is also affected by pH; for example, its half-life is significantly longer in acidic media (7 hours at pH 4) than in alkaline conditions (25 seconds at pH 10) (Dubey *et al.,* 2022) [11].

Considerations for Food Quality

Safety in ozonation also extends to the integrity of the food products themselves. Improper utilization can have "lethal effects" on the physiology and quality of food (Dubey *et al.*, 2022) [11].

1. **Decoloration:** Highly pigmented fruits and vegetables are susceptible to decoloration due to ozone's strong oxidizing potential.
2. **Lipid Stability:** Ozone can affect the stability of high-fat foods, such as dairy products.
3. **Optimization:** To avoid adverse effects, it is vital to define the optimal concentration and contact time for different types of food products

Challenge to industry (Dubey *et al.*, 2022) [11]

1. **Organic Matter:** The presence of organic matter in the treatment medium can either promote or inhibit the radical chain reactions of ozone, making it difficult to determine a universal effective concentration for all products.
2. **Bacterial Regrowth:** Breakdown products of organic contaminants during ozonation can actually serve as nutrients for remaining bacteria, potentially leading to noticeable bacterial growth in ozone-sterilized water
3. **Optimization Needs:** Because ozone efficacy varies by species and product, the **optimal concentration and contact time** must be precisely defined for every different type of food to avoid quality loss.
4. **System Design:** Plant operators face hurdles related to process operation and system design when integrating ozone into a facility.
5. **Consumer Perception**: The industry must still address consumer acceptability regarding ozone-treated food products

2.12 Future prospects of ozone technology

The prospects for ozone technology in the food processing industry are considered bright and expansive, particularly as an alternative to traditional chemical disinfectants. Its potential to provide a chemical-free, cost-effective, and safe method for ensuring food safety makes it a focal point for researchers, regulating authorities, and consumers. Key areas for future growth and the specific developments needed to realize its full potential include:

- **Expanded Industrial Applications:** Ozone is expected to play an increasingly vital role in various operational sectors beyond simple food disinfection:
- **"Hurdle" Technology and Combinations:** Ozone's antimicrobial efficacy is significantly boosted when combined with other methods like ultraviolet radiation, ultrasound, or edible coatings. This synergy lowers the required ozone dosage, protecting the sensory and nutritional qualities of sensitive foods
- **Wastewater Recycling and Treatment:** Its ability to disinfect wash water and facilitate wastewater recycling is a major perspective for future industrial sustainability.
- **Sanitization of Infrastructure:** It is projected to become a standard, potent sanitizer for plant equipment, including **Cleaning in Place (CIP)** systems, due to its lack of hazardous residues.
- **Contamination-Free Supply Chains:** Wider commercialisation of the technology aims to ensure a safe, contamination-free supply chain from harvest to packaging.

AI integration: Ozone concentration, exposure limit, product specific ozone standardization can be monitored easily with less human intervention.

These prospects paved the way for better utilization of ozone technology in the field of food preservation and sanitization.

3. Conclusion

Ozone is a promising emerging food preservation technology that offers effective microbial control and shelf-life extension without leaving harmful chemical residues. Its strong oxidizing power, broad-spectrum antimicrobial activity, and environmentally friendly nature make it an attractive alternative to conventional preservatives. Although challenges such as equipment cost, process optimization, and potential quality changes at high doses remain, ongoing research and technological advancements are expanding its applications across dairy, meat, fruits, vegetables, and food-processing industries. With increasing consumer demand for safe, minimally processed, and sustainable foods, ozone has significant potential to play an important role in the future of food preservation.

References

1. Achen M, Yousef AE. Efficacy of ozone against *Escherichia coli* O157:H7 on apples. Journal of Food Science. 2001;66(9):1380-1384.
2. Alexopoulos A, Plessas S, Kourkoutas Y, Stefanis C, Vavias S, Voidarou C, *et al.* Experimental effect of ozone upon the microbial flora of commercially produced dairy fermented products. International Journal of Food Microbiology. 2017;246:5-11.
3. Al-Haddad KS, Al-Qassemi RA, Robinson R. The use of gaseous ozone and gas packaging to control populations of *Salmonella* Infantis and *Pseudomonas aeruginosa* on the skin of chicken portions. Food Control. 2005;16(5):405-410.
4. Arora SK, Dobhal N, Tiwari B, Gupta A. Traditional Indian methods to preserve food. International Journal of Environment, Agriculture and Biotechnology. 2025;10(3):246-251.
5. Botondi R, Lembo M, Carboni C, Eramo V. The use of ozone technology: An eco-friendly method for the sanitization of the dairy supply chain. Foods. 2023;12(5):987.
6. Cárdenas FC, Andres S, Giannuzzi L, Zaritzky N. Antimicrobial action and effects on beef quality attributes of a gaseous ozone treatment at refrigeration temperatures. Food Control. 2011;22(8):1442-1447.
7. Cavalcante D, Júnior BL, Tribst A, Cristianini M. Microbiological quality of Minas Frescal cheese treated with ozonated water. International Food Research Journal. 2013;20(5):2911-2916.
8. Çetinkaya N, Pazarlar S, Paylan İC. Ozone treatment inactivates common bacteria and fungi associated with selected crop seeds and ornamental bulbs. Saudi Journal of Biological Sciences. 2022;29(11):103480.
9. Chacha JS, Zhang L, Ofoedu C, Suleiman R, Dotto JM, Roobab U, *et al.* Revisiting non-thermal food processing and preservation methods—Action

mechanisms, pros and cons: A technological update (2016-2021). Foods. 2021;10(6):1430.
10. Chuwa C, Vaidya D, Kathuria D, Gautam S, Sharma S, Sharma B. Ozone (O_3): An emerging technology in the food industry. Food and Nutrition Journal. 2020;5:224.
11. Dubey P, Singh A, Yousuf O. Ozonation: An evolving disinfectant technology for the food industry. Food and Bioprocess Technology. 2022;15(9):2102-2113.
12. Eglezos S, Dykes GA. Reduction of environmental *Listeria* using gaseous ozone in a cheese processing facility. Journal of Food Protection. 2018;81(5):795-798.
13. Epelle EI, Emmerson A, Nekrasova M, Macfarlane A, Cusack M, Burns A, *et al*. Microbial inactivation: Gaseous or aqueous ozonation? Industrial & Engineering Chemistry Research. 2022;61(28):9600-9610.
14. Epelle EI, Macfarlane A, Cusack M, Burns A, Okolie JA, Mackay W, *et al*. Ozone application in different industries: A review of recent developments. Chemical Engineering Journal. 2022;454:140188.
15. Giménez B, Zaritzky N, Graiver N. Ozone treatment of meat and meat products: A review. Frontiers in Food Science and Technology. 2024;4:1351801.
16. Hamid Z, Meyrick BK, Macleod J, Heath EA, Blaxland J. The application of ozone within the food industry: Mode of action, current and future applications, and regulatory compliance. Letters in Applied Microbiology. 2024;77(11):ovae101.
17. Jaksch D, Margesin R, Mikoviny T, Skalny JD, Hartungen E, Schinner F, *et al*. The effect of ozone treatment on the microbial contamination of pork meat measured by detecting the emissions using PTR-MS and by enumeration of microorganisms. International Journal of Mass Spectrometry. 2004;239(2-3):209-214.
18. Joshi MM, Pawar VS, Agarkar BS, Lolge RM. Ozone: A green technology for food preservation and safety. Indian Food Industry Magazine. 2025;4(1):41-52.
19. Kalchayanand N, Worlie D, Wheeler T. A novel aqueous ozone treatment as a spray chill intervention against *Escherichia coli* O157:H7 on surfaces of fresh beef. Journal of Food Protection. 2019;82(11):1874-1878.
20. Li T, Zheng P, Li X, Lu Y, Şen A, Siriwattananon L, *et al*. Advances in ozone oxidation technology: Mechanisms, applications, and challenges in postharvest fruit preservation. Comprehensive Reviews in Food Science and Food Safety. 2026;25(2):e70437.
21. Mohamed Z, Rasco B. Inactivation of microbes by ozone in the food industry: A review. African Journal of Food Science. 2021;15(4):113-120.
22. Morandi S, Brasca M, Lodi R, Battelli G. Use of ozone to control *Listeria monocytogenes* in various types of cheese. Scienza e Tecnica Lattiero-Casearia. 2009;60:211-215.
23. Muhlisin M, Utama DT, Lee JH, Choi JH, Lee SK. Effects of gaseous ozone exposure on bacterial counts and oxidative properties in chicken and duck breast meat. Korean Journal for Food Science of Animal Resources. 2016;36(3):405-412.
24. Munhõs M, Navarro R, Nunez S, Kozusny-Andreani D, Baptista A. Paper presented at the XXVI Brazilian Congress on Biomedical Engineering; 2018 Oct 21-25; Armação de Búzios, Rio de Janeiro, Brazil.
25. Muthukumar A, Muthuchamy M. Optimization of ozone in gaseous phase to inactivate *Listeria monocytogenes* on raw chicken samples. Food Research International. 2013;54(1):401-406.
26. Panebianco F, Rubiola S, Buttieri C, Di Ciccio PA, Chiesa F, Civera T. Understanding the effect of ozone on *Listeria monocytogenes* and resident microbiota of Gorgonzola cheese surface: A culturomic approach. Foods. 2022;11(17):2640.
27. Segat A, Biasutti M, Iacumin L, Comi G, Baruzzi F, Carboni C, *et al*. Use of ozone in production chain of high-moisture mozzarella cheese. LWT - Food Science and Technology. 2014;55(2):513-520.
28. Sert D, Mercan E. Effects of ozone treatment to milk and whey concentrates on degradation of antibiotics and aflatoxin and physicochemical and microbiological characteristics. LWT - Food Science and Technology. 2021;144:111226.
29. Sert D, Mercan E, Kara Ü. Butter production from ozone-treated cream: Effects on characteristics of physicochemical, microbiological, thermal and oxidative stability. LWT - Food Science and Technology. 2020;131:109722.
30. Sheelamary M, Muthukumar M. Effectiveness of ozone in inactivating *Listeria monocytogenes* from milk samples. World Journal of Young Researchers. 2011;1(3):40-44.
31. Tabla R, Roa I. Use of gaseous ozone in soft cheese ripening: Effect on the rind microorganisms and the sensorial quality. LWT. 2022;170:114066.
32. Talib A, Samad A, Hossain MJ, Muazzam A, Anwar B, Atique R, *et al*. Modern trends and techniques for food preservation. Food Life. 2024;2024(1):19-32.
33. Tampubolon BD, Setyoko AT, Bangun DA, Gultom RBF, Anggundari WC, Anggraeni P, *et al*. Effect of ozonation on microbiological quality, nutritional value, and shelf life of fresh cow's milk. International Journal of Design & Nature and Ecodynamics. 2025;20(5):1093-1102.
34. Torlak E, Sert D. Inactivation of *Cronobacter* by gaseous ozone in milk powders with different fat contents. International Dairy Journal. 2013;32(2):121-125.
35. Xue W, Macleod J, Blaxland J. The use of ozone technology to control microorganism growth, enhance food safety and extend shelf life: A promising food decontamination technology. Foods. 2023;12(4):814.
36. Younis FI, Fayed AE, Elbatawy OI, Elsisi A. A comparison between ozonation and thermal process in relation to cow's milk attributes with emphasis on pathogens. Arab Universities Journal of Agricultural Sciences. 2019;27(5):2593-2600.