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Ozone Technology in Food Processing and Preservation: Recent Advances, Sustainable Applications, Mechanisms, and Future Perspectives for Enhanced Food Safety

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ABSTRACT: Ozone technology has emerged as a promising non-thermal and eco-friendly approach in modern food processing and preservation, driven by increasing consumer demand for safe, minimally processed, and chemical-free foods. Ozone (O₃), a powerful oxidizing agent, exhibits strong antimicrobial activity against a wide range of foodborne pathogens, including bacteria, fungi, and viruses, making it highly effective for decontamination of fruits, vegetables, meat, seafood, grains, and processing environments. The application of ozone in food systems spans multiple domains, including washing and sanitizing of raw materials, disinfection of process water and equipment, odor removal, and surface decontamination. It can be applied in both gaseous and aqueous forms, enabling versatility across different food matrices and processing conditions. Importantly, ozone decomposes rapidly into oxygen without leaving harmful residues, aligning with the principles of green processing and clean-label food production. Ozone treatment has been shown to enhance shelf life while maintaining the sensory, nutritional, and physicochemical quality of food products. It can delay microbial spoilage, inhibit enzymatic browning, and in some cases stimulate beneficial biochemical responses such as increased antioxidant activity. Additionally, its application in post-harvest handling and storage contributes to improved food safety and reduced post-harvest losses. Despite these advantages, the effectiveness of ozone depends on several intrinsic and extrinsic factors, including concentration, exposure time, temperature, humidity, and the nature of the food matrix. Improper application may lead to quality deterioration or oxidative damage, necessitating optimized processing parameters and strict control measures.

Overall, ozone technology represents a sustainable and innovative solution for modern food preservation, offering significant potential to replace or complement conventional chemical sanitizers and thermal treatments. Future research is expected to focus on process optimization, integration with other non-thermal technologies, and large-scale industrial implementation to fully harness its benefits for global food safety and security.

1. INTRODUCTION

Food safety and preservation remain central challenges in the global food system, driven by increasing population demands, globalization of food supply chains, and heightened consumer awareness regarding food quality. The modern food industry is under continuous pressure to deliver safe, nutritious, and minimally processed foods while extending shelf life and reducing post-harvest losses. Conventional preservation methods, though effective, often compromise food quality and sustainability, thereby necessitating the exploration of innovative technologies such as ozone-based processing.

1.1 Importance of Food Safety and Preservation

Food preservation is defined as the process of extending the shelf life of food products beyond their natural spoilage period while ensuring safety and quality. It is essential to control microbial growth, enzymatic reactions, and physicochemical deterioration that lead to food spoilage (Parray et al., 2025; Fellows, 2017). Foodborne diseases remain a major global concern, caused by pathogens such as *Salmonella spp.*, *Listeria monocytogenes*, and *Escherichia coli*, which contaminate food at various stages of production and distribution. Effective preservation methods are therefore essential to reduce health risks and improve public safety (Xue et al., 2023). Post-harvest losses significantly affect global food security. It is estimated that a substantial portion of food production is lost due to microbial spoilage and inadequate preservation technologies. Preservation not only enhances shelf life but also reduces food waste and improves economic sustainability. Moreover, consumer preferences have shifted toward fresh, minimally processed foods with high nutritional value and no chemical additives. This has created a demand for “clean-label” technologies that ensure safety without compromising food quality (Singh and Heldman, 2014). Ozone technology fits well within this framework due to its residue-free nature and strong antimicrobial activity.

1.2 Limitations of Conventional Preservation Methods

Conventional food preservation methods such as thermal processing, refrigeration, drying, and chemical preservation have been widely used in the food industry. However, these techniques exhibit several drawbacks that limit their effectiveness in modern food systems. Thermal processing methods, including pasteurization and sterilization, effectively reduce microbial populations but can lead to degradation of heat-sensitive nutrients, changes in flavor, and undesirable texture modifications (Fellows, 2017). Chemical preservatives, although effective, are increasingly viewed negatively due to potential health risks and consumer concerns about synthetic additives is shown in table 1. The growing demand for natural and additive-free foods has reduced the acceptance of chemical preservation methods (Pandiselvam et al., 2019). Refrigeration and freezing slow microbial growth but do not eliminate microorganisms completely. These methods also require continuous energy input, contributing to environmental and economic burdens. Furthermore, some microorganisms can survive under low-temperature conditions. Additionally, no single conventional method is universally effective against all types of microorganisms in diverse food matrices, highlighting the need for alternative preservation approaches (Mahapatra et al., 2005)

Table 1. Comparison of Conventional Preservation Methods and Their Limitations

Method	Principle	Advantages	Limitations
Thermal Processing	Heat inactivation	Effective microbial kill	Nutrient loss, sensory degradation
Refrigeration	Low temperature	Slows spoilage	Energy-intensive, incomplete inactivation
Freezing	Ice crystal formation	Long shelf life	Texture damage, thawing issues
Chemical Preservatives	Microbial inhibition	Cost-effective	Health concerns, residues
Drying	Moisture removal	Shelf stability	Loss of nutrients and flavor

1.3 Emergence of Non-Thermal Technologies

To address the limitations of conventional preservation methods, non-thermal technologies have emerged as promising alternatives. These technologies aim to ensure microbial safety while preserving the nutritional and sensory quality of food products. Non-thermal technologies include high-pressure processing (HPP), pulsed electric fields (PEF), ultraviolet (UV) radiation, cold plasma, and ozonation. Among these, ozone has gained particular importance due to its high oxidation potential and broad-spectrum antimicrobial activity.

Ozone (O_3) is a powerful oxidizing agent capable of destroying bacteria, fungi, viruses, and spores by oxidizing cellular components such as lipids, proteins, and nucleic acids. It has been widely used in food processing for sanitization, water treatment, and surface decontamination (Guzel-Seydim et al., 2004; Nath et al., 2014). A key advantage of ozone is its rapid decomposition into oxygen, leaving no harmful residues, which makes it an environmentally friendly and sustainable preservation method (Xue et al., 2023; Pandiselvam et al., 2019). Ozone can be applied in both gaseous and aqueous forms, providing flexibility in treating different food products such as fruits, vegetables, meat, seafood, and grains. Studies have demonstrated its effectiveness in reducing microbial load and extending shelf life while maintaining product quality (Parrray et al., 2025; Tiwari et al., 2010).

1.4 Scope and Objectives of the Review

The increasing demand for sustainable and non-thermal food processing technologies, this review aims to provide a comprehensive analysis of ozone technology in food processing and preservation.

The primary objectives of this review include:

- Understanding the physicochemical properties and antimicrobial mechanisms of ozone
- Evaluating its applications in different food sectors
- Assessing its impact on food quality, safety, and shelf life
- Comparing its advantages over conventional preservation methods
- Identifying limitations, safety concerns, and regulatory aspects
- Highlighting emerging trends and future research directions

This review also emphasizes the role of ozone as a green technology that aligns with modern food industry requirements for sustainability, clean-label processing, and reduced environmental impact. By critically analyzing current research findings, this study aims to provide a scientific basis for the effective implementation of ozone technology in food systems.

2. OZONE: PROPERTIES AND MECHANISM OF ACTION

Ozone (O_3) is a highly reactive triatomic form of oxygen widely used in food processing due to its strong oxidizing capacity and broad-spectrum antimicrobial activity. Its application in food systems is primarily driven by its ability to inactivate microorganisms, degrade chemical contaminants, and decompose into oxygen without leaving harmful residues. These unique characteristics make ozone an environmentally sustainable and efficient alternative to conventional chemical sanitizers (Premjit et al., 2022; Kim et al., 1999; Rice, 2002)

2.1 Chemical and Physical Properties of Ozone

Ozone is a pale blue gas with a characteristic pungent odor, formed by three oxygen atoms arranged in a bent molecular structure. This structure contains weak bonds and unpaired electrons, contributing to its high instability and reactivity. The oxidation potential of ozone (2.07–2.08 V) is significantly higher than that of chlorine, enabling it to oxidize a wide range of organic and inorganic substances, including microbial cell components. Due to its instability, ozone decomposes rapidly into molecular oxygen, particularly in aqueous environments, with a half-life of approximately 20–30 minutes depending on conditions. Ozone is more soluble in water than oxygen and exhibits higher antimicrobial efficiency in aqueous form. However, its solubility decreases with increasing temperature and pH, affecting its practical applications in food systems. Additionally,

ozone can react via direct oxidation or indirectly through the formation of reactive oxygen species (ROS), such as hydroxyl radicals, enhancing its effectiveness in microbial inactivation.

2.2 Methods of Ozone Generation (Corona Discharge, UV Radiation, Electrolysis)

Ozone is not stored due to its instability and must be generated on-site. It is produced by dissociating oxygen molecules into atomic oxygen, which subsequently recombines to form ozone.

The primary methods of ozone generation include:

(i) Corona Discharge Method

This is the most widely used industrial method. High-voltage electrical discharge is passed through oxygen or air, causing the dissociation of O_2 molecules into atomic oxygen, which recombines to form O_3 . This method offers high efficiency and is suitable for large-scale applications (Rice, 2002; Rakness, 2005).

(ii) Ultraviolet (UV) Radiation Method

In this method, ultraviolet light (wavelength <240 nm) splits oxygen molecules into atomic oxygen, which then forms ozone. This technique is commonly used for small-scale applications and water treatment but has lower efficiency compared to corona discharge.

(iii) Electrolysis Method

Electrolysis of water produces ozone by generating oxygen radicals at the anode. This method produces high-purity ozone and is suitable for specialized applications such as medical and high-purity water treatment systems. Each method has its advantages and limitations depending on the scale, cost, and intended application in food processing (Ziyaina and Rasco, 2021).

2.3 Mechanism of Antimicrobial Action

The antimicrobial activity of ozone is primarily attributed to its strong oxidizing ability, which disrupts critical cellular components of microorganisms.

Ozone inactivates microorganisms through the following mechanisms:

- **Oxidation of Cell Membrane Lipids:** Ozone reacts with unsaturated fatty acids in microbial cell membranes, leading to increased permeability and cell lysis.
- **Protein Oxidation:** It modifies proteins and enzymes, disrupting metabolic pathways.
- **Nucleic Acid Damage:** Ozone can damage DNA and RNA, inhibiting replication and transcription.
- **Oxidative Stress Induction:** It generates reactive oxygen species (ROS), leading to cellular damage and death.

These effects collectively result in the inactivation of bacteria, fungi, viruses, and spores. Ozone has been shown to be effective against a wide range of foodborne pathogens and spoilage microorganisms. Unlike conventional disinfectants, ozone does not rely on residual toxicity but instead rapidly oxidizes microbial components, making it highly efficient for food safety applications.

2.4 Factors Affecting Ozone Efficacy (pH, Temperature, Humidity, Organic Load)

The effectiveness of ozone treatment depends on several intrinsic and extrinsic factors that influence its stability, solubility, and reactivity is shown in table 2.

Table 2. Factors Affecting Ozone Efficacy in Food Systems

Factor	Effect on Ozone Activity
pH	Higher pH accelerates ozone decomposition, reducing effectiveness
Temperature	Increased temperature reduces ozone solubility and stability

Humidity	High humidity enhances microbial inactivation in gaseous ozone
Organic Load	Organic matter consumes ozone, reducing antimicrobial efficiency
Exposure Time	Longer exposure increases microbial reduction
Concentration	Higher concentration improves effectiveness but may damage food

pH: Ozone is more stable in acidic conditions, while alkaline pH accelerates its decomposition.

Temperature: Higher temperatures reduce ozone solubility and increase its decomposition rate.

Humidity: In gaseous applications, higher relative humidity enhances ozone's antimicrobial activity by facilitating its interaction with microbial cells.

Organic Matter: The presence of organic compounds can react with ozone, reducing its availability for microbial inactivation.

Additionally, intrinsic factors such as food surface characteristics, microbial load, and product composition also influence ozone effectiveness.

3. FORMS AND MODES OF OZONE APPLICATION IN FOOD SYSTEMS

Ozone can be applied in multiple forms in food processing systems, primarily as gaseous ozone, aqueous ozone, and in combination with ice or packaging environments. The choice of application mode depends on the type of food matrix, processing requirements, and desired level of microbial reduction. Ozone's versatility in both gaseous and dissolved states allow it to be used across a wide range of food industries, including fresh produce, meat, seafood, grains, and beverages (Nath et al., 2014; Hamid et al., 2024).

3.1 Gaseous Ozone Treatment

Gaseous ozone is widely used in food storage, packaging environments, and surface decontamination processes is shown in fig.1. Due to its high diffusivity, ozone gas can penetrate crevices and inaccessible areas, making it effective for disinfecting food surfaces and storage facilities.

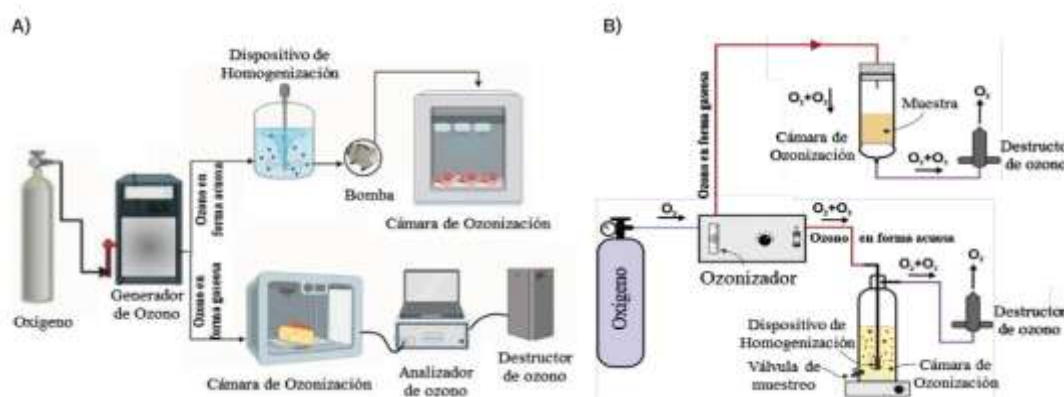


Figure 1: Gaseous Ozone Treatment

Gaseous ozone is commonly applied in:

- Cold storage rooms for fruits and vegetables
- Grain storage facilities as a fumigant alternative to methyl bromide
- Meat and seafood storage environments
- Food processing equipment and air sanitation

Studies have shown that gaseous ozone effectively reduces microbial load and delays spoilage in fresh produce such as apples, berries, and leafy vegetables (Tzortzakakis, 2007; Hamid et al., 2024). It is also used to control airborne microorganisms and odors

in food processing environments. However, its effectiveness depends on factors such as gas concentration, exposure time, and relative humidity. Excessive ozone exposure may lead to oxidative damage, affecting food quality attributes such as color and texture. Additionally, worker safety must be considered due to ozone's toxicity at high concentrations.

3.2 Aqueous Ozone Treatment

Aqueous ozone is one of the most widely used forms of ozone in food processing, particularly for washing and sanitizing fresh produce and food contact surfaces.

Ozone dissolved in water exhibits higher antimicrobial efficiency compared to gaseous ozone due to better contact with microbial cells. It is extensively used for:

- Washing fruits and vegetables
- Sanitizing meat and seafood surfaces
- Disinfection of processing water and equipment
- Removal of pesticide residues

Aqueous ozone acts through both direct oxidation and indirect reactions involving hydroxyl radicals, enhancing microbial inactivation efficiency (Premjit et al., 2022). It also decomposes rapidly into oxygen, leaving no harmful residues, making it suitable for clean-label processing.

Despite its advantages, aqueous ozone has limitations such as short half-life and reduced effectiveness in the presence of organic matter. Efficient mass transfer systems, such as bubble diffusers, are required to ensure proper dissolution and uniform distribution of ozone in water (Graham, 2000; Pandiselvam et al., 2019).

3.3 Ozonated Ice and Water

Ozonated ice is an emerging application of ozone technology, particularly in the seafood and meat industries. It involves the incorporation of ozone into ice or chilled water systems used for storage and transportation.

Ozonated ice offers several advantages:

- Continuous release of ozone during melting
- Extended shelf life of perishable products
- Reduction of microbial contamination during storage

This method is particularly effective in preserving fish and seafood, where it inhibits microbial growth and slows down spoilage reactions. Ozonated ice has been reported to maintain freshness and quality by reducing bacterial load and enzymatic activity (Parray et al., 2025; Gimenez et al., 2024). Ozonated chilled water systems are used in processing lines for meat and poultry to reduce contamination during washing and handling stages. The combined cooling and antimicrobial effects enhance overall preservation efficiency.

3.4 Ozone in Packaging and Storage Environments

Ozone is increasingly being integrated into food packaging and storage systems to enhance product safety and shelf life is shown in table 3. It can be applied directly within packaging environments or used to sanitize packaging materials.

Applications include:

- Active packaging systems incorporating ozone generators
- Modified atmosphere storage combined with ozone treatment
- Sanitization of packaging materials before filling
- Cold storage environments with controlled ozone levels

Ozone has been shown to effectively reduce microbial contamination on packaging surfaces and prevent cross-contamination during storage (Nath et al., 2014). It is also used in controlled atmosphere storage of fruits and vegetables to delay ripening and extend shelf life. However, ozone interaction with packaging materials must be carefully considered, as it may cause degradation of certain polymers. Studies indicate that materials such as polyethylene and polypropylene exhibit varying levels of resistance to ozone exposure (Karaca and Smilanick, 2011).

Table 3. Comparison of Ozone Application Modes in Food Systems

Application Mode	Advantages	Limitations
Gaseous Ozone	High penetration, effective air disinfection	Oxidative damage risk, safety concerns
Aqueous Ozone	High antimicrobial efficiency, residue-free	Short half-life, affected by organic matter
Ozonated Ice	Continuous ozone release, ideal for seafood	Limited large-scale adoption
Packaging Ozone	Prevents cross-contamination, extends shelf life	Material compatibility issues

4. APPLICATIONS OF OZONE IN FOOD PROCESSING

Ozone technology has gained significant attention in food processing due to its strong oxidizing ability, broad-spectrum antimicrobial activity, and residue-free decomposition into oxygen. It is widely applied across various food sectors, including fresh produce, meat, seafood, dairy, cereals, and beverages. Ozone can be applied in gaseous and aqueous forms, enabling flexibility in industrial processing operations (Nath et al., 2014; Prabha et al., 2015; Pandiselvam et al., 2019). Its effectiveness in microbial inactivation, pesticide degradation, and shelf-life extension has made it a promising alternative to conventional chemical sanitizers (Rice, 2002; Kim et al., 1999; Brodowska et al., 2018).

4.1 Fruits and Vegetables (Washing, Surface Decontamination)

Fresh fruits and vegetables are highly susceptible to microbial contamination and post-harvest spoilage. Ozone treatment, particularly in aqueous form, is widely used for washing and sanitizing produce. Ozone effectively reduces microbial populations, including bacteria, fungi, and yeasts, by oxidizing cellular components. It also helps in degrading pesticide residues and removing organic contaminants from produce surfaces (Karaca and Velioglu, 2007). Recent studies indicate that ozonation can delay ripening, reduce enzymatic browning, and extend shelf life without significantly affecting nutritional quality (Botondi et al., 2021; Food Chemistry, 2025). However, improper ozone exposure may cause oxidative damage, leading to texture softening or color changes, necessitating controlled application conditions.

4.2 Meat and Poultry Processing

Ozone has been effectively applied in meat and poultry processing for surface decontamination, equipment sanitation, and odor removal. It is particularly useful in reducing pathogenic microorganisms such as *Salmonella spp.*, *Listeria monocytogenes*, and *Escherichia coli* (Gimenez et al., 2024).

Ozone treatment in meat processing can be applied as:

- Gaseous ozone for storage and air sanitation
- Aqueous ozone for washing carcasses and surfaces

Research shows that ozone reduces microbial contamination without leaving chemical residues, making it suitable for clean-label food production. It also helps in controlling odors and improving hygienic conditions in processing environments. Nevertheless, ozone may cause lipid oxidation in fatty tissues if applied at high concentrations, which can affect flavor and shelf life.

4.3 Seafood Preservation

Seafood is highly susceptible to microbial spoilage due to its high moisture content and nutrient availability. Ozone has been widely used in seafood processing to enhance microbial safety and extend shelf life.

Ozone is applied in seafood processing through:

- Ozonated water for washing fish and shellfish
- Ozonated ice for storage and transportation
- Gaseous ozone in cold storage

Ozonated ice is particularly effective as it provides continuous antimicrobial action during melting, thereby reducing microbial growth and maintaining freshness (Prabha et al., 2015; Nath et al., 2014). Studies have demonstrated improved sensory quality, reduced microbial load, and extended shelf life in seafood treated with ozone. However, excessive ozone exposure may lead to protein oxidation and texture changes, necessitating careful control of processing parameters.

4.4 Dairy Industry Applications

In the dairy industry, ozone is primarily used for sanitation of processing equipment, pipelines, storage tanks, and packaging materials. It serves as an effective alternative to chemical disinfectants such as chlorine.

Ozone applications in dairy processing include:

- Cleaning-in-place (CIP) systems
- Disinfection of milk storage tanks
- Sanitization of packaging materials

Ozone effectively destroys biofilms and microbial contaminants without leaving residues, making it suitable for maintaining hygiene in dairy processing environment (Nath et al., 2014). Furthermore, ozone-treated water is used for cleaning and sanitizing surfaces, reducing the reliance on chemical sanitizers and improving environmental sustainability.

4.5 Grain and Cereal Storage

Ozone is widely used in grain storage for controlling insects, molds, and mycotoxins. It acts as a fumigant, replacing traditional chemical fumigants such as phosphine and methyl bromide.

Ozone applications in grain storage include:

- Insect and pest control
- Reduction of fungal contamination
- Degradation of mycotoxins such as aflatoxins

Ozone penetrates grain masses and effectively inhibits microbial growth, thereby improving storage stability and safety (Nath et al., 2014; Ozonation review, 2023). Unlike chemical fumigants, ozone decomposes into oxygen, leaving no toxic residues.

5. ROLE OF OZONE IN FOOD PRESERVATION

Ozone has emerged as a highly effective non-thermal preservation technology due to its strong oxidative potential and ability to inactivate a wide range of microorganisms without leaving harmful residues. Its multifunctional role in food preservation includes microbial inactivation, shelf-life extension, control of spoilage organisms, and enzyme inhibition. These attributes make ozone a sustainable and eco-friendly alternative to conventional chemical preservatives (Xue et al., 2023; Pandiselvam et al., 2019; Nath et al., 2014).

5.1 Microbial Inactivation and Food Safety Enhancement

Ozone is one of the most powerful oxidizing agents used in food processing, capable of inactivating bacteria, fungi, viruses, and spores through oxidative damage to cellular components. The antimicrobial action of ozone is primarily attributed to:

- Oxidation of cell membrane lipids leading to leakage of cellular contents
- Damage to proteins and enzymes disrupting metabolic pathways

- Oxidative degradation of nucleic acids inhibiting replication

Ozone has been reported to be effective against major foodborne pathogens such as *Escherichia coli*, *Salmonella spp.*, and *Listeria monocytogenes* (Khadre et al., 2001; Kim et al., 1999). Its high oxidation potential enables rapid microbial inactivation compared to traditional sanitizers (Rice, 2002). Furthermore, ozone can penetrate biofilms and disrupt microbial communities, enhancing sanitation efficiency in food processing environments (Xue et al., 2023).

5.2 Shelf-Life Extension

One of the most significant roles of ozone in food preservation is its ability to extend the shelf life of food products by reducing microbial load and slowing down physiological deterioration.

Ozone treatment delays spoilage by:

- Reducing initial microbial contamination
- Slowing respiration rates in fruits and vegetables
- Inhibiting ethylene production and ripening

Studies have shown that ozone treatment significantly extends the shelf life of fresh produce such as fruits and vegetables while maintaining sensory and nutritional quality (Glowacz et al., 2015). Ozonation combined with other preservation techniques (e.g., modified atmosphere packaging) has demonstrated synergistic effects in extending shelf life (Fasake et al., 2022). Ozone also reduces moisture loss and microbial spoilage in meat and seafood, thereby enhancing product stability during storage.

5.3 Control of Spoilage Microorganisms

Spoilage microorganisms, including bacteria, yeasts, and molds, are responsible for food deterioration and economic losses. Ozone effectively controls these organisms through oxidative mechanisms. Ozone treatment has been shown to:

- Inhibit fungal growth and spore germination
- Reduce yeast populations in food systems
- Prevent mold formation during storage

It is particularly effective in controlling post-harvest diseases in fruits and vegetables and reducing fungal contamination in grains (Ziyaina and Rasco, 2021). Ozone also plays a critical role in reducing mycotoxin-producing fungi, thereby enhancing food safety and preventing toxin accumulation.

5.4 Enzyme Inactivation and Browning Prevention

Enzymatic reactions such as browning and degradation significantly affect food quality during storage. Ozone has been shown to inhibit key enzymes responsible for these reactions. Ozone contributes to enzyme inactivation by:

- Oxidizing enzyme active sites
- Altering protein structure and function
- Reducing enzymatic activity involved in browning

Enzymes such as polyphenol oxidase (PPO) and peroxidase (POD), which are responsible for browning reactions in fruits and vegetables, are effectively inhibited by ozone treatment (Pandiselvam et al., 2019) is shown in table 5. This leads to:

- Reduced enzymatic browning
- Preservation of color and appearance
- Improved sensory quality

Ozone treatment has also been reported to maintain the physicochemical properties of food products by slowing enzymatic degradation processes.

Table 5. Role of Ozone in Food Preservation

Function	Mechanism	Impact on Food
Microbial Inactivation	Oxidation of cell components	Enhanced food safety
Shelf-Life Extension	Reduced microbial load, delayed ripening	Increased storage stability
Spoilage Control	Inhibition of fungi and bacteria	Reduced food deterioration
Enzyme Inactivation	Oxidation of enzyme proteins	Prevention of browning

6. IMPACT OF OZONE ON FOOD QUALITY

Ozone application in food systems not only enhances safety but also significantly influences food quality attributes, including nutritional composition, sensory properties, and physicochemical characteristics. While ozone is generally considered a mild and non-thermal technology, its effects are highly dependent on concentration, exposure time, and food matrix. Proper optimization ensures preservation of quality, whereas excessive exposure may lead to oxidative degradation (Anjali et al., 2022; Xue et al., 2023).

6.1 Nutritional Quality

Ozone treatment has been widely reported to maintain or even enhance the nutritional profile of foods when applied under controlled conditions. Ozone interacts with food components primarily through oxidation, which can influence vitamins, phenolic compounds, and antioxidants. Studies have shown that ozone treatment can enhance antioxidant activity by stimulating stress-related metabolic pathways in plant tissues (Food Control, 2022).

Ozone treatment has been reported to:

- Preserve vitamin C and phenolic compounds under optimized conditions
- Increase bioavailability of bioactive compounds
- Maintain overall nutritional integrity in fruits and vegetables

However, excessive ozone exposure may lead to degradation of sensitive nutrients such as ascorbic acid due to oxidative reactions. Therefore, treatment parameters must be carefully controlled.

6.2 Sensory Attributes (Color, Texture, Flavor)

Sensory quality is a critical factor influencing consumer acceptance, and ozone treatment plays a dual role in preserving and sometimes altering these attributes. Ozone treatment helps maintain sensory quality by:

- Reducing microbial spoilage, thereby preserving freshness
- Preventing discoloration and maintaining natural color
- Retaining firmness and texture in fresh produce

Research indicates that ozone-treated foods generally exhibit minimal changes in sensory attributes compared to untreated samples when proper concentrations are used.

In fruits and vegetables, ozone delays ripening and senescence, thereby maintaining visual appeal and texture. However, at higher concentrations, ozone may cause:

- Texture softening due to cell wall degradation
- Off-flavors due to oxidation of lipids and volatile compounds

6.3 Physicochemical Properties

Ozone treatment can significantly influence the physicochemical properties of food, including pH, moisture content, color parameters, and structural characteristics. Key physicochemical changes include:

- Modification of starch and protein structures
- Changes in water activity and moisture retention
- Alteration of rheological properties

Ozone oxidation leads to structural modification of starch molecules by introducing carbonyl and carboxyl groups, affecting functional properties such as gelatinization and viscosity. In cereal products, ozone treatment has been shown to:

- Improve dough strength
- Enhance baking quality
- Modify functional properties of proteins and starch

These changes can be beneficial for food processing applications but must be carefully controlled to avoid undesirable effects.

6.4 Oxidative Effects and Quality Degradation

Despite its advantages, ozone's strong oxidizing nature can lead to quality degradation if not properly controlled is shown in table 6. Ozone-induced oxidation can result in:

- Lipid oxidation, leading to rancidity and off-flavors
- Protein denaturation, affecting texture and functionality
- Pigment degradation, causing color changes

Studies highlight that lipid-rich foods such as meat and dairy products are particularly susceptible to oxidative damage during ozone treatment. However, these negative effects can be minimized by:

- Optimizing ozone concentration and exposure time
- Combining ozone with other preservation methods
- Applying ozone under controlled environmental conditions

Overall, when properly managed, ozone treatment provides a balance between microbial safety and quality preservation.

Table 6. Impact of Ozone on Food Quality Attributes

Quality Parameter	Positive Effects	Negative Effects (if overexposed)
Nutritional Quality	Retains vitamins, enhances antioxidants	Nutrient degradation
Sensory Attributes	Maintains color, texture, freshness	Off-flavors, softening
Physicochemical Properties	Improves functional properties	Structural alterations
Oxidative Stability	Controls spoilage	Lipid and protein oxidation

7. ADVANTAGES OF OZONE TECHNOLOGY

Ozone technology has emerged as a promising non-thermal preservation method in the food industry due to its multifunctional benefits, including environmental sustainability, high antimicrobial efficacy, and compatibility with modern consumer demands. Its ability to act as a powerful oxidant while decomposing into oxygen makes it superior to many conventional chemical sanitizers (Prabha et al., 2015; Singh and Singh, 2021). The increasing adoption of ozone in food systems is driven by its eco-

friendly nature, strong antimicrobial activity, clean-label compatibility, and reduced dependence on water and chemicals (Xue et al., 2023; Hong et al., 2024)

7.1 Residue-Free and Eco-Friendly Nature

One of the most significant advantages of ozone technology is its environmentally sustainable nature. Ozone decomposes rapidly into oxygen, leaving no harmful residues or toxic by-products in treated food or processing environments. Unlike traditional chemical sanitizers such as chlorine, ozone does not produce carcinogenic by-products or chemical residues. This makes it highly suitable for applications where food safety and environmental protection are critical (Rice, 2002; Kim et al., 1999).

Ozone is recognized as an eco-friendly technology because it:

- Decomposes into oxygen after application
- Eliminates the need for chemical storage and disposal
- Reduces environmental pollution

Studies confirm that ozone leaves no residual compounds on food or contact surfaces, making it safe and sustainable for food processing applications

7.2 Strong Oxidizing and Broad-Spectrum Antimicrobial Activity

Ozone is one of the strongest oxidizing agents available for food processing, with a higher oxidation potential than chlorine, enabling rapid and effective microbial inactivation. Its antimicrobial activity is attributed to the formation of reactive oxygen species (ROS), which cause oxidative damage to microbial cell membranes, proteins, and DNA. Ozone is effective against:

- Bacteria (*E. coli*, *Salmonella*, *Listeria*)
- Fungi and molds
- Viruses and spores

Ozonated water has demonstrated superior microbial reduction compared to conventional sanitizers due to its high redox potential. Additionally, ozone exhibits non-selective antimicrobial action, meaning it can inactivate a wide range of microorganisms without promoting resistance, unlike some chemical disinfectants.

7.3 Compatibility with Clean-Label Trends

The demand for clean-label foods—free from synthetic additives and chemical preservatives—has significantly increased in recent years. Ozone technology aligns perfectly with this trend.

Ozone is considered a natural processing aid because:

- It is generated from oxygen
- It leaves no chemical residues
- It does not alter food composition significantly

Ozonation has been widely recognized as a clean-label compatible technology, helping maintain food quality without synthetic preservatives. Furthermore, regulatory approvals (e.g., GRAS status by FDA) have supported its application in food processing, increasing consumer confidence in ozone-treated products

7.4 Reduced Water and Chemical Usage

Ozone technology contributes significantly to sustainable food processing by reducing the consumption of water and chemical sanitizers. Key advantages include:

- Reduced chemical usage: Ozone replaces conventional disinfectants such as chlorine and hydrogen peroxide

- Water recycling: Ozonated water can be reused in processing systems
- Lower operational costs: Reduced need for chemical procurement and disposal

Ozone enables efficient sanitation with minimal water usage, making it suitable for modern sustainable food processing systems as shown in table 7. It also enhances cleaning efficiency in equipment and processing lines, reducing overall resource consumption (Panebianco et al., 2022)

Table 7. Key Advantages of Ozone Technology in Food Processing

Advantage	Mechanism	Industrial Impact
Residue-Free Nature	Decomposition into oxygen	Safe and eco-friendly processing
Strong Antimicrobial Activity	Oxidative damage to microbes	Enhanced food safety
Clean-Label Compatibility	No chemical additives	Consumer acceptance
Reduced Resource Usage	Lower water and chemical demand	Sustainable processing

8. Limitations and Challenges

Despite its numerous advantages, ozone technology presents several limitations that restrict its universal application in food processing. These challenges are primarily associated with high operational costs, safety concerns, limited penetration ability, and oxidative damage risks. Understanding these constraints is essential for optimizing ozone applications and ensuring safe, effective implementation in food systems (Singh and Singh, 2021; Tiwari et al., 2010).

8.1 Equipment and Operational Costs

One of the major barriers to the widespread adoption of ozone technology is the high initial investment and operational costs associated with ozone generation systems. Ozone must be generated on-site due to its instability and short half-life, which eliminates the possibility of storage or transportation. This necessitates the installation of specialized ozone generators and monitoring systems (Tiwari et al., 2010).

Additional cost-related challenges include:

- High capital cost of ozone generators and auxiliary equipment
- Energy consumption for continuous ozone production
- Maintenance and replacement of system components

Furthermore, integrating ozone systems into existing food processing lines may require infrastructure modifications, increasing overall operational costs (Mayookha et al., 2023).

8.2 Safety Concerns and Toxicity at High Concentrations

Although ozone is effective as a disinfectant, it is also toxic to humans at high concentrations, posing safety risks for workers and requiring strict regulatory control.

Exposure to high levels of ozone can cause:

- Respiratory irritation and lung damage
- Eye and skin irritation
- Long-term health effects upon prolonged exposure

Ozone's high reactivity also makes it corrosive to certain materials, which can affect equipment durability and safety (Frontiers, 2025).

To mitigate these risks, food industries must implement:

- Proper ventilation systems
- Ozone sensors and monitoring devices
- Strict adherence to occupational exposure limits

Accurate dosing and controlled application are critical to prevent harmful effects on both workers and food products.

8.3 Limited Penetration in Solid Foods

A significant limitation of ozone is its restricted penetration into solid food matrices, which limits its effectiveness primarily to surface decontamination. Research indicates that aqueous ozone can penetrate only a few millimeters into food tissues, while gaseous ozone can penetrate deeper but still remains limited compared to other preservation methods. This limitation results in:

- Ineffectiveness against internalized microorganisms
- Reduced efficacy in dense or solid food products
- Dependence on surface exposure for microbial inactivation

Therefore, ozone is more suitable for surface sanitation of fresh produce, meats, and grains rather than deep microbial control.

8.4 Risk of Over-Oxidation

Ozone's strong oxidative nature, while beneficial for microbial inactivation, can also lead to undesirable quality degradation when applied in excess is shown in table 8. Excessive ozone exposure can cause:

- Lipid oxidation, leading to rancidity and off-flavors in meat and dairy products
- Protein denaturation, affecting texture and functionality
- Vitamin degradation, reducing nutritional quality

Studies highlight that ozone-induced oxidation can significantly impact food quality, particularly in lipid-rich products (Çelebi et al., 2024). Ozone may generate undesirable by-products due to non-selective oxidation, affecting sensory and physicochemical properties (Frontiers, 2025). Careful optimization of ozone concentration, exposure time, and environmental conditions is essential to balance microbial safety with quality preservation.

Table 8. Limitations and Challenges of Ozone Technology

Limitation	Cause	Impact on Food Processing
High Cost	Need for on-site generation and equipment	Increased capital and operational expenses
Safety Concerns	Toxicity at high concentrations	Health risks for workers
Limited Penetration	Low diffusion into solid foods	Surface-only effectiveness
Over-Oxidation	Strong oxidizing nature	Quality degradation and nutrient loss

9. REGULATORY ASPECTS AND SAFETY GUIDELINES

The application of ozone in food processing is governed by international regulatory frameworks to ensure its safe and effective use. Regulatory agencies such as the U.S. Food and Drug Administration and the Food Safety and Standards Authority of India have established guidelines regarding ozone's approval status, permissible limits, and occupational safety requirements. These regulations emphasize the use of ozone under Good Manufacturing Practices (GMP) and controlled conditions to ensure food safety and worker protection (Rice, 2002; Xue et al., 2023).

9.1 Approval Status (FDA, FSSAI and Global Perspective)

Ozone has received global recognition as a safe antimicrobial agent for food processing. The U.S. Food and Drug Administration granted ozone Generally Recognized As Safe (GRAS) status for use in food processing, storage, and treatment. Ozone is permitted as a secondary direct food additive under 21 CFR 173.368, allowing its use in both gaseous and aqueous forms in direct contact with food. Furthermore, the FDA formally approved ozone in 2001 as an antimicrobial agent for food applications under GMP conditions. Similarly, the United States Department of Agriculture approved ozone for use in meat and poultry processing, reinforcing its safety and industrial applicability. In India, the Food Safety and Standards Authority of India regulate food safety under the Food Safety and Standards Act (2006). Although ozone is not always explicitly listed as a standalone additive, it is permitted as a processing aid and disinfectant under hygiene and sanitation guidelines, provided it does not leave harmful residues. Globally, ozone is also recognized by organizations such as:

- World Health Organization
- Food and Agriculture Organization

These bodies acknowledge ozone's role in improving food safety and water quality.

9.2 Permissible Limits and Usage Guidelines

Although ozone is widely approved, its application must comply with strict concentration limits and exposure guidelines to ensure safety. According to FDA guidelines:

- Ozone must be used under Good Manufacturing Practices (GMP)
- Concentrations should be optimized based on food type and processing conditions
- Ozone application must not adversely affect food quality

For example, ozone concentrations as low as 0.1 ppm in water systems are effective for microbial control in bottled water processing under GMP conditions. In juice processing, ozone treatment must achieve a 5-log reduction of pathogens as required by Hazard Analysis Critical Control Point (HACCP) regulations. Typical application ranges include:

- 0.1–5 ppm (aqueous ozone) for washing and sanitation
- 0.01–0.1 ppm (gaseous ozone) for storage environments

In India, Food Safety and Standards Authority of India emphasizes adherence to:

- Food hygiene standards
- Safe limits for disinfectants
- Absence of harmful residues in final products

Thus, ozone usage must be carefully controlled through validated processing systems.

9.3 Worker Safety and Handling Protocols

While ozone is beneficial for food safety, it poses occupational health risks at high concentrations, necessitating strict safety protocols. Exposure to ozone can lead to:

- Respiratory irritation
- Lung tissue damage
- Eye and skin irritation

Regulatory agencies such as the Occupational Safety and Health Administration recommend exposure limits is shown in table 9, typically:

- 0.1 ppm (8-hour exposure limit)

- Lower limits for continuous exposure in enclosed environments

To ensure worker safety, industries must implement:

- Proper ventilation systems
- Ozone monitoring and alarm systems
- Personal protective equipment (PPE)
- Automated ozone control systems

Additionally, training programs are essential to ensure proper handling and emergency response. Ozone systems should be designed to prevent leakage and ensure controlled application.

Table 9. Regulatory and Safety Guidelines for Ozone in Food Processing

Aspect	Regulatory Requirement	Practical Implication
Approval Status	GRAS (FDA), permitted under GMP	Safe for food processing
Usage Limits	Controlled ppm levels	Prevents overexposure
Process Validation	HACCP compliance	Ensures microbial safety
Worker Safety	OSHA exposure limits	Protects personnel health
Residue Control	No residual ozone allowed	Maintains food safety

10. Integration with Emerging Technologies

The integration of ozone with emerging non-thermal technologies has gained significant attention in modern food processing due to the need for enhanced microbial safety, improved quality retention, and sustainable processing. While ozone alone is effective, its combination with technologies such as ultrasonication, ultraviolet (UV) radiation, and cold plasma forms a synergistic preservation strategy, often referred to as hurdle technology. These combined approaches enhance antimicrobial efficacy while minimizing adverse effects on food quality (Xue et al., 2023; Dubey et al., 2022)

10.1 Ozone with Ultrasonication

The combination of ozone with ultrasonication (also called sono-ozonation) has emerged as a powerful technique for improving microbial inactivation and mass transfer efficiency. Ultrasonication generates acoustic cavitation, producing microbubbles that collapse violently, resulting in localized high temperature and pressure. This phenomenon enhances ozone effectiveness by:

- Increasing mass transfer of ozone into food matrices
- Disrupting microbial cell structures
- Enhancing oxidation reactions

Studies report that sono-ozonation significantly improves microbial reduction compared to ozone alone, particularly in fresh produce washing and wastewater treatment (Pandiselvam et al., 2019; Tiwari et al., 2010). Ultrasonication helps remove surface contaminants, allowing ozone to penetrate more effectively. This combination has shown promising results in:

- Fruits and vegetables sanitation
- Meat surface decontamination
- Juice processing

However, excessive ultrasound intensity may cause structural damage to food tissues, requiring optimization of processing parameters.

10.2 Ozone Combined with UV and Cold Plasma

The integration of ozone with UV radiation and cold plasma technologies enhances antimicrobial efficacy through the generation of reactive species.

Ozone + UV Radiation

UV radiation can generate ozone and reactive oxygen species simultaneously, leading to:

- Enhanced DNA damage in microorganisms
- Increased oxidative stress
- Improved disinfection efficiency

This combination is widely used in water treatment and surface sterilization systems.

Ozone + Cold Plasma

Cold plasma generates reactive species such as:

- Reactive oxygen species (ROS)
- Reactive nitrogen species (RNS)

When combined with ozone, these species create a highly oxidative environment, resulting in:

- Rapid microbial inactivation
- Biofilm disruption
- Enhanced surface sterilization

Cold plasma–ozone systems are particularly effective for:

- Packaging sterilization
- Fresh produce decontamination
- Meat and seafood processing

Recent studies highlight that such combined technologies offer greater efficiency at lower ozone concentrations, reducing the risk of quality degradation (Xue et al., 2023)

10.3 Hurdle Technology Approaches

Hurdle technology involves the use of multiple preservation methods to create a combined inhibitory effect on microorganisms, ensuring food safety while maintaining quality. In ozone-based hurdle systems, ozone is combined with:

- Modified atmosphere packaging (MAP)
- Refrigeration
- pH control
- Natural antimicrobials

The effectiveness of hurdle technology is based on:

- Creating multiple stress factors for microorganisms
- Disrupting microbial metabolism and survival mechanisms
- Enhancing overall preservation efficiency

According to recent studies, combining ozone with other preservation methods significantly improves microbial inactivation and shelf-life extension while preserving sensory and nutritional quality is shown in table 10. Hurdle technology also helps in:

- Reducing required ozone concentration
- Minimizing oxidative damage
- Improving energy efficiency

This integrated approach is considered a future direction in food preservation, aligning with clean-label and sustainable processing trends.

Table 10. Integration of Ozone with Emerging Technologies

Technology Combination	Mechanism	Key Advantages	Applications
Ozone + Ultrasonication	Cavitation + oxidation	Enhanced mass transfer, improved microbial inactivation	Fruits, vegetables, juices
Ozone + UV	UV-induced ROS + ozone oxidation	DNA damage, high disinfection efficiency	Water treatment, surface sterilization
Ozone + Cold Plasma	ROS & RNS generation	Rapid microbial inactivation, biofilm removal	Packaging, meat, produce
Hurdle Technology	Multiple preservation barriers	Improved safety and quality retention	Multi-food systems

11. INDUSTRIAL APPLICATIONS AND CASE STUDIES

Ozone technology has transitioned from laboratory-scale research to large-scale industrial implementation across multiple sectors of the food industry. Its applications range from sanitation and water treatment to preservation and storage systems. Real-world case studies demonstrate its effectiveness in improving food safety, extending shelf life, and reducing operational costs. The adoption of ozone technology is driven by its high antimicrobial efficiency, eco-friendly nature, and compatibility with modern processing systems (Nath et al., 2014; Prabha et al., 2015; Pandiselvam et al., 2019). Industrial-scale ozonation is now widely applied in fruits and vegetables, meat processing, dairy industries, beverage production, and grain storage systems.

11.1 Commercial Implementation in Food Industries

Ozone technology has been successfully integrated into various industrial food processing operations, particularly for sanitation and preservation purposes.

Key Industrial Applications

- **Fresh Produce Industry:** Ozonated water is widely used for washing fruits and vegetables to reduce microbial load and pesticide residues.
- **Meat and Poultry Processing:** Ozone is used for carcass decontamination and sanitation of processing equipment.
- **Beverage Industry:** Ozone is extensively used in bottled water and juice processing for microbial control and water purification.
- **Grain Storage:** Gaseous ozone is applied for insect control and mycotoxin reduction in stored cereals.

Industrial systems often integrate ozone into processing lines, storage environments, and cleaning-in-place (CIP) systems, ensuring continuous sanitation and improved hygiene. Ozone is used in air treatment systems within food processing facilities to control airborne contamination and maintain hygienic conditions.

11.2 Success Stories and Practical Examples

Several case studies highlight the successful application of ozone technology in real-world food processing scenarios.

Case Study 1: Fresh Produce Industry

Commercial produce washing systems using ozonated water have demonstrated:

- Significant reduction in microbial contamination
- Extended shelf life of fruits and vegetables
- Reduced reliance on chemical sanitizers

Ozone-treated produce shows improved quality retention and reduced spoilage losses

Case Study 2: Poultry Processing

Ozone has been successfully used in poultry processing plants for:

- Carcass decontamination
- Reconditioning of chilling water
- Reduction of pathogenic microorganisms

The United States Department of Agriculture approved ozone for poultry water treatment, demonstrating its industrial viability

Case Study 3: Beverage Industry

In bottled water and juice processing:

- Ozone ensures microbial safety without chemical residues
- Improves water quality by removing odors and contaminants

This application is widely adopted due to ozone's GRAS status and high disinfection efficiency

Case Study 4: Grain Storage Systems

Ozone fumigation in grain storage facilities has shown:

- Effective control of insects and molds
- Reduction of mycotoxin contamination
- Improved storage stability

These applications demonstrate ozone's versatility across different food sectors.

11.3 Economic Feasibility

The economic feasibility of ozone technology depends on both initial investment costs and long-term operational benefits is shown in table 11.

Cost Considerations

- High initial cost for ozone generators and installation
- Energy consumption for ozone production
- Maintenance and monitoring costs

Economic Benefits

- Reduced chemical usage and procurement costs
- Lower water consumption due to reuse systems
- Decreased product losses due to spoilage

- Improved shelf life and product quality

Ozone eliminates the need for chemical storage and transportation, which significantly reduces operational costs over time. Moreover, ozone-based systems contribute to:

- Sustainability goals
- Reduced environmental impact
- Compliance with clean-label trends

Several industrial studies indicate that although the initial investment is high, ozone technology becomes cost-effective in the long term due to reduced operational expenses and improved efficiency (Prabha et al., 2015; Singh and Singh, 2021).

Table 11. Industrial Applications and Economic Analysis of Ozone Technology

Sector	Application	Benefits	Economic Impact
Fruits & Vegetables	Washing, decontamination	Reduced microbes, longer shelf life	Lower spoilage losses
Meat & Poultry	Carcass sanitation	Pathogen reduction	Improved safety compliance
Beverages	Water and juice treatment	Residue-free disinfection	Reduced chemical cost
Grain Storage	Fumigation	Pest and mold control	Reduced storage losses
Dairy	CIP sanitation	Equipment hygiene	Reduced cleaning chemicals

12. FUTURE TRENDS AND RESEARCH DIRECTIONS

Ozone technology continues to evolve as a sustainable and efficient non-thermal processing method in the food industry. Emerging research focuses on integrating ozone with advanced technologies, improving process efficiency through automation, and aligning with sustainability goals. Future developments are expected to enhance ozone's applicability in smart food systems, nanotechnology-enabled processing, and circular economy models is shown in table 12 (Pandiselvam et al., 2026; Xue et al., 2023). The increasing demand for clean-label, minimally processed foods and environmentally friendly technologies has accelerated research into optimizing ozone-based systems for industrial scalability and precision control.

12.1 Process Optimization and Automation

Process optimization and automation are critical for improving the efficiency, safety, and scalability of ozone technology in food processing. Modern ozone systems are increasingly integrated with:

- Sensors and real-time monitoring systems
- Programmable logic controllers (PLC)
- Internet of Things (IoT)-based automation

These technologies enable precise control of ozone concentration, exposure time, and environmental conditions, ensuring consistent processing outcomes. Automated systems also reduce human intervention and enhance safety by minimizing exposure risks. Recent advancements indicate that high-efficiency ozone generators and automated dosing systems improve energy efficiency and operational reliability, making ozone more viable for large-scale industrial applications

Furthermore, process optimization strategies include:

- Modeling ozone diffusion and reaction kinetics
- Optimizing process parameters for different food matrices
- Integration with HACCP-based control systems

Such innovations are expected to enable precision food processing, where ozone application is tailored to specific product requirements.

12.2 Nano-enabled Ozone Applications

Nanotechnology offers significant opportunities for enhancing ozone-based food processing systems. Emerging research focuses on:

- **Nano-bubble ozone systems** for improved solubility and stability
- **Nano-encapsulation techniques** for controlled ozone release
- Enhanced interaction between ozone and microbial cells

Nano-bubble technology increases ozone dissolution in water, improving its antimicrobial efficiency and prolonging its activity. This leads to:

- Better penetration into food matrices
- Reduced ozone consumption
- Improved microbial inactivation

Additionally, nanotechnology enables the development of advanced antimicrobial coatings and packaging materials, further enhancing food preservation capabilities. However, challenges such as nanomaterial safety, regulatory concerns, and cost must be addressed before widespread commercialization.

12.3 Smart Packaging Integration

The integration of ozone technology with smart and intelligent packaging systems represents a significant advancement in food preservation. Smart packaging systems incorporate:

- Sensors for detecting spoilage and microbial activity
- Active packaging materials releasing ozone or antimicrobial agents
- Real-time monitoring of food quality

These systems can:

- Extend shelf life by controlling microbial growth
- Provide real-time feedback on food freshness
- Reduce food waste through improved monitoring

Nanotechnology further enhances smart packaging by enabling nano-sensors and traceability systems, improving supply chain transparency and food safety. Future developments are expected to integrate ozone with:

- Modified atmosphere packaging (MAP)
- Biodegradable packaging materials
- Digital food tracking systems

12.4 Sustainability and Circular Food Systems

Sustainability is a key driver in the future development of ozone technology in food processing. Ozone contributes to sustainable food systems by:

- Reducing chemical usage and environmental pollution
- Enabling water recycling and reuse in processing operations

- Minimizing food waste through improved preservation

Ozone's ability to decompose into oxygen without leaving harmful residues makes it a green processing technology, supporting circular economy principles. In circular food systems, ozone can be integrated into:

- Wastewater treatment and reuse
- By-product valorization processes
- Energy-efficient food processing systems

Moreover, ozone-based technologies align with global sustainability goals by:

- Reducing carbon footprint
- Enhancing resource efficiency
- Supporting eco-friendly food production

Future research will focus on:

- Life cycle assessment (LCA) of ozone systems
- Integration with renewable energy sources
- Development of low-energy ozone generation technologies

Table 12. Future Trends in Ozone Technology for Food Processing

Research Area	Key Innovations	Expected Impact
Process Optimization	Automation, IoT, sensors	Improved efficiency and safety
Nanotechnology	Nano-bubbles, nano-encapsulation	Enhanced antimicrobial activity
Smart Packaging	Sensors, active packaging	Real-time quality monitoring
Sustainability	Water reuse, eco-friendly systems	Reduced environmental impact

13. CONCLUSION:

The application of ozone technology in food processing and preservation has emerged as a highly promising, eco-friendly, and efficient alternative to conventional chemical sanitizers and thermal treatments. As a strong oxidizing agent, ozone demonstrates remarkable antimicrobial efficacy against a wide spectrum of foodborne pathogens, including bacteria, viruses, fungi, and spores, while also contributing to the degradation of pesticide residues and mycotoxins. Its ability to decompose into oxygen without leaving harmful residues positions ozone as a sustainable solution aligned with global food safety and environmental goals (Kim et al., 1999; Khadre et al., 2001). From a technological standpoint, both gaseous and aqueous ozone applications have shown significant effectiveness across diverse food matrices such as fruits, vegetables, cereals, meat, seafood, and dairy products. The integration of ozone with advanced non-thermal technologies—such as ultrasound, pulsed light, and cold plasma—has further enhanced its efficiency, enabling synergistic effects that improve microbial inactivation while preserving sensory and nutritional quality (Tiwari et al., 2010; Misra et al., 2015). These combined approaches are particularly valuable in meeting consumer demand for minimally processed, “clean-label” foods. Despite its advantages, certain limitations must be acknowledged. The high reactivity of ozone can lead to oxidative damage in sensitive food components such as lipids, pigments, and vitamins if not carefully controlled. Factors such as ozone concentration, exposure time, temperature, and food composition significantly influence treatment outcomes. Therefore, process optimization and precise control systems are essential to ensure efficacy while minimizing quality degradation (Rice et al., 2012; Pandiselvam et al., 2019).

Recent advancements in nano-enabled ozone delivery systems and smart packaging technologies have opened new frontiers for controlled and targeted ozone application. Nano-bubbles and encapsulation techniques improve ozone stability and penetration, while intelligent packaging systems incorporating ozone sensors enable real-time monitoring of food freshness and

safety. These innovations not only enhance the efficiency of ozone utilization but also contribute to reducing food waste and improving supply chain transparency (Jiang et al., 2021; Ahmed et al., 2020). Furthermore, the role of ozone technology in supporting sustainable food systems cannot be overstated. By reducing reliance on chemical preservatives, lowering water usage in sanitation processes, and minimizing environmental pollution, ozone aligns with circular economy principles and global sustainability targets. Its application in wastewater treatment and post-harvest management further strengthens its position as a multifunctional tool in modern food processing industries (Brodowska et al., 2018). In conclusion, ozone technology represents a versatile and sustainable approach to food preservation, offering significant benefits in terms of safety, quality, and environmental impact. However, its successful industrial adoption depends on overcoming current challenges related to process control, scalability, and regulatory harmonization. Future research should focus on optimizing application parameters, developing hybrid technologies, and exploring innovative delivery systems to fully harness the potential of ozone in the evolving landscape of food processing and preservation.

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Conflicts of Interest:

The authors declare that there are no conflicts of interest associated with this publication. All opinions, analyses, and conclusions presented in this review are solely those of the authors and do not necessarily reflect the views of the funding agencies or affiliated institutions.

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